GALLIUM

By Deborah A. Kramer

Gallium demand in the United States was supplied by imports, primarily high-purity gallium from France and low-purity material from Russia. Optoelectronic devices manufactured from gallium arsenide (GaAs) continued to be the principal use for gallium. Increased demand for GaAs devices in telecommunications uses prompted several U.S. GaAs manufacturers to increase their production capabilities. Work is also continuing to commercialize blue light-emitting diodes (LED's) and laser diodes, which could provide additional end-use markets for gallium.

World production of virgin gallium was estimated to be 72 metric tons; most of the demand for this material was centered in Japan, the United States, and Western Europe. Significant quantities of new scrap were recycled and supplemented demand, particularly in Japan.

Production

No production of primary gallium was reported in 1997. *(See table 1.)* Eagle-Picher Industries Inc. recovered and refined gallium from domestic and imported sources at its plant in Quapaw, OK. Recapture Metals Inc., Blanding, UT, recovered gallium from scrap materials, predominantly scrap generated during the production of GaAs. Recapture Metals' facilities have the capability of processing about 15 metric tons of high-purity gallium per year. The company recovers gallium from its customers' scrap on a fee basis and purchases scrap and low-purity gallium for processing into high-purity material.

Consumption

More than 95% of the gallium consumed in the United States is in the form of GaAs. GaAs is manufactured into optoelectronic devices (LED's, laser diodes, photodetectors, and solar cells) and integrated circuits (IC's). Analog IC's were the largest end-use application for gallium, with 49% of total consumption. Optoelectronic devices accounted for 44% of domestic consumption, and the remaining 7% was used in digital IC's, research and development, and other applications. *(See tables 2 and 3.)*

Gallium data are collected by the U.S. Geological Survey from two voluntary surveys of U.S. operations. In 1997, there were 15 responses to the "Consumption of Gallium" survey, representing 68% of the total canvassed. Significant quantities of gallium are used by universities and Government research facilities, which are not canvassed by the survey. In tables 1 through 3, data representing gallium consumption were adjusted to reflect full-industry coverage.

LED's consist of layers of an epitaxially grown material on a substrate. These epitiaxial layers are normally gallium aluminum arsenide (GaAlAs), gallium arsenide phosphide (GaAsP), or indium gallium arsenide phosphide (InGaAsP), while the substrate material is either GaAs or gallium phosphide (GaP). The materials used to fabricate LED's determine the color of light that is emitted. With GaP substrates, the wavelength of light can cover the spectrum from pure green, to red. With GaAs substrates, light emitted from an LED is limited to wavelengths at the red and infrared end of the spectrum. Manufacturers are working to develop an LED that operates in the blue and violet end of the spectrum made from gallium nitride (GaN).

Laser diodes operate on the same principle as LED's, but they convert electrical energy to a coherent light output. Laser diodes, also called semiconductor lasers or injection laser diodes, principally consist of an epitaxial layer of GaAs, GaAlAs, or InGaAsP on a GaAs substrate. The two most commonly used laser diodes are GaAlAs and InGaAsP diodes. GaAlAs laser diodes operate at about 780 to 900 nanometers and are used in a wide variety of consumer products and in communications systems. GaAlAs diodes are used in compact disk players, nonimpact laser printers, and optical video disk players. They also are used in short-range fiber optic communications systems, satellite communications, radar transmission, and local cable transmission systems. InGaAsP laser diodes operate at longer wavelengths, 1,300 to 1,500 nanometers, and are primarily used for transmission of high-frequency, long-distance signals in fiber optic communication systems and in cable television supertrunks.

Photodiodes, or detectors, are used to detect a light impulse generated by a source, such as an LED or laser diode, and convert it to an electrical impulse. Photodiodes are fabricated from the same materials as LED's and are used primarily as light detectors in fiber optics systems. There are two types of gallium-based photodiodes—GaAlAs epitaxially grown on a GaAs substrate, used to detect light at short wavelengths, and InGaAsP on an indium phosphide (InP) substrate, used to detect light at longer wavelengths.

Because of its ability to convert light to electrical energy, GaAs has been demonstrated to be an excellent material for solar cells. Although solar cells are not in widespread use, they have been used to power communications satellites.

There are two types of IC's produced commercially—analog and digital. Analog IC's are designed to process signals generated by radar and military electronic warfare systems, as well as those generated by satellite communications systems. Digital IC's essentially function as memory and logic elements of computers.

There are two basic methods used to fabricate GaAs single crystal ingots—boat growth, horizontal Bridgeman (HB) or gradient freeze technique, and the liquid-encapsulated Czochralski (LEC) technique. Ingots produced by the HB method are D-shaped and have a typical cross-sectional area of about 2 square inches. By contrast, single crystal ingots grown by the LEC method are round and are generally 3, 4, or 6 inches in diameter. LEC is the most widely used crystal growth technique.

After the ingots are grown, the ends are cut off, and the ingot is shaped by grinding the edges. Ingots are then sliced into wafers. Wafers go through several stages of surface preparation, polishing, and testing before they are ready for device manufacture or epitaxial growth. Wafer preparation steps are done in a clean room and with minimal contact to avoid introducing surface contaminants.

Pure GaAs is semi-insulating, which means that it is not a conductor of electricity. In order to manufacture devices from GaAs wafers, the wafers must be doped with another metal or metals. Normally, this is accomplished either by ion implantation or by some type of epitaxial growth.

In ion implantation, ions of another metal are implanted into specific areas of the semi-insulating GaAs to make those areas electronically active. After doping, optoelectronic device or IC manufacture can be completed through deposition of layers of metals and insulators by various techniques.

The deposition of an epitaxial layer is another means of creating electronically active regions on the GaAs substrate. There are four principal methods for growing epitaxial layers—liquid-phase epitaxy (LPE), vapor-phase epitaxy (VPE), metal-organic chemical vapor deposition (MOCVD), and molecular-beam epitaxy (MBE). LPE is an earlier method of epitaxy generally not considered suitable for complex semiconductor production, because it can not be as precisely controlled as the other three techniques. In LPE, the substrate wafer is contained in a graphite boat within a quartz furnace tube, where it is contacted with solutions containing the metals to be deposited. Cooling the solution causes the metals to precipitate on the substrate. LPE produces relatively thick epitaxial layers, and the boundaries between layers are gradual rather than sharply defined.

Two methods of VPE are used to grow epitaxial layers on a GaAs substrate—the hydride method and the chloride method. In VPE, GaAs substrates are mounted in a reactor. To make GaAsP epitaxial layers, two gaseous streams are introduced into the reactor. In the hydride process, one gas stream combines arsine (AsH_3) and phosphine (PH_3) with a hydrogen carrier gas, and the other gas stream is a hydrochloric acid gas that has been passed over a gallium reservoir to form gallium trichloride, and which also is mixed with a hydrogen carrier gas. Dopants are added to the gas streams if necessary. Gallium trichloride reacts with the AsH_3 and PH_3 gases to deposit a GaAsP layer on the substrate. In the chloride process, arsenic trichloride and phosphorous trichloride gases are substituted for AsH_3 and PH_3. VPE technology can coat multiple wafers at a time, and the layer thickness, molecular composition, and dopant concentration can be more closely controlled than with LPE.

In MOCVD, (also called metal organic vapor phase epitaxy, or MOVPE, outside the United States) wafers are placed in a quartz reactor, maintained at atmospheric or slightly reduced pressure, at a temperature between 650° to 750° C. Metals to be deposited are in the forms of gases that chemically combine on the heated substrate. For example, to prepare a GaAlAs layer, gallium and aluminum are present in the form of organic gases, generally trimethyl or triethyl gallium and aluminum [$(CH_3)_3Ga$ or $(C_2H_5)_3Ga$ and $(CH_3)_3Al$ or $(C_2H_5)_3Al$] in a hydrogen carrier gas. Arsenic is in the form of AsH_3 in the hydrogen carrier gas. Dopants may also be added. The flow rates of these gases are carefully controlled. As the gases mix in the reactor and contact the hot wafers, they react to form GaAlAs and methane or ethane, and the GaAlAs deposits on the substrate wafers.

With MBE, the GaAs substrate is mounted on a heating block in a reactor maintained under a vacuum, along with effusion cells containing the elements to be deposited. For a GaAlAs layer, the effusion cells would contain gallium, aluminum, arsenic, and dopants. The elements are heated to temperatures that cause them to evaporate. By precise opening and closing of mechanical shutters in front of the effusion cells, the concentration of each element as it deposits can be carefully controlled.

With both MOCVD and MBE, the process may be repeated to build many thin layers of materials with differing compositions. After the epitaxial layers are deposited, device manufacture can be completed through deposition of metallic and insulating layers.

In 1997, Kopin Corp. increased its capacity for processing 4-inch wafers by MOCVD. The company installed a new multiple-wafers-per-run reactor in the fourth quarter of 1996, which came fully on-line in mid-1997 to increase capacity to 30,000 wafers per year. A second reactor, received in the third quarter of 1997, will increase production capacity to 40,000 wafers per year by the beginning of 1998. Kopin produces epitaxial wafer materials for advanced semiconductor circuit applications (Kopin Corp., Wafer engineered epitaxial materials, accessed September 29, 1997, at URL http://www.kopin.com/epi.htm). Kopin also introduced a new indium gallium phosphide (InGaP) heterojunction bipolar transistor for use in wireless and fiber optics communications. The InGaP device has greater temperature stability and reliability than the traditional GaAlAs device and is easier to process. Typical applications for the InGaP transistor include analog-to-digital converters, oscillators, and power amplifiers for higher frequency wireless, digital radar, satellite, and collision avoidance systems (GaAsNET, Kopin introduces next generation HBT wafers, accessed January 16, 1998, at URL http://www.gaasnet.com/news/ Kopin_0897.html).

Quantum Epitaxial Designs announced that it would increase production capacity for MBE wafers by adding a fourth multiwafer MBE reactor at its Bethlehem, PA, facility. The company supplies 3-, 4-, and 6-inch MBE wafers (GaAs, GaAlAs, InGaAs, and InP) as substrates for electronic devices and quantum-well infrared photodetectors (GaAsNET, QED increases manufacturing capacity by adding a fourth multiwafer system, accessed Janaury 16, 1998, at URL http://www.gaasnet.com/news/ QED_0397.html).

Epitronics Corp. also installed a new multiwafer reactor in the third quarter of 1997 to produce GaAlAs and InGaP heterostructures on GaAs wafers by MOCVD. These heterostructures will be used for manufacturing heterojunction bipolar transistors for wireless communications and direct broadcast satellite applications. When fully operational, the reactor will be capable of processing 2,500 4-inch wafers per month (GaAsNET, ATMI's Epitronics unit to increase epitaxy capacity, accessed January 16, 1998, at URL http://www.gaasnet.com/news/ Epi_0497.html).

As part of its strategy to produce more valued-added products, TRW Inc. acquired privately held MilliWave Technologies Corp. in September. The acquisition allows TRW to expand its products line to highly integrated GaAs-based multichip modules; TRW currently supplies low-cost GaAs integrated circuits. The new firm will be known as TRW MilliWave Inc. The largest market for the new firm's products is in digital radio communications. These systems are commonly used for high-capacity, high-speed intraoffice communications networks (GaAsNET, TRW acquires MilliWave Technologies Corp., accessed January 16, 1998, at URL http://www.gaasnet.com/news/trw_1097.html).

In 1997, Anadigics Inc. began shipping the industry's first commercial GaAs dual-band, dual-mode power amplifier for use in telephone handsets. The 5.8V power amplifier enables subscribers the ability to switch between 800 megahertz (MHz) (cellular) and 1,900 MHz personal communications service operation. Manufacturers now design phones to operate at multiple bands for greater flexibility. The single amplifier can replace two separate power amplifier designs, thus saving cost and board space, which simplifies handset design (Anadigics, Full scale production of dual-band/dual-mode GaAs power amplifier for the cellular and PCS market, accessed September 29, 1997, at URL http://www.anadigics.com/press/dualamp.html).

Researchers continue to advance the development of blue laser diodes. Cree Research Inc. demonstrated a pulsed laser diode that operates at 403 nanometers at room temperature. The company used a silicon carbide substrate with GaN as the lasing medium (Robinson, 1997). Researchers at Xerox Corp. produced a blue diode laser that operates at 427 nanometers; the device consists of gallium indium nickel quantum wells on a sapphire substrate (Hardin, 1997). In both of these devices, considerable research and development must be done before the laser diodes can be commercialized. Potential applications for blue laser diodes include compact disk players, laser printers, and undersea communications.

Commercial production of blue LED's is farther along than laser diode production. Hewlett-Packard Co. announced the commercial availability of a blue indium gallium nitride LED that operates at 475 nanometers (Hewlett-Packard Corp., HP offers its first high-brightness blue LED lamps, accessed September 15, 1997, at URL http://www.hp.com/HP-COMP/news/pr/15jul97.html). Epitronics is offering engineering quantities of GaN-on-sapphire substrates for blue and green LED's. Production for this material is expected to grow to full-scale by 1999 (GaAsNET, Epitronics announces improved wafer substrate for blue light emitting devices, accessed January 16, 1998, at URL http://www.gaasnet.com/news/ Epi_0797.html). Several technical papers describing the production methods and development of blue and green LED's highlight the commercial progress of the devices (Steigerwald and others, 1997; Edmond and Lagaly, 1997; Eiting, Grudowski, and Dupuis, 1997).

Prices

Producer-quoted prices for gallium in 1997 did not change from those at yearend 1996. *(See table 4.)* Traders reported that gallium prices edged up during the beginning of the year to about $400 per kilogram for 99.9999%-pure material and remained at that level throughout the year.

Foreign Trade

U.S. gallium imports decreased significantly in 1997, with most of the decline in imports from Canada and France. France (60%) and Russia (24%) remained the principal sources of imported gallium. *(See table 5.)* In addition to gallium metal, significant quantities of GaAs wafers were imported into the United States. A total of 14,900 kilograms of undoped GaAs wafers was imported in 1996, mostly from Japan (60%) and Germany (19%). Japan (48%), the Czech Republic (10%), and Canada (9%) were the main import sources for doped GaAs wafers, totaling 119,000 kilograms during the year. Quantities of GaAs wafers reported by the Bureau of the Census may include the weight of the packaging material, and thus may be overstated.

World Review

Estimated crude gallium production was 72 tons in 1997, which was about a 31% increase from estimated production in 1996. Kazakstan, with an estimated 18 tons of exports to Japan, was responsible for much of the increase in production. Principal world producers were Australia, Kazakstan, and Russia. China, Hungary, Japan, and Slovakia also recovered gallium. For part of the year, Rhône-Poulenc S.A. fed its purification facility in France from crude gallium produced at its 50-ton-per-year plant in Australia and from gallium produced in Germany. France, Japan, and the United States were the main world gallium refiners. *(See table 6.)*

Australia.—Rhône-Poulenc suspended operations at its Pinjarra, Western Australia, gallium recovery facility in May. The company stated that demand for gallium in the LED market in Japan has declined, and use of gallium in integrated circuits has not increased sufficiently to offset the decline in LED demand. Rhône-Poulenc will supply its customers with gallium produced in Germany and refined in France to meet their needs (Metal Bulletin, 1997).

Japan.—Gallium demand in Japan for 1997 was estimated to be 107 tons, a 16% increase from 1996 demand of 92 tons. Kazakstan (18 tons), France (11.5 tons), and Russia (8 tons) were the principal sources of gallium imports, which were estimated to total 53 tons. Domestic production supplied 6 tons of demand; the rest of the demand was met by recycled material. Epitaxial wafers for LED's, with 49% of total demand, were the largest end-use application for gallium. Dowa Mining Co. expects that gallium demand in Japan for 1998 will remain flat or drop slightly as inventories that were built up in 1997 are reduced (Roskill's Letter from Japan, 1997).

New Japan Radio Co. planned to triple production of GaAs IC's to 3 million units per month by June 1998 because of increasing demand by the mobile communications market. At the same time, the company will be converting its existing production line from 3-inch to 4-inch wafers. Total cost of an additional 4-inch production line and the upgrade is estimated to be ¥1.5 million (GaAsNET, New Japan Radio to expand GaAs production, accessed January 16, 1998, at URL http://www.gaasnet.com/news/ NJR_0997.html).

United Kingdom.—Epitaxial Products International announced plans to nearly double capacity at its MOVPE production facilities. By increasing the size of its production facilities to 40,000 square feet, the company will have room to add eight MOVPE reactors. The company provides custom GaAs and InP MOCVD wafers for optoelectronic, optical and electronic applications and is Europe's only merchant supplier of MOCVD wafers (GaAsNET, EPI announces expansion of production facilities and introduction of HBT's, accessed January 16, 1998, at URL http:// www.gaasnet.com/ news/epi_1097.html).

Current Research and Technology

Researchers at the University of Georgia reportedly synthesized the first gallium-gallium triple bond (gallyne). If this material has been synthesized, it may open up new areas of chemistry for gallium. Not all scientists are convinced that the gallyne has been created. One prominent University of California professor does not believe that the structural data (bond length and geometry) presented supports the triple bond existence (Dagani, 1997).

Scientists at Israel's Weizmann Institute of Science produced GaAs crystals 25% purer than those previously made by improving the vacuum system used to grow the samples. The scientists stated that the purity improvement is more of a technologic than a scientific breakthrough, but ultrapure crystals are important in determining how electrons travel. By cooling the GaAs crystal to one-tenth of one degree above absolute zero (-273 °K), the electrons traveled a long distance (120 micrometers) before scattering. Over the long paths, the electrons have wavelike properties, but over short distances, they behave more like particles (Science News, 1997).

Emcore Corp., along with its partner M/A Com Inc., reported that production of pseudomorphic high-electron-mobility transistors by MOCVD yields devices with properties equivalent to those produced by MBE. The program was completed in mid-July under a phase II Small Business Innovative Research program for the U.S. Air Force. Producing these devices by MOCVD can reduce overall manufacturing costs by 30% (GaAsNET, Emcore MOCVD technology produces a 35 GHz 0.5 watt pHEMT MMIC, accessed January 16, 1998, at URL http://www.gaasnet.com/news/ emcore2_0997.html).

Scientists at the Massachusetts Institute of Technology developed a photonic crystal specially designed to bend light sharply with near-perfect transmission. At a bend of 90°, light is transmitted in a 2-dimensional GaAs crystal at 100% transmission with 98% efficiency. This ability to bend light in smaller spaces would allow a greater number of bends in a circuit, thus reducing the circuit size, leading to further miniaturization of lasers and optical computer chips. The team hopes to demonstrate a three-dimensional photnic crystal within a few years (Tatterson, 1997).

Diode lasers with aluminum-free active areas were produced by scientists at the University of Wisconsin-Madison and Coherent Inc. The researchers developed InGaAsP/GaAs diodes that operate at 830 nanometers at twice the power of conventional GaAlAs/GaAs diodes. The new diodes also are expected to operate more reliably than conventional laser diodes. Removing aluminum from laser diodes is desirable because the aluminum can oxidize in rising temperatures, attacking and degrading the laser cavity (Photonics Spectra, 1997).

Scientists at the National Aeronautics and Space Administration's Jet Propulsion Laboratory have proposed that thin films of ternary amorphous refractory compounds be used as gate metals and diffusion barriers to improve reliability of GaAs and InP devices. The composition of the compounds would be $M_xSi_yN_z$, where M is tantalum, tungsten, or molybdenum. Advantages of the proposed compounds include the elimination of palladium and platinum from metal gate contacts thus eliminating hydrogen degradation, deposition of uniform layer thicknesses of the compounds as low as 10 nanometers, and smoother contact surfaces (NASA Tech Briefs, 1997).

Engineers at Northwestern University fabricated what they claim is the smallest optical switch yet produced. The switch, called a microcavity resonator, consists of a ring or disk made of layered GaAs and GaAlAs. Light at a specific wavelength travels down a narrow waveguide where it leaks into the resonator and circulates. The circulating light then channels into another waveguide. By combining the resonators with lasers on a chip, light could be used to communicate over optical fibers (Peterson, 1997).

Spectolab Inc., a unit of Hughes Electronics Corp., announced the successful operation of a dual-junction GaAs solar cell with the launch of PanAmSat Corp.'s PAS-5 satellite. The dual-junction cells nearly double the light conversion efficiency of traditional silicon solar cells, which means that solar panels using the cells either provide twice the power or be one-half the weight of traditional solar panels. The dual junction GaAs cell was demonstrated to convert 21.6% of the available light into electrical power as compared with silicon, which has a conversion rate of 12.3%. The cells consist of a germanium substrate, a GaAs layer, and a gallium indium phosphide layer (Florida Today, Solar cell efficiency nearly doubled, accessed October 20, 1997, at URL http://www.afn.org/~fcpj/ space/art/ft917.htm). These same type of solar cells were supplied to another Hughes subsidiary, Hughes Space and Communications Inc., for the Orion 3 satellite, which will be used for business communications in Asia and Oceania. The Hubble Space Telescope will also be retrofitted with GaAs solar cells during its 1999 servicing mission (McHale, 1997).

Outlook

One of the keys to increasing GaAs usage is to improve the production process. For example, one U.S. firm has demonstrated a liquid-encapsulated Czochralski growth technique that produces single-crystal, 4-inch-diameter GaAs ingots weighing 22 kilograms, rather than the 8-kilogram ingots that normally are produced. These larger ingots will yield 375 wafers per ingot compared with the 50 to 80 wafers that are produced from an 8-kilogram ingot. With the economies of scale, wafers produced from the large ingot cost less per unit area than wafers from the smaller ingot (about $2.20 vs. $2.55 per square inch) (M/A Com Inc., Growth and properties of very large crystals of semi-insulating gallium arsenide, accessed May 4, 1998, at URL http://www.macom-gaaswafers.com/GaAs IC1.html). Efforts such as this, coupled with increases in wafer throughput in epitaxial growth and increased wafer size, will result in overall cost reduction for GaAs-based devices.

Another key is developing new end uses for gallium. GaN LED's and laser diodes represent a potential new end use. One market research firm estimates that the GaN portion of the LED market was $140 million in 1997, and that this market will grow at an average annual rate of 44% to reach $3 billion by 2006 (Emcore Corp., EMCORE unveils bright blue LED technology, accessed May 4, 1998, at URL http://www.emcore.com/press/blueLED.html). If this prediction holds true, significant quantities of gallium will be required for the new application.

In the near term, GaAs usage is expected to increase, especially in communications markets. Increased usage of cellular communications and direct broadcast satellite applications are expected to drive the increase in demand for gallium.

References Cited

Dagani, Ron, 1997, A triple bond for gallium: Chemical & Engineering News, v. 75, no. 24, June 16, p. 9-10.

Edmond, John, and Lagaly, Jeffrey, 1997, Developing nitride-based blue LEDs on SiC substrates: Journal of Metals, v. 49, no. 9, p. 24-26.

Eiting, C.J., Grudowski, P.A., and Dupuis, R.D., 1997, The x-ray characterization of InGaN and AlGaN heterostructures for blue-light emitters: Journal of Metals, v. 49, no. 9, p. 27-30.

Hardin, R.W., 1997, Xerox makes colorful splash with blue diode laser: Photonics Spectra, v. 31, no. 12, p. 30.

McHale, John, 1997, GaAs solar cells prove more efficient than silicon: Military & Aerospace Electronics, v. 8, no. 5, p. 4.

Metal Bulletin, 1997, Rhône-Poulenc to suspend output at Pinjarra: Metal Bulletin, no. 8178, May 15, p. 10.

NASA Tech Briefs, 1997, Diffusion barriers for GaAs and InP devices: NASA Tech Briefs, v. 21, no. 6, p. 42.

Peterson, I., 1997, Ringing up a microscopic light switch: Science News, v. 151, no. 25, June 21, p. 380.

Photonics Spectra, 1997, Aluminum-free diodes offer doubled power potential: Photonics Spectra, v. 31, no. 4, p. 46.

Robinson, M.K., 1997, American blue diode laser pulses atop silicon carbide substrate: Photonics Spectra, v. 31, no. 7, p. 32.

Roskill's Letter from Japan, 1997, Gallium—Japanese demand is estimated to rise by 16% in 1997: Roskill's Letter from Japan, no. 260, December, p. 11-14.

Science News, 1997, High vacuum produces ultrapure crystals: Science News, v. 152, no. 7, August 16, p. 102.

Steigerwald, Daniel, Rudaz, Serge, Liu, Heng, Kern, R.S., Götz, Werner, and Fletcher, Robert, 1997, III-V nitride semiconductors for high-performance blue and green light emitting devices: Journal of Metals, v. 49, no. 9, p. 18-23.

Tatterson, K.G., 1997, Crystal simulation shows promise in high-efficiency light bending: Photonics Spectra, v. 31, no. 2, p. 30.

SOURCES OF INFORMATION

U.S. Geological Survey Publications

Gallium. Ch. in Mineral Commodity Summaries, annual.[1]

Gallium, germanium, and indium. Ch. in United States mineral resources, U.S. Geological Survey Professional Paper 820, 1973.

Other

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.

Roskill Information Services Ltd. Gallium 1990, 5th ed.

[1]Prior to January 1996, published by the Bureau of Mines.

TABLE 1
SALIENT U.S. GALLIUM STATISTICS 1/

(Kilograms unless otherwise specified)

	1993	1994	1995	1996	1997
Production	--	--	--	--	--
Imports for consumption	15,600	16,900	18,100	30,000	19,100
Consumption	11,300	15,500	16,900	21,900	23,600
Price per kilogram	$400	$395	$425	$425	$425

1/ Data are rounded to three significant digits.

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

(Kilograms)

End use	1996	1997
Optoelectronic devices:		
Laser diodes and light-emitting diodes	11,600	8,350
Photodetectors and solar cells	1,280	2,080
Integrated circuits:		
Analog	8,200	11,500
Digital	623	631
Research and development	184	38
Other	38	961
Total	21,900	23,600

1/ Data are rounded to three significant digits; may not add to totals shown.
2/ Includes gallium metal and gallium compounds.

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

(Kilograms)

Purity	Beginning stocks	Receipts	Consumption	Ending stocks
1996:				
99.99% to 99.999%	857	39	462	434
99.9999%	532	8,970	9,080	422
99.99999% to 99.999999%	55	13,300	12,300	1,020
Total	1,440	22,300	21,900	1,880
1997:				
99.99% to 99.999%	434	1,400	999	834
99.9999%	422	10,200	10,400	181
99.99999% to 99.999999%	1,020	12,100	12,100	1,000
Total	1,880	23,700	23,600	2,020

1/ Consumers only.
2/ Data are rounded to three significant digits; may not add to totals shown.

TABLE 4
YEAREND GALLIUM PRICES

(Dollars per kilogram)

Gallium metal, 99.999999%-pure, 100-kilogram lots	$525
Gallium metal, 99.99999%-pure, 100-kilogram lots	425
Gallium metal, 99.9999%-pure, 100-kilogram lots	390
Gallium metal, 99.9999%-pure, imported	$380- 425
Gallium oxide, 99.99%-pure, imported	275- 350

Source: American Metal Market.

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

(Kilograms)

	1996		1997	
Country	Quantity	Value	Quantity	Value
Canada	5,900	$1,590,000	290	$41,500
China	159	41,700	910	338,000
France	16,300	5,360,000	11,400	4,710,000
Hungary	493	128,000	997	224,000
Japan	1,310	164,000	166	48,000
Netherlands	1,500	578,000	201	62,100
Russia	3,360	1,240,000	4,540	1,520,000
Other	989 r/	336,000 r/	502	217,000
Total	30,000	9,440,000	19,100	7,160,000

r/ Revised.
1/ Data are rounded to three significant digits; may not add to totals shown.

Source: Bureau of the Census.

TABLE 6
ESTIMATED WORLD ANNUAL PRIMARY GALLIUM
PRODUCTION CAPACITY, 1/ DECEMBER 31, 1997

(Metric tons)

Continent and country	Capacity
North America: United States 2/	3
Europe:	
France	20
Germany	20
Hungary	4
Kazakstan	10
Slovakia	3
Russia	30
Total	87
Asia:	
China	8
Japan	7
Total	15
Oceania: Australia 2/	50
World total	155

1/ Includes capacity at operating plants as well as at plants on standby basis.
2/ Standby capacity as of December 31, 1997.