GALLIUM

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By yearend, worldwide gallium supplies were insufficient to meet consumption rates. Free market gallium prices skyrocketed to reach $1,500 to $2,000 per kilogram, a level not seen since the early 1960s when technologic improvements in gallium recovery processes brought down the price from $3,000 per kilogram.

Gallium demand in the United States was met by imports, primarily high-purity material from France and low-purity material from Kazakhstan. More than 95% of the gallium consumed in the United States was in the form of gallium arsenide (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. U.S. GaAs manufacturers completed many of their capacity expansions that had been announced earlier and continued planning additional capacity expansions. Many of these expansions involved conversions from 4-inch wafer processing capacity to 6-inch capability, which is considered the next plateau in GaAs processing ability. Growth in the wireless communications industry was cited as the principal driving force behind most of the GaAs production expansions.

World production of virgin gallium was estimated to be 90 metric tons (t). Total demand for refined gallium, however, was estimated to be 120 t and 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 2000 (table 1). Eagle-Picher Industries Inc. recovered and refined gallium from domestic and imported sources at its plant in Quapaw, OK. Recapture Metals Inc. in Blanding, UT, recovered gallium from scrap materials, predominantly those generated during the production of GaAs. Recapture Metals facilities have the capability to process about 17 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.

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 63% of total consumption. Optoelectronic devices accounted for 32% of domestic consumption, and the remaining 5% was used in digital ICs, research and development, and other applications (tables 2, 3).

Gallium consumption data are collected by the U.S. Geological Survey from one voluntary survey of U.S. operations. In 2000, there were 13 responses to the consumption of gallium survey, representing 59% 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.

Projected growth in GaAs components for wireless applications led to the completion of several new GaAs manufacturing facilities and announcements of more expansions. In 2000, M/A-Com Inc., Lowell, MA, completed an expansion of its GaAs wafer fabrication capacity, adding a new high-volume 6-inch wafer manufacturing line. The expansion resulted from a multiyear agreement with Sanders Corp., based in Nashua, NH, in which M/A-Com will use existing capacity and equipment at the Sanders facility to

Gallium in the 20th Century

Although gallium had been discovered in 1875, it was not produced in the United States until 1915, and commercial-scale recovery did not begin until 1943. Until 1960, gallium had very limited uses. Most of its consumption was for experimental purposes; small quantities were used as a specialized mirror coating, in high-temperature thermometers, and in low-melting-point metal alloys. Although few statistical data are available, U.S. demand for gallium was considered negligible (fewer than 50 kilograms) until 1965. Introduction of the gallium-arsenide-based light-emitting diode (LED) changed the consumption pattern of gallium from that of a laboratory curiosity to a metal with some consumer applications. LEDs, used in such applications as displays in digital watches and hand-held calculators, were responsible for large annual increases in consumption from the mid-1960s until the mid-1970s. Gallium consumption continued to grow throughout the remainder of the century as new uses were developed.

By 2000, the consumption of gallium in the United States had reached nearly 40 metric tons. Almost all of this was for gallium arsenide components in electronic applications. LEDs remained in widespread use for many electronic displays, including window brake lights in automobiles. Gallium-arsenide-based laser diodes were used in such items as CD and DVD players, and gallium-arsenide-based integrated circuits were used in sophisticated military radars. Scientists continue to investigate gallium's properties, which may lead to the development of new applications for gallium. As a result, growth in gallium consumption was expected to continue well into the 21st century.

manufacture monolithic microwave integrated circuits (MMICs) on 6-inch GaAs wafers for wireless and telecommunications markets. Sanders will continue to manufacture MMICs at the same facility for aerospace and defense applications. The new manufacturing line is expected to be operational by the first half of 2001 (GaAsNet, June 8, 2000, M/A-Com doubles GaAs fab capacity, adds six-inch wafer line, accessed June 9, 2000, at URL http://www.gaasnet.com/news/macom_08062000.html). In March, M/A-Com completed the acquisition of the GaAsTEK subsidiary of ITT Corp., Roanoke, VA, which manufactures GaAs MMICs for defense industries (M/A-Com Inc., March 7, 2000, M/A-Com completes GaAsTEK acquisition, accessed March 30, 2000, at URL http://www.macom.com/about/press.asp?ID=35). This acquisition, along with the use of the Sanders facilities, gives M/A-Com four GaAs manufacturing facilities in the United States—Colorado Springs, CO; Lowell, MA; Nashua, NH; and Roanoke, VA.

In March, EMCORE Corp. completed the first phase of an expansion at its Somerset, NJ, GaAs manufacturing facility to meet increased demand for the company's heterojunction bipolar transistor (HBT) and pseudomorphic high-electron-mobility transistor (pHEMT) products; this phase doubled the company's capabilities to produce 4- and 6-inch wafers. In August, EMCORE completed a second expansion that again doubled its GaAs wafer production capacity. The first phase of the expansion added 186 square meters (m^2) of production space, which accommodated six additional epitaxial production machines. The second phase, consisting of 650 m^2, will accommodate 10 metal-organic chemical vapor deposition (MOCVD) production tools, to bring the total to 18, allowing a total annual production capacity of 360,000 6-inch wafers (EMCORE Corp., March 2, 2000, EMCORE nearly doubles production capacity for GaInP HBTs and pHEMTs to meet wireless and fiber optic market demands, accessed November 30, 2000, at URL http://www.emcore.com/html_documents/News_clips/2000/doubles_capacity.htm; GaAsNet, August 2, 2000, EMCORE completes expansion of NJ manufacturing facility, increasing capacity by 400%, accessed August 9, 2000, at URL http://www.gaasnet.com/news/emcore_02082000.html). The company also plans to triple production capacity at its EMCORE West site in Albuquerque, NM, that houses its solar cell, optical component, and networking products. The expansion will add 3,300 m^2 of capacity to the existing 4,640-m^2 facility. Completion was scheduled for yearend 2000 (GaAsNet, June 8, 2000, EMCORE plans to significantly expand Sandia Technology Park site, accessed June 9, 2000, at URL http://www.gaasnet.com/news/emcore_08062000.html).

In October, Kopin Corp. completed a 5,500-m^2 facility near its headquarters in Taunton, MA, that is expected to generate about 40% of the company's GaAs HBT business. The new facility was expected to be operational by the first quarter of 2001. As part of the expansion, Kopin ordered six HBT systems from AIXTRON AG to be delivered in the first quarter of 2001. After delivery of the new systems, Kopin will have a total of 22 machines—8 capable of handling multiple 4-inch HBTs and 14 that can handle 6-inch HBTs. Total annual production capacity will be more than 400,000 4-inch and 200,000 6-inch wafers (GaAsNet, May 16, 2000, Kopin establishes second site for HBT production, accessed June 9, 2000, at URL http://www.gaasnet.com/news/kopin_16052000.html; GaAsNet, June 11, 2000, Kopin Corporation orders six additional HBT systems from AIXTRON, accessed June 21, 2000, at URL http://www.gaasnet.com/news/kopin_11062000.html). Also in October, Kopin acquired privately held Super Epitaxial Products Inc., which conducted research and development on optoelectronic materials. Kopin believes that the acquired mix of products, combined with its technical expertise, will allow the company to provide components for existing and emerging optical communications applications. Under the terms of the agreement, 1.7 million shares of Kopin stock with an estimated value of $25 million were exchanged for all of the outstanding shares of Super Epitaxial Products (GaAsNet, October 31, 2000, Kopin acquires Super Epitaxial Products to add opto wafers, accessed October 31, 2000, at URL http://www.gaasnet.com/news/kopin_31102000.html).

ATMI Inc. (formerly Epitronics Corp.) planned to increase production capacity at its Phoenix, AZ, facility by constructing a 4,640-m^2 facility that will contain 11 AIXTRON metal-organic vapor phase epitaxy (MOVPE) reactors and will have space for 8 more. The expansion is in response to growing wireless telecommunications applications. In addition, ATMI is expanding its development of gallium nitride (GaN) wafers for blue laser diodes. The company has developed and patented a process for growing high-purity GaN wafers 50 millimeters (mm) in diameter and, based on this success, has been awarded a U.S. defense industry contract to develop the GaN wafer production capabilities further (GaAsNet, October 23, 2000, A T M I announces major HBT capacity expansion, accessed October 31, 2000, at URL http://www.gaasnet.com/news/ATMI_23102000.html).

In September, TriQuint Semiconductor Inc. purchased a wafer fabrication facility in Richardson, TX, from Micron Technology LLC for $87 million. The new facility will allow TriQuint to relocate its current Texas operation from leased space within 2 years. The company planned to install new 6-inch wafer fabrication lines that would duplicate the ones in its Hillsboro, OR, facility first, then relocate its Texas operations to the new facility. By the time the new installation, relocation, and reconfiguration are complete, the new facility will have greater capacity than the company's combined Texas and Oregon capacity (GaAsNet, September 6, 2000, TriQuint Semiconductor completes purchase of Richardson fabrication facility, accessed September 21, 2000, at URL http://www.gaasnet.com/news/triquint_06092000.html).

Sumitomo Electric Industries Ltd. announced that it would construct its first U.S. plant to produce semiconductor materials. The new plant, which will be sited in Hillsboro, OR, will initially focus on GaAs wafers for the wireless communications market and have a production volume of 20,000 wafers per month by 2002. A U.S. location would allow Sumitomo Electric Industries to meet the needs of some of its larger customers in the Western United States, such as TriQuint, TRW Inc., and Motorola Inc; 50% of Sumitomo Electric Industries' market was estimated to be in North America. The new facility also will serve as the company's U.S. headquarters. A new 12,000-m^2 GaAs production plant in Kobe, Japan, which was scheduled to be completed by July 2001, will supply 5-inch wafers to the new U.S. plant (Paul Kallender, Electronic Engineering Times, December 19, 2000, Sumitomo adds U.S. fab to GaAs expansion plans, accessed April 6, 2001, at URL http://www.eetasia.com/ART_8800066750_499481,590626.HTM).

AXT Inc. (formerly American Xtal Technology Inc.) announced that it would triple its GaAs substrate production capacity by the end of the third quarter of 2001. Most of the expansion will be in Beijing, China, where the company operates a 5,750-m^2 facility for GaAs production and has purchased a 3,340-m^2 building adjacent to this facility. If AXT can acquire additional nearby buildings, it plans to increase its total capacity to 14,800 m^2. AXT also planned a 1,850-m^2 expansion at its Fremont, CA, plant in 2001 (AXT Inc., May 3, 2000, American Xtal Technology announces a 3x expansion of its GaAs substrate capacity by Q301, accessed February 8, 2001, at URL http://www.axt.com/050300.htm). The company also planned to discontinue its laser diode and consumer product lines in 2001 to concentrate on its core products—high-brightness LEDs and vertical cavity surface-emitting lasers (VCSELs).

ANADIGICS Inc. planned to add cleanroom space and equipment to nearly double its 6-inch indium gallium phosphide (InGaP) HBT, pHEMT, and metal semiconductor field effect transistor (MESFET) production capability. The $10 million expansion, which began in response to an increased demand for the company's wireless and broadband communications products, would link directly with ANADIGICS' existing production line at its Warren, NJ, facility. The completion was scheduled for the beginning of 2001 (GaAsNet, January 16, 2000, ANADIGICS announces plans to expand 6-inch manufacturing operation, accessed January 21, 2000, at URL http://www.gaasnet.com/news/anadigics_16012000.html).

Agilent Technologies Inc. planned to construct a new 6-inch GaAs wafer fabrication facility in Ft. Collins, CO, to produce enhancement-mode pHEMTs for handsets for mobile phones. The first phase of the project, which was scheduled to be completed by the end of 2002, will include 1,400 m^2 of cleanroom that can process 48,000 6-inch wafers per year. Until the new facility is completed, Agilent plans to produce the devices in its existing Santa Clara, CA, facility (Agilent Technologies Inc., October 18, 2000, Agilent Technologies plans six-inch wafer production fab for breakthrough E-pHEMT process, accessed November 30, 2000, at URL http://www.agilent.com/about/newsroom/presrel/2000/18oct2000a.html). Agilent ordered three molecular beam epitaxy (MBE) systems from Thermo VG Semicon Ltd. for its new facility.

Conexant Systems Inc. completed an expansion of its GaAs manufacturing facilities in Newbury Park, CA, in April. Conexant invested $80 million in capital equipment to increase its annual capacity to 95,000 4-inch wafer starts from 15,000. The new manufacturing facilities can be upgraded to 6-inch wafer capability; this conversion will increase capacity to the equivalent of 210,000 4-inch wafer starts per year. Conexant planned to use most of its expanded capacity to manufacture GaAs HBT amplifiers for the digital cellular handset market, and a small portion would be used to manufacture GaAs-HBT-based transceivers for optical communications (Conexant Systems Inc., April 10, 2000, Conexant increases manufacturing capacity five-fold for wireless communications and optical networking products, accessed April 25, 2000, via URL http://www.conexant.com).

Motorola tripled the capacity of its GaAs wafer fabrication facility in June by converting from 4-inch to 6-inch wafer capabilities and equipping the facility to its fullest capacity. The company also purchased MOCVD equipment from EMCORE for the expanded facility. This is one of the first facilities to be fully converted to 6-inch wafer capability for all GaAs technologies—MESFETs, pHEMTs, and HBTs (GaAsNet, June 16, 2000, Motorola Semiconductor completes six-inch conversion of GaAs fab three months ahead of schedule, accessed June 21, 2000, at URL http://www.gaasnet.com/news/motorola_16062000.html).

Intelligent Epitaxy Technology, Inc. (IntelliEPI), Richardson, TX, announced that it had raised $25 million in funding, which would be used to expand its production capacity. IntelliEPI planned to acquire 2,040 m^2 of additional cleanroom space and purchase four additional 6-inch multiwafer MBE systems (GaAsNet, October 14, 2000, Intelligent Epitaxy Technology, Inc. successfully raises $25 million, accessed October 31, 2000, at URL http://www.gaasnet.com/news/ie_13102000.html).

TECSTAR Inc., a Newport Beach, CA, manufacturer of solar cells, announced the formation of a new optoelectronics products organization to meet the growing demand for epitaxial wafers used in high-brightness LEDs and related optoelectronics devices. TECSTAR operated a GaAs MOCVD foundry at its Applied Solar Division. This division's facilities became available in the first quarter of 2000 to support manufacturers of high- and ultrahigh-brightness LED devices and lamps (Compound Semiconductor, January 13, 2000, TECSTAR announces formation of new optoelectronics product group, accessed April 10, 2001, via URL http://www.compoundsemiconductor.net). One of the companies that signed a long-term supply agreement with TECSTAR for use of its MOCVD production capacity was Advanced Photonics Ltd. of Shanghai, China.

TRW signed an agreement with Endgate Corp. to merge its subsidiary TRW Milliwave Inc. and create a new company, Endwave Corp. TRW manufactures transceiver modules that use GaAs MMICs for broadband systems, and Endgate manufactures transceivers, antennas, and outdoor units that enable high-speed wireless telecommunications links. The combination of these two entities into one single company will vertically integrate the production of the devices and include a long-term GaAs supply agreement with TRW. After the merger was completed, Endwave was owned about 53% by TRW and 47% by Endgate. The new firm will be headquartered in Sunnyvale, CA, and will maintain manufacturing and design facilities in Sunnyvale, Santa Clara, and Diamond Springs, CA. In July, Endwave filed an initial public offering to raise $115 million to be used for general corporate purposes and working capital (GaAsNet, March 14, 2000, TRW and Endgate announce merger forming Endwave Corporation, accessed March 14, 2000, at URL http://www.gaasnet.com/news/trw_05032000.html; GaAsNet, July 16, 2000, Radio frequency products firm Endwave files IPO, accessed August 9, 2000, at URL http://www.gaasnet.com/news/endwave_16072000.html).

Prices

In 2000, producer-quoted prices for high-purity gallium were the same as those at yearend 1999 (table 4). Quoted prices, however, do not reflect the actual price trends that occurred during the year. According to Mining Journal, prices remained relatively stable during the first three-quarters of the year, with prices for 99.9999%-pure to 99.99999%-pure material remaining at $500 to $600 per kilogram (Mining Journal, 2000). With a severe shortage of supply in the latter part of 2000, free market prices for gallium skyrocketed, with price levels of up to $1,500 per kilogram being reported by yearend (Mining Journal, 2001).

Foreign Trade

U.S. gallium imports increased by 64% from those in 1999 (table 5). France (63%), Kazakhstan (12%), Russia (5%), and the United Kingdom (5%) were the principal sources of imported gallium. In addition to gallium metal, GaAs wafers were imported into the United States. In 2000, 31,500 kilograms (kg) of undoped GaAs wafers was imported, an increase of 47% from that in 1999. Lebanon (59%) and Japan (40%) were the principal sources. [Material identified as shipped from Lebanon probably was transshipped, and the country of origin is misidentified, because Lebanon does not produce GaAs wafers.] Japan (31%), the Republic of Korea (21%), and Taiwan (15%) were the main import sources for doped GaAs wafers, totaling 296,000 kg during the year, a decrease of 5% from that in 1999. Quantities of GaAs wafers reported by the U.S. Census Bureau may include the weight of the packaging material and thus may be overstated.

World Review

Estimated crude gallium production was 90 t in 2000. Principal world producers were Germany, Japan, Kazakhstan, and Russia. China, Hungary, Slovakia, and Ukraine also recovered gallium. Refined gallium production was estimated to be about 120 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.

World demand for gallium was forecast to be 210 t in 2000 by Dowa Mining Co. Ltd.; this figure included significant quantities of recycled gallium scrap. Regional demand was estimated to be as follows: Japan, 140 t; the United States, 49 t; Europe, 13 t; and other countries, 8 t. Dowa Mining projected that demand in 2001 would increase to 243 t (Roskill's Letter from Japan, 2001).

Strategies Unlimited estimated that the world market for compound semiconductors (mostly based on GaAs components) reached $18 billion in 2000, an increase of 60% from that in 1999. Optoelectronics had the largest share of the compound semiconductor market, with 80% of the total. Of the optoelectronics market, 60% was for communications applications, 16% for lamps and displays, and 24% for other applications (Hausken, 2001).

China.—The Institute of Semiconductors, which was a part of the Chinese Academy of Sciences, and four other companies signed an agreement in September to commercialize the Institute's semi-insulating GaAs technology. Under the agreement, Compound Crystal Technology Co. Ltd. would be set up by the five entities with capitalization of 100 million yuan (Y) (about $12 million), including technology valued at Y30 million (about $3.6 million). The five entities planned to invest Y300 million to Y400 million (about $36 million to $48 million) in importing production equipment and building a plant. The planned plant, the only one of its kind in China, was expected to produce single-crystal and epitaxial wafers of semi-insulating GaAs (Compound Semiconductor, September 5, 2000, Chinese firms establish venture to commercialize GaAs technology, accessed April 9, 2001, via URL http://www.compoundsemiconductor.net).

France.—Picogiga SA announced that it would double its capacity to produce epitaxial wafers at its Courtaboeuf plant by 2001. The company ordered three MBE reactors from Riber S.A. in July, two MBE reactors from Thermo VG Semicon in September, and three MBE reactors from Applied Epi Inc. in November. Five of the new reactors can process seven 6-inch wafers at a time, instead of four, which was the existing standard. Picogiga planned to allocate specific reactors to the fabrication of HBT wafers in order to increase efficiency and yields. All of the new reactors, however, will be capable of producing both HEMT and HBT wafers. The company also purchased 8,000 m^2 of land adjacent to its existing facility to allow for future expansion (GaAsNet, July 11, 2000, Picogiga purchases more production equipment for 6 inch wafers, accessed July 17, 2000, at URL http://www.gaasnet.com/news/picogiga2_0700.html; GaAsNet, October 20, 2000, VG Semicon receives Picogiga orders for two V150 production MBE systems, accessed October 31, 2000, at URL http://www.gaasnet.com/ news/vg_20102000.html; GaAsNet, November 5, 2000, Picogiga purchases three Applied Epi production MBE systems, accessed November 8, 2000, at URL http://www.gaasnet.com/news/appliedepi_05112000.html). Picogiga exported most of its production, with about 70% sold in the United States.

Germany.—In March, GEO Gallium S.A., a subsidiary of GEO Specialty Chemicals Inc., announced that it would increase gallium extraction capacity at its Stade plant by more than 50% by the summer of 2000. The company also said that, since it acquired the gallium business from Rhodia Inc. in 1999, it had increased the capacity at its Salindres, France, gallium refinery by more than 30% (Compound Semiconductor, March 1, 2000, GEO Gallium S.A. to expand its gallium extraction plant in Stade, Germany, accessed November 2, 2000, at URL http://www.compoundsemiconductor.net/PressReleases/2000/PR030100005.htm). With the expansions, estimated annual capacity at the Stade plant was 30 t, and at Salindres, 26 t.

Japan.—Gallium supply in Japan in 2000 was estimated to be 158 t, a 39% increase from the 1999 level, and demand was estimated to be 140 t in 2000, a 21% increase from that in 1999. Of the supply, 14 t came from domestic production, 65.8 t from imports, and 93.7 t from recycled scrap. Japan's imports in 2000 mainly came from Kazakhstan (23%), the United States (23%), and France (21%). Smaller quantities were imported from China, Germany, Hungary, Russia, and Slovakia. Dowa Mining planned to increase its production of gallium to between 14 t and 15 t in 2001 from the 2000 level of 8 t. The company also was investing in technology to recycle low-grade scrap (Roskill's Letter from Japan, 2001).

Hitachi Cable Ltd. announced plans to expand its GaAs production facilities further. By June 2001, the company plans to increase its monthly capacities as follows: Liquid-encapsulated Czochralski (LEC) substrates to 45,000 4-inch wafers, about 2.3 times existing capacity; boat-grown and vertical-gradient-freeze (VGF) substrates to 95,000 wafers, about 1.5 times existing capacity; MOVPE wafers to 24,000 4-inch diameter wafers, about 3 times existing capacity; and liquid-phase-epitaxial wafers to 59,000 wafers, about 1.7 times existing capacity. Total investment for the increased capacity was estimated to be 12 billion yen (¥) ($98.4 million) in equipment and plant upgrades (Hitachi Cable Ltd., October 11, 2000, Investment in compound semi-conductor facilities is upwardly revised to 12 billion yen this fiscal year, accessed February 8, 2001, via URL http://www2.hitachi-cable.co.jp/apps/smcinfo.nsf/new).

In December, Matsushita Electronics Corp. announced that it would invest ¥22 billion ($198 million) to build a new 6-inch GaAs plant at its Uozu plant in Toyama Prefecture. Construction was scheduled to begin in January 2001, and the facility would be ready for operation in June 2002. This will be the company's second compound semiconductor production facility, and when finished, it will have a capacity of 6,000 6-inch wafers per month, more than double its existing output. The company said the new capacity is intended to keep up with growing demand from mobile appliance manufacturers. This would be the first 6-inch GaAs facility in Japan (Compound Semiconductor, 2000).

Fujitsu Quantum Devices was spending approximately $48 million to increase capacity at its 4-inch GaAs facility in Yamanashi Prefecture to 5,200 from 4,000 wafers per month. The company also planned to outsource some of its production so it would have a combined capacity equivalent to 8,000 4-inch wafers per month by the end of fiscal year 2002. In August, New Japan Radio Corp. announced that it planned to increase production of GaAs MMICs for use in mobile communications terminals. The company operated a 4-inch GaAs facility in Kawagoe (Compound Semiconductor, 2000).

Sumitomo Electric Industries planned to expand its manufacturing capabilities for GaAs. The company had invested more than ¥5 billion ($48 million) in new capital equipment for its existing compound semiconductor facility near Osaka, which resulted in increased GaAs substrate production in October. Sumitomo Electric Industries' 4-inch GaAs wafer capacity increased by 30%, 6-inch wafer capacity increased fivefold, and epitaxial wafer production tripled. Additional capacity expansion was already underway for 2001. The next phase of capital investment will increase not only GaAs substrates and epitaxial wafers but indium phosphide (InP) substrates as well (Compound Semiconductor, August 26, 2000, Sumitomo Electric expands capacity, accessed April 11, 2001, via URL http://www.compoundsemiconductor.net).

Toyoda Gosei Co. announced that it had begun mass producing GaN-base violet LEDs, becoming the world's first company to do so. Initially, the Toyota Motor Corp. affiliate will combine the LED with an optical catalyst for use in car air purifiers. The auto air purifier will decompose organic substances in the air into water and carbonic acid by exposing a titanium oxide optical catalyst to light from a violet LED. The device was installed in Toyota's remodeled Mark II passenger car released in October. The LED was expected to eventually be used in home electronics and lighting equipment, with projected annual sales of ¥1 billion ($8.2 million) in 2 to 3 years. Toyoda Gosei has already mass-produced green, blue, and blue-green LEDs. The 380-nanometer (nm) wavelength of the violet LED is shorter than that of other LEDs. Researchers at the firm added special materials in forming layers of GaN to produce the violet light. Toyoda Gosei and Nichia Corp. were suing each other over alleged LED patent infringements. In July, the Tokyo District Court ordered Toyoda Gosei to suspend production and sales of blue LEDs, and the firm took the case to a higher court (Compound Semiconductor, November 9, 2000, Toyoda Gosei mass produces violet LEDs, accessed April 17, 2001, via URL http://www.compoundsemiconductor.net).

Taiwan.—In December, WIN Semiconductors Corp. finished building the first 6-inch GaAs MMIC foundry in Taiwan. Initial production was expected to be 10,000 wafer starts per year. By 2004, when the foundry was expected to be running at capacity, production would be 100,000 wafer starts per year (WIN Semiconductors Corp., December 12, 2000, WIN Semiconductors' GaAs MMIC wafer fab is officially opened—Leading the industry into the era of 6" wafer foundry services, accessed April 10, 2001, at URL http://www.winfoundry.com/news-htm/News010108142614.htm).

Advanced Wireless Semiconductor Co. began construction of a 6-inch GaAs HBT processing line in June. The new line would complement the company's existing 4-inch line. Both lines would have the capability to process 600 wafers per week. Advanced Wireless also signed a multiyear agreement with U.S.-based Conexant in which Advanced Wireless would supply Conexant with an additional 30,000 wafer starts per year. Production began in the fourth quarter of 2000 (Tim Whitaker, Compound Semiconductor, 2000, Fab four address growing GaAs markets, accessed April 9, 2001, via URL http://www.compoundsemiconductor.net).

Two Taiwanese companies, United Epitaxy Co. (UEC) and Epistar Corp., placed orders for a total of 25 MOCVD systems. UEC ordered 20 systems, 10 each from AIXTRON and EMCORE. The AIXTRON systems will be used to produce aluminum indium gallium phosphide (AlInGaP) high-brightness LEDs and 4- and 6-inch HBT epiwafers and to manufacture nitride LEDs. EMCORE was scheduled to deliver 10 MOCVD systems to UEC by mid-2002. The new systems will be used to produce high-brightness LEDs and electronic materials. UEC already had six EMCORE systems, which were used for the production of AlInGaP LEDs. Epistar purchased five AIXTRON reactors as part of its new expansion scheme. The machines will be used for AlInGaP-based yellow, orange, and red high-brightness LEDs in addition to blue and green nitride wafer manufacturing (Compound Semiconductor, 2000, MOCVD spending spree in Taiwan, accessed April 11, 2001, via URL http://www.compoundsemiconductor.net).

United Kingdom.—A new company to manufacture compound semiconductors was started in 2000 using technology and equipment transferred from the University of Glasgow and the University of Strathclyde. Compound Semiconductor Technologies Ltd. opened a facility in Glasgow that could produce GaAs, InP, gallium arsenide phosphide, and gallium aluminum arsenide wafers. In addition, the company planned to produce GaN using technology from the University of Strathclyde. At yearend, the company was producing about 100 2- and 3-inch wafers per month, but the equipment has the capability to process 4-inch wafers (Compound Semiconductor Technologies Ltd., September 2000, Glasgow wafer fab in gallium nitride bid, accessed February 8, 2001, at URL http://www.compoundsemi.co.uk/news-waferfab.htm).

IQE plc, a manufacturer of epitaxial wafers, acquired Wafer Technology Ltd., a substrate supplier, in November. The acquisition would allow IQE to have a captive substrate supplier for its epitaxial production. Wafer Technology produced 2- to 4-inch GaAs and InP substrates, as well as specialty III-V substrates, using the LEC and VGF methods (GaAsNet, November 24, 2000, IQE acquires Wafer Technology Limited, accessed November 27, 2000, at URL http://www.gaasnet.com/news/iqe_24112000.html).

Filtronic Compound Semiconductors Ltd., a unit of Filtronic plc, opened its new GaAs fabrication plant in August. The company acquired the facility in Newton Aycliffe, County Durham, England, from Fujitsu Ltd. in 1999. The 28,800-m^2 facility was purchased for about $20 million with financial assistance from the United Kingdom Government. Filtronic invested about $56 million in a retrofit before starting operations. Phase one of this plant was intended to provide a throughput of 30,000 6-inch wafers per year. This first stage utilizes about one-third of the available area, and Filtronic said that market demand would determine the future growth. Around 200 individual pieces of equipment had been purchased for the new plant, including 2 multiple-6-inch-wafer MBE systems. The company was also converting the former Litton Solid State Plant in Santa Clara, CA, to 6-inch operation, which would focus on process development and fast MMIC prototyping (Tim Whitaker, Compound Semiconductor, 2000, Fab four address growing GaAs markets, accessed April 9, 2001, via URL http://www.compoundsemiconductor.net).

Current Research and Technology

LumiLeds Lighting announced a breakthrough in its high-flux LEDs, with improvements in optical output power and efficiency. Aluminum indium gallium nitride (AlInGaN) technology is the standard technology for LEDs in the blue and green areas of the color spectrum. LumiLeds also has developed a unique power package that allows higher power LEDs to be housed and operated. Typical output of the new devices are blue LEDs, 100 milliwatts (mW) (5 to 8 lumens); green LEDs, 40 mW (10 to 20 lumens); and blue-green LEDs, 70 mW (15 to 25 lumens). By comparison, the industry standard 5-mm LED output was less than 10 mW in the blue spectrum. These devices also exhibited superior electrical and thermal characteristics. The new material was used in production LEDs beginning in November 2000 (LumiLeds Lighting, November 3, 2000, LumiLeds Lighting announces breakthrough in high-flux AlInGaN LEDs, accessed April 9, 2001, at URL http://www.lumileds.com/news/AlInGaN.html). LumiLeds Lighting is a joint venture between Agilent Technologies Inc. and Philips Lighting Co.

LumiLeds Lighting also announced a new product for channel-letter lighting that could replace neon as the primary lighting source in this application. The new “LED Rail” is a string of LEDs mounted on a patented rail system that allows for easy installation in standard channel letter housings. The LEDs are spaced such that they backlight the channel letter in a consistent manner. This was among the first solid-state lighting products on the market designed exclusively for channel letter lighting. The LED Rail contains no glass tubes. It is simply a string of wire with LED modules attached in fixed intervals. Glass can be a problem in signage because of breakage caused by harsh weather, transportation, and vandalism. The LED Rail operates at a lower voltage than neon, and it is easier to install than glass because there is no glass to bend. LumiLeds claimed that the LED Rail saves up to 80% of the energy used to light the same size neon-powered channel letters (Compound Semiconductor, March 31, 2000, LumiLeds Lighting introduces neon replacement solution for channel letter lighting using LEDs, accessed April 10, 2001, via URL http://www.compoundsemiconductor.net).

TriQuint received $3.1 million in funding from the U.S. Department of Commerce’s National Institute of Standards and Technology to develop advanced, high-performance, low-cost GaAs-based HBT power amplifiers and incorporate them in compact multifunction chips for use in next-generation wireless communications and broadband cable systems. The 2.5-year project began in November, and the goal was to develop the HBT and build prototype cable television repeater amplifiers and circuits for advanced wireless base stations. TriQuint’s partners in the project are ATMI and Linear Circuit Innovations Inc. (National Institute of Standards and Technology, October 2000, Advanced HBT power amplifier technology for broadband communications systems, accessed April 10, 2001, at URL http://jazz.nist.gov/atpcf/prjbriefs/prjbrief.cfm?ProjectNumber=00-00-4019).

Applied Optoelectronics Inc. (AOI) entered into a licensing agreement with Lucent Technologies Inc. that gave AOI the right to manufacture and distribute quantum-cascade lasers for applications in industries other than telecommunications. The agreement marked the first time Lucent had licensed this technology. AOI was pursuing sensor applications in markets such as combustion diagnostics, environmental sensing, medical diagnostics, industrial process control, and law enforcement, and the new lasers were expected to be commercially available by September 2000. The quantum-cascade laser was invented and demonstrated in 1994 at Bell Laboratories. It operates in the midinfrared portion of the spectrum, in which it previously had been difficult for scientists to create high-efficiency lasers. This spectral region is particularly important from an applications standpoint because many chemicals—including pollutants, industrial chemicals, explosives, and medically important substances—can only be sensitively detected using midinfrared lasers. Efforts to create high-performance, low-cost laser-based sensors for these materials had been hampered by the high price or limited spectral or power performance of existing lasers. The crystal structure of the quantum-cascade laser contains up to 1,000 alternating layers of different types of crystalline material, some thinner than one-billionth of an inch (Lucent Technologies Inc., July 12, 2000, Applied Optoelectronics, Inc. signs licensing agreement with Lucent Technologies, accessed August 17, 2000, at URL http://www.lucent.com/press/0700/000712.bla.html).

Researchers at the U.S. Naval Research Laboratory and at Sarnoff Laboratories announced the development of the first room-temperature III-V laser diode that emits light at a wavelength greater than 3 micrometers (μm). The diodes consist of 10 W-shaped quantum wells grown on a gallium antimonide substrate. The W structure consists of a central gallium indium antimonide hole sandwiched between two indium arsenide electron wells, which are in turn bracketed by two high aluminum gallium arsenide antimonide barriers. This structure allows excellent electron confinement, allowing a low threshold current, which enable continuous wave operation at relatively high temperatures (195 K). The research team’s next goal was to have the device operate at temperatures above 230 K to avoid the need for cryogenic cooling. Potential applications for the devices include portable pollution monitors, medical diagnostics, and chemical weapons site detectors (Gaughan, 2000).

A research team at the Tokyo Institute of Technology created a hybrid iron and semiconductor material that changes magnetic properties when excited by light. The device consists of 20 alternating layers of ferrite and GaAs on a GaAs substrate. The researchers excited the device with light perpendicular to its surface and observed positive magnetoresistance. When the light was turned off, the magnetization returned to its original value, which indicates that the magnetization is reversible and not caused by a change in the structure of the device. If this is fully commercialized, it may lead to development of faster optical storage media and may also produce a new light-sensitive toner for photocopiers (Whipple, 2000).

In October, Isonics Corp., Golden, CO, and Epichem Inc., Allentown, PA, announced that they would establish a 2-year, jointly funded program to produced isotopically pure gallium for the semiconductor and optoelectronic business. The improved thermal conductivity provided by isotopically pure gallium can increase the performance and reliability some GaAs-base devices. Because the thermal conductivity of GaAs is about one-third that of silicon, improved thermal properties are likely to have substantial positive impact on the GaAs device performance (Isonics Corp., October 26, 2000, Isonics and Epichem start development of isotopically pure gallium, accessed November 2, 2000, at URL http://www.isonics.com/pr63.htm).

GaN continued to generate significant research interest at the academic level as well as on a commercial level. More than 100 companies and 200 universities worldwide were engaged in GaN material processing and device development. Europe with 37% and North America with 33% were the geographic areas where most of the groups were doing research and development (R.V. Steele, Compound Semiconductor, 2000, Update on GaN technology and markets, accessed April 9, 2001, via URL http://www.compoundsemiconductor.net). Much of the work centered on improving growth techniques and improving properties so that LEDs and laser diodes based on GaN technology could be commercialized.

AXT announced two new LED products, high-brightness cyan and green, which complimented the company's current offering of red, amber, yellow, and blue LEDs. The new 505-nm AlInGaN-based high-brightness cyan LED has a minimum power output of 1.2 mW at 20 milliamperes. High-brightness cyan LEDs were primarily used in traffic signals. Industry analysts estimated that the LED traffic signal market would reach approximately $100 million for 2000, and would grow at a rate of approximately 50% per year over the next few years. The new 525-nm AlInGaN-based high-brightness green LED has a minimum power output of 0.75 mW at 20 milliamperes. Because green is a primary color for light, by mixing red, green, and blue lights, many colors can be produced, including white light. With the high efficiency of this new product, many outdoor applications also would become feasible. High-brightness green LEDs were used in very large outdoor full-color displays, indoor displays, special-purpose illumination, cellular phone back lighting, traffic signals, as well as many consumer applications (Compound Semiconductor, April 28, 2000, American Xtal Technology announces new cyan and green LED products, accessed April 17, 2001, via URL http://www.compoundsemiconductor.net). The company received a multimillion dollar contract for the new LEDs in September.

Cree Inc., Durham, NC, reported it demonstrated the first MMIC made from GaN grown on a semi-insulating silicon carbide substrate. The initial device achieved 20 watts of pulsed radio frequency (RF) output power at 9 gigahertz (GHz), which exceeded the highest output power of GaAs MMICs available for this frequency range. The company also demonstrated a record-setting 10 GHz radio frequency power performance from a GaN HEMT. The GaN HEMT transistor was incorporated into a hybrid amplifier that achieved 40 watts of pulsed radio frequency output power at 10 GHz. This was more than 2.5 times higher than had been publicly reported for a single semiconductor device at this frequency. Cree's work on GaN hybrid and MMIC amplifiers was funded in part by the Air Force Research Laboratories and the Office of Naval Research, respectively. The GaN discrete devices and MMICs that were under development were being targeted for high frequency (5 to 35 GHz) commercial broadband communications, as well as military radar and communications applications (GaAsNet, August 19, 2000, Cree achieves record power performance at 10 GHz, accessed August 29, 2000, at URL http://www.gaasnet.com/news/cree_19082000.html).

Cree Lighting Co., a subsidiary of Cree, reported that it demonstrated a near-ultraviolet-violet indium gallium nitride LED with 28% quantum efficiency. This was the highest known external quantum efficiency publicly reported for an LED in the ultraviolet-to-blue portion of the wavelength spectrum. The LED emits at 400 nm and has a power output of 17 mW. LEDs in this portion of the light spectrum are important for making white solid-state light bulbs using phosphors to convert the wavelength of the light emitter to the visible spectrum, then mix colors to make a white bulb. High quantum efficiency is critical to making energy-efficient, solid-state light bulbs. The new emitter demonstrated an overall efficiency of 22% (Compound Semiconductor, July 28, 2000, Cree demonstrates 28% quantum efficient InGaN LED, accessed April 17, 2001, via URL http://www.compoundsemiconductor.net). Cree acquired Nitres Inc. in May 2000, renamed the company Cree Lighting, and began operating it as a wholly owned subsidiary. Nitres focuses on developing and commercializing nitride-based semiconductor materials and device technology; some research was funded though government and military contracts.

Cree and North Carolina State University filed a patent infringement lawsuit against Japan's Nichia Corp. and Nichia America Corp. in the U.S. District Court for the Eastern District of North Carolina. The lawsuit sought enforcement of a patent relating to GaN-based semiconductor devices manufactured using lateral epitaxial overgrowth (LEO) technology. The patent, U.S. patent No. 6,051,849, entitled "Gallium nitride semiconductor structures including a lateral gallium layer that extends from an underlying gallium nitride layer," was issued to North Carolina State University in April 2000 and was licensed to Cree under a June 1999 agreement from which Cree obtained rights to a number of LEO and related techniques. In its complaint, Cree alleges that Nichia was infringing the patent by importing, selling, and offering for sale in the United States certain GaN-based laser diodes covered by one or more claims of the patent. The lawsuit sought damages and an injunction against the infringement (Weiss, 2000).

Kyma Technologies Inc., a Research Triangle Park, NC, developer and supplier of nitride substrates, developed a 2-inch diameter, 50-μm thick epitaxial GaN layer, on a sapphire wafer, which was to be used as the core technology for a variety of applications within the optoelectronic, communications, and semiconductor industries. With existing technology, the typical epitaxial layer is 1 to 2 μm for sapphire-based GaN wafers. Kyma planned to ship samples to device developers by the end of 2000, with production quantities available in the first quarter of 2001 (Compound Semiconductor, November 2, 2000, 2-inch gallium nitride epitaxial substrate completed by Kyma Technologies, accessed April 17, 2001, via URL http://www.compoundsemiconductor.net).

ATMI developed and patented processes that allow the manufacture of high-purity GaN wafers 50 mm and larger in diameter; large area GaN wafers were not commercially available because of the difficulty of producing bulk GaN crystals. Based on their success with the patented technique, ATMI committed significant additional funding for continued development and pilot manufacturing capacity. In addition, ATMI was awarded contracts totaling nearly $4 million from the Office of Naval Research and the Ballistic Missile Defense Organization for further development of GaN wafers for electronic and optoelectronic devices (Compound Semiconductor, October 17, 2000, A T M I announces optical materials initiative; gallium nitride wafer and epi expansion to support blue laser development, accessed April 17, 2001, via URL http://www.compoundsemiconductor.net).

Nitronex Corp., a Raleigh, NC, semiconductor startup, announced that it received $500,000 in venture capital from Centennial Venture Partners, a $10 million venture fund started by North Carolina State University to help launch start-up companies affiliated with the university. Nitronex, founded in 1998, was set to begin scaling its proprietary technology for growing GaN on silicon. The company's PENDEO™ process, developed with researchers at North Carolina State, allows it to combine GaN with silicon to take advantage of the properties of both materials (Compound Semiconductor, February 7, 2000, Nitronex lands additional venture capital, accessed April 17, 2001, via URL http://www.compoundsemiconductor.net).

In July, Spectrolab Inc., Sylmar, CA, a unit of Boeing Co., claimed to have set a new world record by manufacturing satellite solar cells able to convert 29% of the sun's rays into spacecraft power. This surpassed the company's previous record of 27%, announced in April, for a space solar cell, and came only 7 months after achieving a 32.3% efficiency in terrestrial solar cells. Spectrolab planned to start production of this triple-junction GaAs-base solar cell in the third quarter of 2000. The average maximum power efficiency was expected to be 27.4%, with an end-of-satellite-life efficiency of 24.1% after 15 years in geosynchronous orbit (Spectrolab Inc., July 12, 2000, Spectrolab sets new world record with space solar cell efficiency of 29 percent, accessed November 28, 2000, via URL http://www.spectrolab.com).

Spectrolab announced that it would supply its solar cells to Dornier Satellitensysteme GmbH (DSS) of Germany under a technical assistance agreement between the two companies for qualification testing in the DSS space solar array systems. This was the first European agreement for Spectrolab since it received U.S. Government approval to provide solar components to major European spacecraft manufacturers. DSS was expected to purchase several hundred thousand multijunction solar cells through 2002. Once they are qualified, Spectrolab's multijunction GaAs solar cells are expected to improve the DSS solar array power performance by 40% compared to earlier designs using silicon cells. These multijunction space solar cells have an average efficiency of 24.5% and were qualified by the major U.S. satellite manufacturers. Spectrolab had been working under a jointly funded development contract with the U.S. Air Force to deliver 35%-efficient space solar cells by 2002 (Spectrolab Inc., May 20, 2000, Spectrolab to supply solar cells to German satellite builder Dornier, accessed April 19, 2001, via URL http://www.spectrolab.com).

In June, EMCORE announced that the company's new triple-junction GaAs-base solar cells with 26% efficiency were in production and were being shipped to customers for space qualifications. During qualification testing, these cells demonstrated a power loss of only 8% under a typical 15-year geostationary orbit characteristic of communication satellites. These new solar cells were expected to significantly improve satellite communications economics by increasing payload capabilities (EMCORE Corp., June 27, 2000, EMCORE announces production of 26% efficiency triple-junction solar cells, accessed April 19, 2001, at URL http://www.emcore.com/html_documents/News_clips/2000/Triple_Junction.htm). The company also produced a dual-junction solar cell for satellite applications that has an efficiency ranking of 25.3%. The dual-junction InGaP/GaAs compound semiconductor solar cell product is grown on a germanium substrate (EMCORE Corp., February 2, 2000, EMCORE announces shipment of world's highest efficiency dual junction solar cells, accessed April 19, 2001, at URL http://www.emcore.com/html_documents/News_clips/2000/shipment_highest_efficency_solar_cell.htm).

Scientists at Sandia National Laboratories were investigating indium gallium arsenide nitride (InGaAsN) as a potential photovoltaic power source for space communications satellites. This material, which may be used as a solar cell, has a potential 40% efficiency rate when put into a multilayer cell, which is nearly twice the efficiency rate of a standard silicon solar cell. An InGaAsN solar cell that could provide power to a satellite would ultimately have four layers. The top layer would consist of indium gallium phosphide, the second of GaAs, the third of 2% nitrogen with indium in GaAs, and the fourth of germanium. Each layer absorbs light at different wavelengths of the solar spectrum. The first layer absorbs yellow and green light, the second absorbs between green and deep red, the third absorbs between deep red and infrared, and the fourth absorbs infrared and far infrared. The absorbed light creates electron hole pairs. Electrons are drawn to one terminal and the holes to the other, thus producing electrical current (U.S. Department of Energy, Sandia National Laboratories, March 8, 2000, New semiconductor alloy's 'crazy physics' makes it a possible photovoltaic power source for satellites, accessed June 16, 2000, at URL http://www.sandia.gov/media/NewsRel/NR2000/InGaAsN.htm).

Also at Sandia, researchers constructed a two-dimensional GaAs artificial crystal that conducts light. The crystal's appearance resembles that of cheesecloth; this structure could be considered essentially a wire for light, because the specific size and periodic placement of the holes create a structure that blocks most light waves while transmitting those in a selected band of wavelengths. Because of the very small light loss, the technique offered the potential of ultimately replacing electronic chips with faster, cooler photonic chips. The technique could be used to combine light with electrons in a single chip. It also could be used to relay and change the direction of optical signals coming through telecommunications lines. The GaAs structure potentially may significantly reduce the energy needed to start and operate a laser. Although researchers say that the crystal structure was easy to fabricate, it was difficult to build and test without the structure cracking (U.S. Department of Energy, Sandia National Laboratories, October 27, 2000, Cheesecloth-like device bends light with little loss, accessed April 24, 2001, at URL http://www.sandia.gov/media/NewsRel/NR2000/cheese.htm).

Working with colleagues at Brown University, research personnel at Sandia demonstrated a prototype of the first VCSEL that emits ultraviolet light. While project work had been ongoing for 3 years, a key advance took place when indium was added to the VCSEL materials mix in August 1999. VCSELs are made of nanoscopically thin layers of semiconductor materials that emit photons when electricity is passed through them. While GaN and aluminum nitride both emit in the ultraviolet range, the efficiency with which those materials make use of input power is not high, only about 1%. Adding indium brought the VCSEL efficiency to a starting point of 20%, although it pushed the wavelength emitted longer into the near-ultraviolet range, about 380 nm. The successful synthesis of highly reflective bottom mirrors from aluminum gallium nitride was another important factor in making the prototype. Among their benefits, ultraviolet VCSELs coated with phosphors have the capability to generate the white light that could be used in indoor lighting. Easily portable ultraviolet laser light also causes weapons-grade fissionable materials and *E. coli* bacteria to fluoresce in the visible spectrum, aiding in the detection of attempted materials thefts and preventing the spread of bacterial epidemics (U.S. Department of Energy, Sandia National Laboratories, October 17, 2000, Sandia VCSEL generates ultraviolet light, accessed April 24, 2001, at URL http://www.sandia.gov/media/NewsRel/NR2000/UVVCSEL.htm).

Outlook

According to information compiled by CIBC World Markets, a unit of the Canadian Imperial Bank of Commerce, the GaAs industry is expected to decline in 2001, the first significant downturn in this industry. The company predicts that unless the cellular phone business shows a significant turnaround, GaAs sales could decline by as much as 15% in 2001. CIBC projected that the total number of mobile phone handsets sales in 2001 would be about 475 million units, an increase from the 410 million units sold in 2000. But there is significant inventory in this industry, which would be sufficient to supply the increase in demand, so the net gain would be essentially zero (Compound Semiconductor, 2001). According to CIBC, the leading world suppliers, based on a percentage of the value in 1999, are Fujitsu (11.1%), Mitsubishi Electric Corp. (10.1%), RF Micro Devices (9.6%), Motorola (7.4%), and Conexant (6.7%).

With a growth rate exceeding 58% per year for the past 5 years, Strategies Unlimited projected that the worldwide market for high-brightness LEDs reached $1.2 billion in 2000 and accounted for 42% of the total LED market. The company projected continued robust growth for the next 5 years, with the market expected to exceed $3.4 billion in 2005 (Compound SemiOnline, April 6, 2001, High brightness LED market forecast to reach $3.4 billion by 2005, accessed May 22, 2001, at URL http://compoundsemi.com/documents/view/generic.php3?id=389#top). The company expects that such markets as backlighting for mobile phones may experience a slowdown, but demand for very-high-brightness products for outside video displays, signage, and traffic signals will remain strong.

Until recently, the only significant market for GaN devices has been for high-brightness blue, green, and white LEDs. Since the announcement of high-brightness GaN-based blue LEDs in late 1993, the market grew from virtually nothing to $420 million by 1999. Since 1995, the growth rate had been estimated to be 79% per year. GaN-based blue, green, and white LEDs are used in a variety of applications, including full-color outdoor signs, automotive interior lighting, traffic signals, backlights for cell phone displays, niche illumination applications, and general purpose indicator and display applications. GaN-based blue-violet laser diodes operating at 405 nm, developed by Nichia, were introduced to the market on a sample basis in early 1999. These devices are used in a variety of applications, including sensing, spectroscopy, laboratory research and next-generation optical storage system development. No commercial blue-laser-based optical storage systems had been introduced. The GaN device market, however, was projected to experience strong growth over the next decade. Blue laser diodes will begin to be used in high-density DVD drives in 2002 and will capture a large share of the optical storage market in subsequent years. The total GaN device market was projected to grow to more than $4.8 billion by 2009 representing a compound annual growth rate of 28% from 1999 (R.V. Steele, Compound Semiconductor, 2000, Update on GaN technology and markets, accessed April 9, 2001, via URL http://www.compoundsemiconductor.net).

Forecasts of large growth in demand for gallium-based devices are based on the assumption of no significant changes in the overall world economy. If there is a significant decline in the world economy, these growth scenarios are too optimistic. Any growth in the use of gallium-based devices, however, will require additional gallium production capacity to be constructed. At current rates of world consumption, there is not enough virgin gallium supply available, as is evidenced by the situation at yearend 2000. Some of the supply problems should be alleviated when GEO Gallium's 100-t/yr gallium extraction plant comes on-stream in Australia in 2002.

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TABLE 1
SALIENT U.S. GALLIUM STATISTICS 1/

(Kilograms, unless otherwise specified)

	1996	1997	1998	1999	2000
Production	--	--	--	--	--
Imports for consumption	30,000	19,100	26,300	24,100	39,400
Consumption	21,900	23,600	26,900	29,800	39,900
Price per kilogram	$425	$595	$595	$640	$640

-- Zero.
1/ Data are rounded to no more than three significant digits.

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

(Kilograms)

End use	1999	2000
Optoelectronic devices:		
Laser diodes and light-emitting diodes	12,500	12,600
Photodetectors and solar cells	712	267
Integrated circuits:		
Analog	15,300	25,200
Digital	686	1,130
Research and development	572	701
Other	60	95
Total	29,800	39,900

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
1999:				
99.99% to 99.999%	890	399	632	657
99.9999%	108	13,600	13,200	485
99.99999% to 99.999999%	1,000	16,000	16,000	1,020 r/
Total	2,000	30,000 r/	29,800	2,160 r/
2000:				
99.99% to 99.999%	657	--	179	478
99.9999%	485	13,400	13,500	341
99.99999% to 99.999999%	1,020	25,400	26,300	136
Total	2,160	38,700	39,900	955

r/ Revised. -- Zero.
1/ Consumers only.
2/ Data are rounded to no more than three significant digits; may not add to totals shown.

TABLE 4
YEAREND GALLIUM PRICES

(Dollars per kilogram)

	1999	2000
Gallium metal, 99.99999%-pure, 100-kilogram lots	640	640
Gallium metal, 99.9999%-pure, 100-kilogram lots	595	595
Gallium metal, 99.9999%-pure, imported	380-425	380-425
Gallium oxide, 99.99%-pure, imported	275-350	275-350

Source: American Metal Market.

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

	1999		2000	
Country	Quantity (kilograms)	Value	Quantity (kilograms)	Value
China	99	$37,100	685	$368,000
France	7,750	3,200,000	24,800	9,510,000
Germany	2,490	1,240,000	731	207,000
Hungary	1,760	491,000	1,470	601,000
Japan	354	286,000	898	746,000
Kazakhstan	7,330	3,350,000	4,840	2,490,000
Korea, Republic of	--	--	1,200	1,430,000
Russia	2,470	1,060,000	2,100	1,590,000
United Kingdom	1,240	532,000	1,940	1,040,000
Other	575	175,000	672	450,000
Total	24,100	10,400,000	39,400	18,400,000

-- Zero.
1/ Data are rounded to no more than three significant digits; may not add to totals shown.

Source: U.S. Census Bureau.

TABLE 6
ESTIMATED WORLD ANNUAL PRIMARY GALLIUM
PRODUCTION CAPACITY, DECEMBER 31, 2000 1/

(Metric tons)

Country	Capacity
Australia 2/	50
China	20
Germany	30
Hungary	8
Japan	20
Kazakhstan	20
Slovakia	8
Russia	19
Ukraine	5
United States 2/	3
Total	183

1/ Includes capacity at operating plants as well as at plants on standby basis.
2/ Standby capacity as of December 31, 2000