

# GALLIUM

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In 2002, U.S. gallium imports, which supply most of the domestic gallium demand, fell to less than one-half the total of 2001. A stagnant economy, especially in the wireless communications segment, and the buildup of inventories of gallium arsenide (GaAs) that began in 2000 limited demand for gallium metal in 2002. In addition, the movement of GaAs wafer manufacturing facilities from the United States to such countries as China, the Republic of Korea, and Taiwan in the past few years has shifted the demand for gallium metal to these countries rather than the United States. Several companies announced closure of their U.S. GaAs manufacturing facilities during 2002. Gallium nitride (GaN) continued to be the focus of research and development activities, particularly on methods to improve its properties and to grow bulk GaN.

More than 95% of gallium consumed in the United States was in the form of GaAs. Analog integrated circuits (ICs) were the largest application for gallium, with optoelectronic devices [mostly laser diodes and light-emitting diodes (LEDs)] as the second largest end use.

World production of virgin gallium was estimated to be 61 metric tons (t). Total production for refined gallium was estimated to be 81 t, and demand for this material was centered in Japan, the United States, and Western Europe. Significant quantities of new scrap were recycled and supplemented supplies, particularly in Japan.

## Production

No domestic production of primary gallium was reported in 2002 (table 1). In May, Eagle-Picher Technologies LLC announced that it was exiting the gallium business because of a drop in demand for gallium-based products from the telecommunications industry. The company, which reprocesses gallium from end users, planned to sell its remaining inventory through the rest of 2002 (Platts Metals Week, 2002). This exit would leave 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 (t/yr) 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. The company's gallium recovery in 2002 was estimated to be about 17 metric tons (t) compared with about 36 t in 2001 (Recapture Metals Inc., 2003§<sup>1</sup>).

Gold Canyon Resources Inc. continued its drilling plan that was begun in 2001 to define the high-gallium-mineralization area at its Cordero property in Humboldt County, NV. According to the

company, combined results from the 2001 and 2002 programs defined two large high-grade zones of gallium mineralization with average grades in excess of 100 grams per metric ton (g/t). These high-grade zones are contained within broad area with a gallium concentration of greater than 30 g/t and are aligned along the "M" fault zone. Both of the high-grade zones exceed 180 meters (m) in width and have a combined strike length of about 1,500 m (Gold Canyon Resources Inc., 2002§).

Although Win-Eldrich Mines Ltd. had announced in 2001 that it planned to begin a bulk sampling program to determine the quantities of gallium at its Painted Hills property in Humboldt County, the company did not report any additional development of the property in 2002.

## 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. Analog ICs were the largest end-use application for gallium, with 46% of total consumption. Optoelectronic devices accounted for 42% of domestic consumption, 9% was used in research and development, and the remaining 3% was used in digital ICs and other applications (tables 2, 3).

Gallium consumption data are collected by the U.S. Geological Survey from a voluntary survey of U.S. operations. In 2002, there were 11 responses to the consumption of gallium survey, representing 50% of the total canvassed. Because of the poor response rate, data in tables 2 and 3 were adjusted by incorporating estimates to reflect full industry coverage. Many of these estimates were based on companies' 2002 10-K reports submitted to the U.S. Securities and Exchange Commission.

**Gallium Arsenide.**—In January, RF Micro Devices Inc. began production in its second GaAs heterojunction bipolar transistor (HBT) fabrication facility in Greensboro, NC, at the company's headquarters. The new facility is equipped initially to produce up to 40,000 wafers per year, and construction of the plant, which was originally scheduled to be completed by yearend 2000, was delayed by the slowdown in the wireless communications industry. RF Micro Devices' current facility can produce up to 60,000 4-inch wafers per year. When the new facility is fully equipped and operating at full capacity, it is expected to be able to produce the equivalent of approximately 210,000 4-inch wafers per year, bringing the projected capacity of the company's two GaAs HBT fabrication plants to the equivalent of approximately 270,000 4-inch wafers per year (Dixon and Whitaker, 2002).

In February, EMCORE Corp. announced that it reached an agreement to acquire certain assets of the Applied Solar Division business of Tecstar Inc. The acquisition will be

<sup>1</sup>References that include a section mark (§) are found in the Internet References Cited section.

executed through a Chapter 11 reorganization of Tecstar. Under the terms of the agreement, EMCORE will pay \$21 million for the solar cell business and operations of Tecstar. The acquisition will allow EMCORE to expand its solar cell product offerings to include solar panel arrays (EMCORE Corp., 2002§).

After its acquisition of Tecstar, EMCORE was awarded a contract to design and develop a solar array to power the CRYOSAT satellite, a project of the European Space Agency. The satellite will monitor land and marine ice mass fluxes to improve the understanding of climate change. The solar array will convert sunlight into electrical power and will provide the primary power source for the CRYOSAT satellite. EMCORE's triple junction solar cells are based on an indium gallium phosphide (InGaP)-GaAs-germanium junction on a germanium substrate stack and typically offer a beginning-of-life efficiency of 26% at 28° C (Compound Semiconductor, 2002d§).

Philips Semiconductors (a division of Royal Philips Electronics) and TriQuint Semiconductor Inc. signed an agreement to form a strategic partnership that allows Philips Semiconductors controlled access to TriQuint's InGaP HBT 150-millimeter (mm) wafer-processing facilities and provides for joint development of future advanced high-performance process technologies. This agreement provides Philips Semiconductors access to TriQuint's technology for critical components in the modules that it designs and manufactures for the wireless communications industry and provides TriQuint with another purchaser for its GaAs devices (TriQuint Semiconductor Inc., 2002§). In July, TriQuint also acquired Infineon Technologies' GaAs integrated circuit business as part of a collaboration between the two companies to develop and produce RF components and modules for customized wireless handsets. TriQuint will not acquire Infineon's manufacturing operations, but instead will enter into an interim supply agreement with Infineon while the business is being transferred to TriQuint's Oregon facility. The transfer is estimated to take about 1 year (Dixon, 2002c). In October, TriQuint also announced that it would acquire a substantial portion of Agere Systems Inc.'s optoelectronics business for \$40 million in cash. The acquisition follows Agere's announcement in August that it was seeking a buyer for all or part of this business and was exiting the optoelectronics business as part of a corporate restructuring effort. The transaction includes products, technology and some facilities related to Agere's optoelectronics business, including lasers and detectors (Compound Semiconductor, 2002n§).

Alpha Industries Inc. and Conexant Systems Inc. agreed in December 2001 to combine Conexant's wireless business with Alpha to create a leader in radio frequency and to complete semiconductor system solutions for mobile communications applications. Under the terms of the agreement, Conexant would spin off its wireless business, including its GaAs wafer fabrication facility in Newbury Park, CA. In March 2002, Conexant and The Carlyle Group formed a new specialty foundry company named Jazz Semiconductor Inc., in which Conexant owns a 45% equity interest, and The Carlyle Group owns the remaining 55%. In the transaction, Conexant contributed its Newport Beach wafer fabrication operations and certain intellectual property to Jazz. As a result, the merger between Alpha and Conexant was completed in June 2002. Alpha and Conexant named the new company Skyworks Solutions Inc. (Compound Semiconductor,

2002m). In September, Skyworks qualified a Taiwanese GaAs foundry, Advanced Wireless Semiconductor Co. (AWSC), as a second source to provide Skyworks with GaAs HBT foundry processing services. Conexant had signed a multiyear agreement with AWSC in December 2000 to supply the company with 30,000 GaAs HBT wafer starts per year to increase Conexant's total capacity to 125,000 wafer starts per year (Compound Semiconductor, 2002l§). Skyworks also announced that it would transfer its InGaP HBT fabrication from the former Alpha facility in Sunnyvale to its Newbury Park facility and close the Sunnyvale plant. The company also planned to continue to use a 4-inch GaAs wafer platform for its devices rather than switch to a 6-inch platform as many companies have already done (Dixon, 2002b).

Raytheon Co.'s RF Components division has formed a foundry alliance with Taiwan-based WIN Semiconductors Corp. to produce GaAs components for the wireless telecommunications market. Raytheon planned to invest \$5 million in WIN and would transfer its 3.0-micrometer ( $\mu\text{m}$ ) gate-length InGaP/GaAs HBT process onto WIN's 6-inch manufacturing line. In exchange, WIN will manufacture InGaP HBT products for Raytheon RF Components and guarantee access to a portion of WIN's foundry capacity. Raytheon's transfer will allow the company to focus its 4-inch foundry in Andover, MA, on lower volume commercial and military products (Compound Semiconductor, 2002o).

Sumitomo Electric Semiconductor Materials Inc. completed a new \$20 million 6-inch GaAs wafer polishing facility in Hillsboro, OR. Construction of the 8,360-square-meter ( $\text{m}^2$ ) building was completed in November 2001. Pilot production began in January 2002, product qualification was conducted in the spring with epitaxial foundries and device manufacturers, and volume production began in June. This is Sumitomo Electric's first compound semiconductor manufacturing facility in the United States (Compound Semiconductor, 2002m§).

Bandwidth Semiconductor LLC expanded its metal-organic chemical vapor deposition (MOCVD) operations from a 370- $\text{m}^2$  facility in Bedford, MA, into a new 1,250- $\text{m}^2$  foundry in a 4,650- $\text{m}^2$  building with an additional 3,700  $\text{m}^2$  for expansion in Hudson, NH. (The company was formed in 1999 with Stratos Lightwave Inc.'s purchase of Spire Corp.'s Optoelectronics Division.) The company purchased a new multiwafer MOCVD reactor designed for the growth of GaAs and indium-phosphide (InP)-based compounds for its new facility (Compound Semiconductor, 2002b§).

Anadigics Inc. has added 930  $\text{m}^2$  of class 10 clean room space to its facility in Warren, NJ, at a cost of about \$10 million. The expansion doubles its capacity and provides the infrastructure that Anadigics needs for an anticipated increase in demand for its wireless products. The additional space will accommodate increased production of 6-inch InGaP HBT wafers, which are used to manufacture power amplifier circuits used in cellular telephones and PDAs (Compound Semiconductor, 2002c).

In response to continuing adverse market conditions, Vitesse Semiconductor Inc. announced that it would exit the GaAs business by September 2003. The company had originally planned to move its GaAs operations from Camarillo, CA, to Colorado Springs, CO, where it operates a 6-inch GaAs fabrication plant. (The Camarillo operation would be devoted to InP production.) However, the company said that the Colorado Springs facility

was only operating at 10% of its capacity, and even if there was a complete recovery in the industry by 2004, the plant would not be fully utilized. Vitesse hopes to partner with a foundry company for its Colorado Springs facility (Whitaker, 2002).

Filtronic plc, a United Kingdom-based manufacturer of GaAs-based components for wireless communications applications, announced that it would close its Filtronic Solid State facility in Santa Clara, CA. The company was looking at its options for the 3-inch GaAs facility, including a possible sale. Filtronic is operating a 6-inch GaAs facility in Newton Aycliffe, United Kingdom, and has agreements to supply 6-inch wafers to M/A-Com Inc., BAE Systems Inc., and Powerwave Technologies Inc. from that facility (Compound Semiconductor, 2002k).

ATMI Inc. discontinued its GaAs epitaxy business in 2002 citing falling revenues from that operation. ATMI anticipated that a write-down will be required covering most of the estimated \$40 million invested in its Phoenix, AZ, GaAs epitaxial wafer business; the company abandoned the lease on this facility after exiting the GaAs business (Compound Semiconductor, 2002d). Although ATMI included a write-off of the GaAs business in its third quarter 2002 financial report, the company plans to seek a joint venture for the business.

Akzo Nobel NV's High Purity Metalorganics unit and Mochem GmbH of Marburg, Germany, merged to form a new metalorganics business, which will operate under the Akzo Nobel name. Mochem is a leading manufacturer of liquid group V products, such as tertiarybutyl arsine, tertiarybutyl phosphine, and dimethylhydrazine. Akzo Nobel manufactures a range of metalorganics for MOCVD and chemical beam epitaxy (CBE), such as trimethylgallium, trimethylindium, and trimethylaluminum. The merger allows the two firms to provide a complete range of products for MOCVD and CBE (Compound Semiconductor, 2002b). Akzo Nobel operates a metalorganics facility in Texas.

Exsil Inc., a firm that reclaims silicon wafers, announced that it has the capability to reclaim 4- and 6-inch GaAs wafers. The company chemically strips and etches the surface of a wafer that has surface defects and then polishes the wafer to remove trace contaminants to meet customers' specifications. The company claims that its reclaimed 6-inch wafers, which cost \$85 to \$100 each, will be more economical than purchasing prime-grade wafers at \$350 to \$400 each or mechanical-grade wafers at \$175 to \$250 each (Exsil Inc., undated§).

**Gallium Nitride.**—In February, Kyma Technologies Inc. announced that it had shipped the industry's first single-crystal 2-inch GaN wafers to an unidentified major device manufacturer. The single-crystal GaN substrates are 500  $\mu\text{m}$  thick and have greater than 90% usable area for circuit fabrication. The 2-inch-diameter substrates are N-type and may be used as base material for a variety of applications in communications and semiconductor products, covering a range of systems from optical storage to wireless handsets to radar (Semiconductor Business News, 2002a§).

RF Micro Devices announced in May that it planned to begin production of GaN wafers in June, with commercial production to begin in 2003 or 2004. The GaN wafers are being produced at the former RF Nitro Communications Inc.'s 4-inch-wafer facility in Charlotte, NC. (In October 2001, RF Micro Devices acquired RF Nitro.) RF Micro Devices hopes that

GaN technology could dominate the power amplifier design in wireless communications base stations. At present, the power amplifier in a base station is based on various technologies, but GaN potentially could allow higher efficiency than existing designs (Semiconductor Business News, 2002b§).

In December, Sony Corp. and Nichia Corp. announced that they had formed an alliance to develop products for the Blu-ray disc recording format. Although the companies have been in collaboration since June, the December agreement extends this collaboration by allowing the companies to share their respective technologies and patents. The two companies will jointly develop 405-nanometer (nm) high-output-power blue-violet laser diodes for Blu-ray disc, a next generation large-capacity optical disc video recording format. Mass production of the devices is expected in spring 2003, and the companies will each manufacture and sell the products resulting from the development program (Compound Semiconductor, 2002i§).

In June, Crystal Photonics Inc. (Sanford, FL) announced that it would export 2-inch GaN substrates to Japan. Instead of being grown on conventional silicon carbide (SiC) or sapphire substrates, this GaN is grown on lithium gallium oxide ( $\text{LiGaO}_2$ ) or lithium aluminum oxide ( $\text{LiAlO}_2$ ) substrates within a hybrid MOCVD-hydride vapor-phase epitaxy (HVPE) reactor. The company claims that the lattice match between the lithium-based substrates and GaN is better than with traditional substrates, but the chemical compatibility is not as good. The hybrid reactor provides a better deposition environment than conventional MOCVD, which improves the chemical compatibility. In addition, there is weak bonding strength between GaN and  $\text{LiGaO}_2$  or  $\text{LiAlO}_2$ , which allows a thick epitaxial layer of GaN to be grown and easily removed from the substrate, leaving a single-crystal free-standing GaN wafer (Compound Semiconductor, 2002g).

**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.

Lumileds Lighting announced a new application in dentistry for its blue GaN-based LEDs operating at around 460 nm. The LEDs are used in place of conventional halogen lamps for curing polymers, which are part of the composite material used to fill teeth. According to Lumileds, several companies are now incorporating its Luxeon V Dental LED-based light source in dental light-curing devices, which provide faster curing times, easier use, and consume less energy than current products. Traditionally, most blue-light sources in dentistry use tungsten filament halogen lamps that incorporate a blue filter to produce light in the 400- to 500-nm region. LEDs offer a number of advantages compared with tungsten for such applications. The use of a monochromatic light source eliminates the need for inefficient color filters, while the low-voltage direct-current operation allows small handheld and cordless designs. Halogen lamps require intensive fan cooling and have a short lifetime compared to LED sources. Additional benefits include instant illumination, precise beam control, minimum glare, low ultraviolet light, mercury-free operation, and a cool light beam that is safe to the touch (Compound Semiconductor, 2002c§).

Lumileds also demonstrated the potential of using white LEDs in the headlights of two concept vehicles—the Ford

Mighty F-350 Tonka concept truck and the Fioravanti Yak concept car. This is the first use of LEDs in headlamp applications. Normally LEDs cannot be used because of the difficulty of creating a powerful enough beam. The concept vehicles' headlamps consist of a cluster of 36 LEDs controlled by software to produce different beam patterns (Compound Semiconductor, 2002e).

Taiwanese LED manufacturer United Epitaxy Corp. (UEC) developed and patented a metal-bonding technology to bond aluminum gallium indium phosphide (AlGaInP) LED epitaxial wafers to silicon substrates, resulting in high-power devices. UEC has successfully developed a large-area, high-power AlGaInP LEDs measuring 2.5 by 2.5 mm. Because heat dissipation is the main problem of such high-power chips, UEC used its metal-bonding technology to bond the AlGaInP LED epitaxial wafer to a silicon substrate, allowing better heat dissipation. To improve the LED's properties further, the company is developing a new technology that will bond the AlGaInP LED epitaxial wafer to a metal heat sink, such as aluminum or copper (Compound Semiconductor, 2002o§).

The Japanese firm Sanken Electric Co. Ltd. introduced AlGaInP-on-silicon red and yellow high-brightness LEDs using its silicon wafer direct-bonding technology. Samples of the devices, which the company says offer up to 100 times the luminosity of its conventional LEDs, were available in October, and commercial production was expected around spring 2003. The company uses silicon substrates to dissipate heat caused by the large currents used in the AlGaInP chips, which would typically be grown on GaAs substrates. Silicon substrates provide a higher thermal dissipation than GaAs, benefit from mature processing technology, and are less expensive (Compound Semiconductor, 2002p).

At the end of 2001, the leading manufacturers of LEDs—Cree Inc., Lumileds, Nichia, Osram Opto Semiconductors GmbH, Rohm Co. Ltd., and Toyoda Gosei Co. Ltd.—were entangled in a series of legal disputes over patents that spread uncertainty among customers and cost millions in legal fees. Primarily because of efforts by Nichia, many of these disputes were resolved in 2002, and companies have entered into licensing and manufacturing agreements.

In October, Osram GmbH granted a patent license to Rohm that allows the Japanese LED manufacturer to make and sell white LEDs using technology covered by Osram's patents. The technology, which was developed by Osram Opto Semiconductors, relates to white LEDs fabricated using blue-emitting indium-gallium-nitride (InGaN)-based chips and a suitable fluorescent converter. In June, Osram Opto and Nichia signed a cross-licensing agreement covering GaN-InGaN-based optoelectronic devices and related packaging technology that resolved an ongoing patent dispute between the two companies (Compound Semiconductor, 2002j§). Also in October, Lumileds and Nichia announced a broad cross-licensing agreement under which they will share intellectual property rights to their respective LED technologies. The companies say that the new relationship will avert patent disputes and associated supply issues. It is also expected to accelerate the design of brighter LEDs by enabling each company to incorporate the research and development efforts of the other in new product development (Compound Semiconductor, 2002g§).

In January, Nichia agreed to sell blue LED chips to Citizen Electronics Co. Ltd. in Japan and also licensed its packaging technology to Citizen to enable them to mass produce white LEDs. According to agreements between the two companies, Citizen Electronics will purchase production quantities of Nichia InGaN dies for the manufacture of packaged white LEDs. The packaging and sale of white LEDs by Citizen Electronics will be licensed under Nichia's white LED patent portfolio (Compound Semiconductor, 2002n). The first LED product that Citizen Electronics developed after its agreement with Nichia was white LED lamps for use in camera-equipped mobile telephones. The LEDs are designed to provide enough illumination to record video clips of several seconds in length under dim lighting conditions, which cannot be accomplished with conventional flash sources (Compound Semiconductor, 2002r).

Two new firms entered the GaN LED market in 2002. Oriol Inc., based in Santa Clara, CA, offered its first products for sale—InGaN blue LEDs operating at 445 nm and 475 nm. The company grows its epitaxial wafers via MOCVD on 2-inch sapphire substrates at its Santa Clara facility and also purchases wafers from United States and Taiwanese producers. The company's estimated capacity was 17 million units per month, and it planned to triple this by early 2003 when it moved into a new facility at Lodi, CA. Tekcore Co. Ltd., a Taiwan-based firm, introduced its first products—470-nm blue and 505-nm green LEDs—in late 2001. The company operated a 2,800-m<sup>2</sup> facility in Nantou, with a capacity of 600 wafers per month. Tekcore planned to increase capacity to 2,200 wafers per month by 2003 and to introduce new products (Dixon, 2002a).

## Prices

In 2002, producer prices for gallium were no longer quoted in American Metal Market. Data for 2002 in table 4 represent the average value of gallium imported into the United States. Press reports indicated that in January, the price of gallium from China, which is low-grade material, was about \$380 per kilogram (Mining Journal, 2002). By March, this price had dropped to \$250 per kilogram, where it remained throughout the rest of 2002. Higher grade gallium was estimated to be priced at about \$450 per kilogram.

The average value of gallium imported into the United States provides some indication of price levels. The average value of gallium imported from China in 2002 was \$229 per kilogram, which agrees with the prices quoted in Mining Journal. Although grades of gallium are not specified in the import data, this material is most likely 99.9%- to 99.99%-pure gallium. The average values of gallium imported from France and Germany, which is most likely high-purity material (99.9999%- to 99.99999%-pure), were \$535 per kilogram and \$560 per kilogram, respectively.

## Foreign Trade

U.S. gallium imports fell to less than one-half the total in 2001 (table 5). China (84%) was the largest source of imported gallium. The drop in gallium imports mainly resulted from a decrease in demand. A stagnant economy and the buildup of inventories of GaAs since 2000 limited demand for gallium

metal in 2002. In addition, the movement of GaAs wafer manufacturing facilities from the United States to such countries as China, the Republic of Korea, and Taiwan in the past few years has shifted the demand for gallium metal to these countries rather than the United States.

In 2002, the Harmonized Tariff Schedule (HTS) code for gallium was changed. Prior to 2002, unwrought gallium was imported into the United States under HTS code 8112.91.1000; this code was changed to 8112.92.1000.

In addition to gallium metal, GaAs wafers were imported into the United States. In 2002, 15,100 kilograms (kg) of undoped GaAs wafers was imported, a 64% drop from that in 2001. Japan (52%) and Lebanon (46%) were the principal sources. At an average value of \$0.38 per kilogram, however, the material from Lebanon is unlikely to be GaAs wafers and is most likely misclassified. Excluding the material from Lebanon, the total imports of undoped GaAs wafers would be 8,160 kg. Japan (44%), Germany (17%), Italy (13%), and Finland (11%) were the main import sources for doped GaAs wafers, totaling 112,000 kg during the year, which was an increase of 20% from that in 2001.

## World Review

Estimated crude gallium production was 61 t in 2002. Principal world producers were China, Germany, Japan, and Russia. Hungary, Kazakhstan, Slovakia, and Ukraine also recovered gallium. China was a significant source of crude gallium in 2002, supplying 84% of U.S. imports and an estimated 22% of Japan's imports. Refined gallium production was estimated to be about 81 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.

**Australia.**—GEO Specialty Chemicals Inc. (2002§) exercised its option to acquire the shares of Rhodia Pinjarra Pty. Ltd., the prior owner of the dormant gallium extraction plant in Pinjarra, Western Australia. The option was exercised on September 4 for approximately \$1.4 million. All other work by GEO on the Pinjarra project was in suspension because of the weak condition of the global gallium market and restrictions under its amended credit facility. According to the 10-year agreement between Alcoa Inc. of Australia and GEO that was completed in December 2001, GEO has 36 months to begin actions to start gallium operations without incurring a penalty.

**China.**—In February, AXT acquired a 51% stake in the Beijing Ji-Ya Semiconductor Material Co., a gallium extraction facility in Shanxi, which gives AXT the right of first refusal on their production. Beijing Ji-Ya will sell output that is not consumed by AXT on the open market. The facility, which began production in late 2001, is capable of providing approximately 20 t/yr of 99.99%-pure gallium, which would be enough to meet most of AXT's peak period needs. Third party processors will be used to refine Beijing Ji-Ya's production to 99.99999% purity. AXT also operates a GaAs wafer production facility in China (Semiconductor Fabtech, 2002§).

**Germany.**—ULM Photonics GmbH opened a new

manufacturing facility in Ulm to serve a growing vertical-cavity surface-emitting laser (VCSEL) market. The company expects the market for 850-nm VCSEL diodes to be \$180 million by 2005 and \$560 million by 2010. The facility is equipped with additional quality assurance equipment and a new molecular beam epitaxy (MBE) system for the growth of GaAs-based VCSELs. The new equipment will help ULM Photonics create more efficient VCSELs by controlling the growth of the crystal. ULM Photonics has been shipping VCSEL arrays and high-speed devices to more than one dozen European and North American customers (Compound Semiconductor, 2002p§).

**Japan.**—In 2001, Japan's virgin gallium production was reported to be 8 t, gallium recovered from scrap was reported to be 50.2 t, and gallium imports were reported to be 67 t, for a total supply of 125 t. Demand in Japan was estimated to be 96 t. The principal source countries for Japan's gallium imports were the United States (21.5 t), Kazakhstan (11.1 t), China (10.9 t), and France (9.7 t). In 2002, production was estimated to have remained at 8 t, with imports dropping to 44.5 t and scrap recovery increasing to 44 t. Gallium demand in Japan was projected to increase to 114 t (Roskill's Letter from Japan, 2002).

Sanyo Electric Co. Ltd. planned to start mass production of violet GaN-based laser diodes in April 2003, primarily for use in next generation, high-capacity optical storage applications. The company would invest around ¥5 billion (about \$43 million) to install production lines at its Tottori Sanyo Electric subsidiary in Tottori Prefecture and planned to produce a maximum of 2 million units per month. Sharp Corp. also announced plans to begin mass production of blue lasers for high-capacity, next-generation optical storage systems in late 2003. In September, Sharp completed a new laser production facility in Hiroshima Prefecture where the new lasers will be produced (Compound Semiconductor, 2002k§).

Sony planned to invest about \$24 million to build a new plant to produce red laser diodes for DVD players. The new plant in Miyagi Prefecture was expected to be operational by summer 2003 and would double Sony's production capacity of 655-nm lasers to 10 million units per month (Compound Semiconductor, 2002q).

**Taiwan.**—WIN announced plans to triple its overall GaAs wafer production capacity in response to growing demand for foundry services. The company added new capacity and chip-production equipment to its existing 6-inch GaAs wafer plant to expand capacity to 4,500 wafers per month from 1,500 wafers per month by yearend. In addition, the company planned to expand its capacity to 8,000 wafers per month at an undisclosed time in the future. WIN was founded in 1999, and its 6-inch GaAs plant opened in 2000 (Semiconductor Business News, 2002c§).

Advanced Epitaxy Technology Inc. (AET), based in Hsinchu, developed a new bonding technology that can bond LED wafers onto different substrates with high yield. Using its virtual-chip bonding technology, AET has demonstrated the bonding of GaN-on-sapphire LED wafers onto GaAs substrates. Removal of the original sapphire substrate from the GaN active layers results in a vertically conducting blue LED on GaAs. The vertically conducting devices can have smaller chip sizes than GaN-on-sapphire LEDs and need only a single bonding wire. AET was originally founded in 1998 to supply epitaxial wafers to the GaAs industry but obtained funding from the Ministry

of Economic Affairs of Taiwan to develop GaN substrates, which are expected to be commercialized by the end of 2003 (Compound Semiconductor, 2002a).

**United Kingdom.**—Epichem Ltd. announced that it would construct a new multiton trimethylgallium facility at its headquarters in Bromborough. When completed, the plant would be the largest of its kind in the world. Epichem's plant would have multikilogram batch sizes, which would reduce product variability and reduce production costs. The company plans to target LED and solar-cell manufacturing applications (Compound Semiconductor, 2002i).

### Current Research and Technology

Researchers at Kansas State University and at the U.S. Department of Energy's Argonne National Laboratory in Illinois developed a neutron detector based on a GaAs chip. The researchers used GaAs in an effort to miniaturize the detectors, making them more portable for such applications as detecting smuggled fissile material, which could be used to fuel nuclear weapons, at ports and airports, and for use by international nuclear nonproliferation inspectors. Currently, two types of neutron detectors are in use—those based on a tube filled with gas that is ionized by neutrons and those based on silicon. The GaAs-based detectors are made by coating semi-insulating GaAs with isotopically enriched boron or lithium and can be manufactured using conventional processes. Using GaAs rather than silicon has several advantages. The detectors can be made smaller, require less than 50 volts of operating power, and operate at room temperature. Replacing silicon with GaAs also improves the lifetime of the detector when it is used in areas with high radiation levels (Newey, 2002b).

In February, Freiburger Compound Materials GmbH of Freiberg, Germany, reported that it produced the first 8-inch-diameter GaAs wafers from vertical-gradient-freeze (VGF) crystals; 6-inch-diameter wafers were the largest that had been produced previously. Freiburger manufactures GaAs substrates using the liquid-encapsulated Czochralski (LEC) crystal growth method and has also developed its own VGF growth technology. Although LEC is a more economical production process, VGF wafers feature different characteristics, such as a lower etch-pit density, which can be an advantage in certain applications. Future applications for semi-insulating GaAs could benefit from the larger wafer diameter because increased wafer size would lead to higher production efficiency and cost savings. In addition, the availability of 8-inch GaAs wafers may allow GaAs epitaxial facilities to use state-of-the-art processing equipment designed for 8-inch silicon processing (Compound Semiconductor, 2002i). Using 8-inch GaAs substrates supplied by Freiburger, MOCVD equipment manufacturer Aixtron AG has grown GaAs epitaxial structures on these wafers in a multiwafer MOCVD system. The company used numerical modeling techniques to scale-up its existing AIX 2600G3 reactor to enable multiple 8-inch-wafer growth (Newey, 2002a).

Kopin Corp. reported improvements to its CyberLite LED technology by developing a new method for depositing ohmic contacts with lower resistance and higher stability in harsh environments. This is the first time an epitaxial contact has been formed on GaN, and Kopin expects this technology to be superior

to polycrystalline contacts that are typically used in the industry. This patent-pending process, combined with other technologic developments, has allowed Kopin to produce LEDs that are as bright as those commercially available but can be driven by much lower voltage (Compound Semiconductor, 2002f§).

Researchers at the University of California, Berkeley and Oriol Inc. in Santa Clara, CA, are using an excimer laser to separate LED heterostructures from their sapphire growth substrate so that they subsequently may bond them to silicon. Using silicon as a substrate for GaN-based LEDs would improve the performance of the devices as well as ease their integration with electronics. The scientists first attach the top of the LED structure to a silicon wafer using Krazy glue. The researchers then melted the bottom of the stack through the sapphire with an excimer laser. The structure is bonded to another silicon wafer with a palladium-indium alloy at 200° C, and the temporary adhesive is removed with acetone. Measurements of properties of the LEDs confirmed that threshold voltages and output in the devices that were remounted on silicon had improved (Photonics Spectra, 2002a).

Researchers at the University of Minnesota in Minneapolis and at Harvard University in Cambridge, MA, have developed a self-assembly technique that may enable the manufacture of novel displays; self-assembly is three-dimensional, so it can work on cylindrical or curved surfaces. To build an LED display by self-assembly, the researchers begin with a flexible copper-polyimide substrate that features an array of solder-covered spots to which LEDs will selectively bond. They insert the substrate into a cylindrical vial with hot water and acetic acid to melt the solder and to remove any metal oxide, respectively, and add the LEDs. Shaking the mix for up to 2 minutes ensures that the components assemble on the solder receptors. A subsequent agitation in another water bath removes any LEDs that have bonded incorrectly. Because the new technique can fabricate curved displays, it could enable the manufacture of novel consumer-level displays, such as sunglass-mounted monitors or pen/cell phone combinations with a screen around the stylus (Photonics Spectra, 2002b).

AmberWave Systems Corp. has devised a way to combine silicon and compound semiconductor materials, such as GaAs, on a single substrate. The new technique has the potential to significantly reduce the cost of optoelectronic devices including space solar cells and communications lasers. Silicon and compound semiconductor materials normally cannot be combined because of their different crystal structures, which create stress between the materials and cause devices to fail. AmberWave eliminates this mismatch by building a buffer layer on the silicon substrate. Layers are deposited from 100% silicon to 100% germanium with a silicon germanium (SiGe) interlayer. The potential of this technology has been successfully demonstrated by creating detector-type devices, including single- and dual-junction aluminum gallium arsenide (AlGaAs)-GaAs and InGaP-GaAs photovoltaic cells. The goal for these devices is comparable performance to solar cells made with III-V compounds on germanium substrates but with lighter weight, lower cost, and improved robustness. The company estimated the weight decrease for replacing a germanium substrate with silicon to be 65%, which would more than double the power output per unit of weight. In addition, silicon substrates can be

produced in larger diameters than germanium substrates, which can lead to a 50% reduction in manufacturing costs (Missile Defense Agency, 2002§).

EMCORE received a patent for a dicing technique that can be used for GaN-based LED dies and other materials grown on sapphire substrates. The new technique uses a laser to separate the processed wafer into individual die and solves issues associated with current separation techniques. Typically die separation is accomplished using a scribe-and-break process, but this method is not well suited to sapphire, which has a hexagonal crystal structure. The typical separation process reduces the usable area of the wafer and results in device yields of about 70% to 80%. The new laser process has yields of 99% for a 2-inch wafer containing 350- $\mu\text{m}$ -size LEDs and typically takes 15 to 20 minutes for a complete wafer (Compound Semiconductor, 2002h).

Cermet Inc., an Atlanta, GA-based manufacturer of GaN and zinc oxide materials, won two Missile Defense Agency contracts to develop bulk and thin-film GaN for military applications. In the first contract, Cermet will tackle bulk GaN fabrication problems and develop low-cost, low-defect-density GaN boules. Substrates produced from the boules will be used in high-power, high-frequency nitride transistors for advanced radar, onboard monitoring, and communication systems. Cermet is also developing GaN thin films for ultraviolet sensors that can be tuned across all ultraviolet wavelengths. The Missile Defense Agency plans to incorporate the tunable sensors into its missile defense systems and also use them to detect airborne biological agents (Compound Semiconductor, 2002f).

In September, ATMI (Danbury, CT) was awarded a contract worth \$9.5 million for the development of highly uniform, robust, aluminum gallium nitride (AlGaIn)-GaN high-electron-mobility transistors (HEMTs) on 4-inch GaN and SiC substrates. The contract has been awarded through the Office of Naval Research and is part of the Defense Advanced Research Project Agency's Wide Bandgap Semiconductor Technology Initiative, which is seeking to speed the development of wide bandgap materials for high-power devices. The work at ATMI will involve the development of bulk growth techniques for large area semi-insulating GaN substrates and highly uniform GaN and AlGaIn epitaxial processes. The contract will run for 18 months with an option to extend the work for a further 6 months (Compound Semiconductor, 2002a§).

In June, Japan's Sumitomo Electric Industries Ltd. reported the development of a novel single-crystal GaN substrate that may be used in violet lasers for high-capacity, next-generation Blu-ray disc optical video recording technology. Sumitomo Electric started shipping samples and is continuing to develop mass-produced substrates. In the epitaxial growth of GaN, sapphire substrates are commonly used, and most research has focused on making GaN-based violet laser devices using sapphire substrates. Because the physical properties of sapphire substrates and GaN are different, sapphire substrates cause dislocation density to become extremely high, which reduces the lifetime of the laser and has led to delays in the practical application of GaN-based violet lasers. Sumitomo Electric's new GaN substrate has a dislocation density of between 10,000 and 100,000; conventional GaN epitaxial layers on sapphire substrates have a dislocation density of about 100,000. After

laser device manufacturers evaluate the new GaN substrate, mass production will start by the time Blu-ray disc comes to market. Sumitomo Electric forecasts the production of low-dislocation GaN substrates to reach 300 per month by April 2003 (Sumitomo Electric Industries Ltd., 2002§).

Koninklijke Philips Electronics N.V. developed an optical disk drive that uses a blue laser diode to store 1 gigabyte of data on a 3-centimeter (cm)-diameter disk. The device's storage capacity, which is 1.5 times that of standard 10-cm-diameter CDs, will allow the device to store thousands of high-resolution digital images or digital music files. Unlike conventional optical disk drives, the new drive uses a plastic lens rather than a glass optic to focus the blue laser beam onto the disk. According to Philips, the plastic component is the smallest objective lens ever used for blue-laser recording and allows a reduction in the height of the drive from 12.5 mm to 7.5 mm. The device, which uses a Nichia laser emitting at 405 nm, works in read-only mode, but the company plans to develop a rewritable drive (Compound Semiconductor, 2002h§).

A research collaboration between Rheinisch-Westfälische Technische Hochschule Aachen in Germany, the Stepanov Institute of Physics in Minsk, Belarus, and MOCVD equipment maker Aixtron AG in Aachen, Germany, demonstrated the first optically pumped InGaIn-GaN blue laser grown on a silicon substrate, which could eventually lead to a low-cost production method for such devices. Silicon wafers are available in diameters of up to 12 inches and potentially offer a lower cost platform for compound semiconductor-based devices. InGaIn-based lasers and LEDs are currently manufactured on expensive smaller diameter (e.g., 2- to 4-inch) SiC and sapphire wafers. According to the researchers, the properties of the new laser are similar to those grown on sapphire and SiC substrates (Compound Semiconductor, 2002j).

A team from Southampton University in the United Kingdom developed a process that could facilitate the transition between optical and electrical signals. The technique involves a structural change in the surface of a piece of gallium when exposed to light. This structural change, which reverses when the light is removed, turns the gallium into a metallic form, producing a change in its conductivity. Gallium has as many as eight or nine crystalline structures; some are good metallic conductors, others are semiconductors. The gallium used in this experiment was in a semiconducting phase. According to the researchers, this is the first observation of light being the main means of transforming conductivity in an elemental metal. This phenomenon occurred over a wide spectrum, from 400 nm to 1.8  $\mu\text{m}$ , covering the infrared and entire visible spectrum. Gallium's sensitivity to infrared radiation is significant for potential telecommunications applications. The work was in the experimental fundamental physics phase (Silicon Strategies, 2002§).

The USGS is conducting research that is focused on determining the distribution and genesis of high concentrations of gallium recently discovered in clays and alunite associated with hydrothermal systems at the McDermitt mercury deposit in Nevada. Large hydrothermal alteration zones are localized within this and other volcanic centers where deposits of clay have been developed and mined. These alteration zones host potentially significant resources of gallium either as a primary

product or as a byproduct of clay extraction. This association may provide a model for other occurrences associated with other types of hydrothermal metallic deposits in the Western United States, and it may represent an important source of this metal that has not been widely recognized before (U.S. Geological Survey, 2003§).

## Outlook

Strategy Analytics Inc. says that because of a continuing inventory use in 2002 to supply a significant portion of demand for GaAs substrates, a balance between supply and demand will not return until 2003. According to the company, the excessive inventory in 2000 was built primarily on expectations of continuing demand through 2001 and fears of a 6-inch wafer shortage. The decline in demand for products manufactured using semi-insulating GaAs wafers in 2001 left some users with inventory levels equivalent to a 10-month supply and led to a 40% decline in the merchant market for semi-insulating GaAs substrates in 2001. Strategy Analytics forecasts that the merchant market for GaAs substrates will show growth through 2006 of about 11% but that GaAs substrate vendors will have to wait until 2003 to see the level of merchant sales that were observed in 2000 (Compound Semiconductor, 2002e§).

After a flat year in 2001, the market for high-brightness LEDs grew by 50% to \$1.8 billion in 2002, according to Strategies Unlimited (a research unit of PennWell Corp.). Growth was mainly driven by the mobile appliance market, which accounted for about 40% of the high-brightness LED market. The mobile appliance market, which includes mobile phone screen and keypad backlights, PDAs, and digital cameras, grew by 114% compared with 2001. Although there was very little growth in handset shipments, more high-brightness LEDs were used in handsets due to a proliferation of full-color screens, larger screens, secondary screens, and backlighting for keypads. In terms of materials, the market was dominated by InGaN-based devices, which accounted for 68% of total high-brightness LED sales. AllInGaP LEDs accounted for 24% of the total market in 2002. Other high-brightness LED markets were signs, which include single-color moving message panels and full-color video screens in sports stadiums, and interior and exterior lighting in automotive applications. These markets had a share of 23% and 18%, respectively, and illumination accounted for 5% of the total market in 2002. Strategies Unlimited predicted steady growth in the high-brightness LED market of about 20% per year for the next 5 years, assuming that normal growth takes place in the general economy (Compound Semiconductor, 2003b).

IC Insights Inc. predicts that the compound semiconductor integrated circuit market will have an average growth rate of 22% per year from 2002 through 2007, an increase to \$4.65 billion from \$1.69 billion. This market consists of GaAs and SiGe. SiGe, which accounted for about 13% of the total shipments in 2002, is expected to increase to about 33% of the total by 2007 at the expense of GaAs; therefore, the growth rate for GaAs will be less than the estimated 22% per year (Compound Semiconductor, 2003a).

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TABLE 1  
SALIENT U.S. GALLIUM STATISTICS<sup>1</sup>

(Kilograms unless otherwise specified)

	1998	1999	2000	2001	2002
Production	--	--	--	--	--
Imports for consumption	26,300	24,100	39,400	27,100	13,100
Consumption	26,900	29,800	39,900	27,700	18,600
Price per kilogram	\$595	\$640	\$640	\$640	\$530 <sup>2</sup>

-- Zero.

<sup>1</sup>Data are rounded to no more than three significant digits.

<sup>2</sup>Estimate, based on average value of U.S. imports of high-purity gallium.

TABLE 2  
U.S. CONSUMPTION OF GALLIUM, BY END USE<sup>1,2</sup>

(Kilograms)

End use	2001	2002
Optoelectronic devices:		
Laser diodes and light-emitting diodes	8,710	7,430
Photodetectors and solar cells	598	386
Integrated circuits:		
Analog	16,800	8,600
Digital	1,230	560
Research and development	242	1,630
Other	95	10
Total	27,700	18,600

<sup>1</sup>Data are rounded to no more than three significant digits; may not add to totals shown.

<sup>2</sup>Includes gallium metal and gallium compounds.

TABLE 3  
STOCKS, RECEIPTS, AND CONSUMPTION OF GALLIUM, BY GRADE<sup>1,2</sup>

(Kilograms)

Purity	Beginning stocks	Receipts	Consumption	Ending stocks
2001:				
99.99% to 99.999%	478	--	190	288
99.9999%	341	3,990 <sup>r</sup>	4,180 <sup>r</sup>	154
99.99999% to 99.999999%	136	10,300 <sup>r</sup>	10,300 <sup>r</sup>	136
Total	955	14,300 <sup>r</sup>	14,700 <sup>r</sup>	578
2002:				
99.99% to 99.999%	288	67	--	355
99.9999%	154	4,820	4,750	224
99.99999% to 99.999999%	136	1,350	1,240	245
Total	578	6,240	5,990	824

<sup>r</sup>Revised. -- Zero.

<sup>1</sup>Consumers only.

<sup>2</sup>Data are rounded to no more than three significant digits; may not add to totals shown.

Note: Data reported in earlier years included estimates for gallium content of gallium compounds. Beginning with revised 2001 data, data in table 3 report gallium metal only.

TABLE 4  
YEAREND GALLIUM PRICES

(Dollars per kilogram)

	2001	2002
Gallium metal, 99.99999%-pure, 100-kilogram lots	640 <sup>1</sup>	NA
Gallium metal, 99.9999%-pure, 100-kilogram lots	595 <sup>1</sup>	NA
Gallium metal, 99.9999%-pure, imported	380-425 <sup>1</sup>	NA
Gallium metal, 99.9999%- to 99.9999%-pure, average value of U.S. imports <sup>e</sup>	905	530
Gallium metal, 99.99%-pure, average value of U.S. imports <sup>e</sup>	511	229
Gallium oxide, 99.999%-pure, imported	275-350 <sup>1</sup>	NA

<sup>e</sup>Estimated. NA Not available.

<sup>1</sup>Source: American Metal Market.

TABLE 5  
U.S. IMPORTS FOR CONSUMPTION OF GALLIUM (UNWROUGHT, WASTE,  
AND SCRAP), BY COUNTRY<sup>1</sup>

Country	2001		2002	
	Quantity (kilograms)	Value	Quantity (kilograms)	Value
China	7,710	\$7,280,000	11,000	\$2,520,000
France	10,600	8,050,000	937	502,000
Germany	890	1,320,000	185	104,000
Hungary	879	904,000	--	--
Japan	742	877,000	263	118,000
Korea, Republic of	200	318,000	--	--
Russia	2,990	2,620,000	299	72,200
United Kingdom	2,170	2,360,000	414	231,000
Other	858	448,000	10	2,600
Total	27,100	24,200,000	13,100	3,550,000

-- Zero.

<sup>1</sup>Data are rounded to no more than three significant digits; may not add to totals shown.

TABLE 6  
ESTIMATED WORLD ANNUAL PRIMARY GALLIUM PRODUCTION  
CAPACITY AS OF DECEMBER 31, 2002<sup>1</sup>

(Metric tons)

Country	Capacity
Australia <sup>2</sup>	50
China	40
Germany	35
Hungary	8
Japan	20
Kazakhstan	20
Russia	19
Slovakia	8
Ukraine	3
Total	203

<sup>1</sup>Includes capacity at operating plants as well as at plants on standby basis.

<sup>2</sup>Standby capacity as of December 31, 2002.