

GALLIUM

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An overall economic decline in the United States resulted in lower demand for gallium from the record-high levels that transpired in 2000. The largest factor influencing domestic gallium demand was the decline in the purchase of new cellular telephone products, a significant consumer of gallium arsenide (GaAs)-based devices. As the gallium demand declined during 2001, the extremely high prices caused by short supplies also dropped until they reached normal levels by midyear. Unlike 2000, when demand for GaAs products was high and U.S. companies were announcing GaAs production capacity expansions, very few additional expansions were announced in 2001. Because gallium nitride (GaN) technology and uses are not as far advanced as those for GaAs, there was significant investment in production technology and development of new applications in 2001.

Gallium demand in the United States was met by imports, primarily high-purity material from France and low-purity material from China and Russia. Because of the drop in gallium consumption, imports also fell by about 31% from those in 2000. More than 95% of gallium consumed in the United States was in the form of GaAs. Analog integrated circuits (ICs) were the largest application for gallium, with optoelectronic devices [mostly laser diodes and light-emitting diodes (LEDs)] as the second largest end use.

World production of virgin gallium was estimated to be 81 metric tons (t). Total production for refined gallium was estimated to be 107 t, and demand for this material was centered in Japan, the United States, and Western Europe. Significant quantities of new scrap were recycled and supplemented supplies, particularly in Japan.

Production

No domestic production of primary gallium was reported in 2001 (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.

Owing to the high price of gallium at the beginning of 2001, companies have been encouraged to look for properties where gallium can be recovered as a principal product rather than as a byproduct of alumina and zinc processing. In May, the Canadian firm Gold Canyon Resources Inc. announced that it had found high levels of gallium at its Cordero gallium property

near the town of McDermitt in Humboldt County, NV. The company began initial drilling in October and announced preliminary results in November. According to the drilling results, gallium concentrations over the property range from 40 parts per million (ppm) to 224 ppm (Gold Canyon Resources Inc., 2001§¹). Gold Canyon continued drilling operations to provide further information on the gallium mineralization and acquired additional land as a buffer zone around the mineralization.

Another Canadian firm, Win-Eldrich Mines Ltd., completed initial surface sampling at its Painted Hills property located in Humboldt County, NV. In its initial samples, the gallium grade averaged 21.7 ppm, and the samples also contained such elements as germanium, lanthanum, titanium, and yttrium. Win-Eldrich felt that the results obtained were sufficient to justify preliminary metallurgical work to determine if a potentially marketable concentrate could be produced. The company planned to begin a bulk sampling program by December 2001 (Win-Eldrich Mines Ltd., 2001§).

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 61% of total consumption. Optoelectronic devices accounted for 34% of domestic consumption, and the remaining 5% was used in digital IC's, 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 2001, there were 10 responses to the consumption of gallium survey, representing 48% of the total canvassed. Owing to the poor response rate, data in tables 2 and 3 were adjusted by incorporating estimates to reflect full industry coverage. Many of these estimates were based on companies' 2001 10-K reports, submitted to the U.S. Securities and Exchange Commission.

Gallium Arsenide.—The Airtron Division of Northrop Grumman Corp. (formerly Litton Airtron), one of the largest U.S. producers of semi-insulating GaAs wafers, closed near the end of the year. The decision to close the operation was made shortly after Northrop Grumman completed its acquisition of Litton Industries Inc. in May. One of the reasons cited for closing the business was a number of cancellations from major customers. In addition, Airtron relied on the low-pressure

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

liquid-encapsulated Czochralski production technique, which was a lower cost process than was acceptable for ion implantation, but the defect densities resulting from this growth technique were too high for epitaxial growth applications. The company wanted to switch to the vertical freeze method of producing GaAs, which results in lower defect densities, but this would require significant capital and research and development expenditures. Before the closure, Northrop Grumman had unsuccessfully attempted to find a buyer for the Airton operation (Meyer, 2001).

EMCORE Corp. opened its new 3,300-square-meter (m^2) GaAs manufacturing facility in Albuquerque, NM, in January. This expansion tripled EMCORE's cleanroom manufacturing capacity, adding to the existing 4,650- m^2 building, which houses the company's solar cell, optical components, and networking products manufacturing facilities (EMCORE Corp., 2001a§).

In May, TRW Inc. spun off its indium phosphide (InP) and GaAs businesses into a new company called Velocium. Although Velocium is focused mainly on developing new InP-based products, it will also include TRW's current commercial operations that produce GaAs components for fiber optic and wireless communications (Compound Semiconductor, 2001q).

Kopin Corp. signed multiyear supply agreements with Anadigics Inc. and Alpha Industries Inc. to supply the companies with its new 6-inch indium gallium phosphide (InGaP) heterojunction bipolar transistor (HBT) wafers. Under the agreement, Anadigics and Alpha Industries will use the HBT wafers for their advanced telecommunications applications (Kopin Corp., 2001a§, b§).

Sony Corp. developed a new integrated dual-wavelength laser diode that produces 780- and 650-nanometer (nm) light for reading both compact disks (CDs) and digital video disks (DVDs). Company researchers reported that the chips performed as well as or better than single laser diodes at the wavelengths. For a single unit to play CDs and DVDs, the machine needs two lasers to read the different size pits on the discs. One operates at the 650-nm wavelength for DVD playback, and the other produces 780-nm light for CDs. The most common approach has been to use two separately manufactured laser diodes, sometimes joining them to one silicon wafer and using a prism to combine their output on one optical path, but this increases the cost. Making the dual-wavelength lasers involves depositing aluminum gallium arsenide (AlGaAs) and indium gallium aluminum phosphide (InGaAlP) active layers on a GaAs substrate and then using wet etching to shape and separate the laser islands for the two wavelengths. Sony fast-tracked the development of the new lasers and installed them on PlayStation 2 units beginning in March 2000. The company has ramped up production of the PlayStation 2 to 2 million units per month in the fall of 2001. Variations of the laser diodes to be are expected to be available for use in such applications as CD read-write (Robinson, 2001).

Gallium Nitride.—RF Nitro Communications Inc. completed its new dedicated facility for GaN epitaxy and wafer processing in July. Located at the company's headquarters in Charlotte, NC, the facility includes class-10 and class-1000 clean rooms and all support systems needed to produce GaN-based heteroepitaxial structures and power transistors. The facility

was designed specifically to become the world's first GaN 4-inch wafer pilot line. Since May 2000, RF Nitro has been selling GaN materials on 2-inch sapphire and silicon carbide (SiC) substrates (Compound Semiconductor, 2001m). RF Micro Devices Inc. (RFMD) acquired RF Nitro in October. According to RFMD, the acquisition would add complementary GaN process technologies and products and InGaP products and proprietary design expertise, would provide RFMD additional research and development resources for advanced technology development, and was expected to strengthen RFMD's position in the wireless infrastructure market. After the acquisition was completed by yearend, RF Nitro started operating under the name RF Micro Devices Charlotte (RF Micro Devices Inc., 2001§).

EMCORE announced that it had signed an agreement with Lumileds Lighting to supply the company with its metal-organic chemical vapor deposition (MOCVD) tools to be used in the production of high-brightness GaN LEDs. A joint venture between Agilent Technologies and Philips Lighting, Lumileds Lighting has purchased multiple EMCORE GaNzilla™ tools in the initial phase of the agreement, as it continues to increase its LED production across all wavelengths, including green, blue, cyan, and white (EMCORE Corp., 2001b§).

AXT, Inc., announced the introduction of production quantities of large, high-flux aluminum indium gallium nitride (AlInGaN) chips in green, cyan, and blue for LED applications. The P2 chips, which are much larger than standard-sized LED chips, are designed for applications such as automotive lighting, dental curing, and general illumination that require the maximum luminous flux per device. The green P2 chips have output powers (at 350 milliamps) up to 27 milliwatts with 17.5 lumens per watt efficiency. The cyan P2 chips, designed for use in traffic signals, have output powers of 30 milliwatts with 12.5 lumens per watt. The new blue AlInGaN-based LEDs have output powers up to 35 milliwatts and achieve efficiencies of 6 lumens per watt (AXT, Inc., 2001§).

In January, Nitronex Corp. announced that it produced the industry's first GaN-based high-electron mobility transistors (HEMTs) on low-cost, 4-inch silicon wafers. Until this development, industry efforts were limited to 2-inch wafers. Partially as a result of this development, the company received an additional \$24.5 million in financing to continue its research. The company was started in 1999, with \$10.1 million in initial funding and has numerous patents in various stages of the review process (Nitronex Corp., 2001§).

Light-Emitting Diodes.—Many LED manufacturers introduced new LEDs based on GaN technology that offer improvements from currently produced LEDs. In many cases the new LEDs are brighter, last longer, and/or can be used in new applications. The following highlights some of these new developments.

Uniroyal Optoelectronics (UOE) (a subsidiary of Uniroyal Technology Corp.) demonstrated two 450-nm and 470-nm high-brightness blue LED's, which, when conventionally packaged, were expected to result in packaged lamp power levels between 4 and 5 milliwatts. Both LED products combine indium gallium nitride (InGaN) materials on sapphire substrates. The 450-nm LED can be used for white light by incorporating a phosphor coating in the packaging design. Applications for this product

include flashlights and night lights. The 470-nm LED is used in such applications as outdoor video displays, biomedical applications, and instrumentation (Uniroyal Technology Corp., 2001§).

In March, Lumileds Lighting introduced a new backlight source based on its gallium-based Luxeon™ LED technology for liquid crystal display monitors, notebooks, and televisions. The company claims that the new LED technology will enable many new features that are currently not available via conventional cold cathode fluorescent lamp (CCFL) backlight technology. Lumileds claims that the new LED source is more durable than CCFL and does not use mercury like CCFLs. The new LEDs also are brighter, with a color range up to 130% of the ideal set by the National Television Standards Committee in the backlight; CCFLs exhibit only 80% of the ideal value (Compound Semiconductor, 2001g).

GELcore (a joint venture between EMCORE and General Electric Lighting) introduced new high-efficiency blue, green, and blue-green InGaN high-brightness LEDs. With these additions, GELcore now offers discrete high-brightness LEDs across the broad visible spectrum; the new addition complements the company's white, red, red-orange, orange, and yellow-amber InGaAlP LEDs introduced in 2000. Applications for the new InGaN LEDs include variable messaging, traffic signals, exit signage, and specialty applications (Compound Semiconductor, 2001d).

LEDtronics Inc. introduced direct incandescent replacement lamps that combine InGaAlP and GaN on silicon carbide LEDs on standard screw bases. The new LED lamps draw only 1.0 to 1.7 watts of power and have an 11-year operating life. Eighteen individual LEDs are configured either to disperse light in a 270° wide angle or a 30° acute angle, depending upon the model and are available in blue, green, orange, red, white, and yellow, as well as derivations of those colors. Additionally, with the use of multiple LEDs, an LED cluster lamp continues to provide light even if one or more emitters fail, unlike when the filament breaks in an incandescent bulb (Compound Semiconductor, 2001f).

Prices

In 2001, producer-quoted prices for high-purity gallium were the same as those at yearend 2000 (table 4). Quoted prices, however, do not reflect the actual price trends that occurred during the year. Prices had skyrocketed at the end of 2000 to more than \$1,500 per kilogram, and this escalation continued in early 2001. By the end of March, gallium prices were reported to have reached \$2,200 to \$2,300 per kilogram in Japan (Mining Journal, 2001b). These prices began to slide in April, however, as Chinese producers and metal traders were trying to sell their stocks. By July, prices had returned to more normal levels of \$500 to \$600 per kilogram for 99.9999%-pure material. The return to normal levels primarily resulted from the slump in demand for gallium-based components in the telecommunications sector (Mining Journal, 2001a). By yearend, prices had fallen even further, with 99.9999%-pure material from Russia offered as low as \$380 per kilogram (Mining Journal, 2001c).

Foreign Trade

U.S. gallium imports declined by 31% from those in 2000 (table 5). France (39%), China (29%), Russia (11%), and the United Kingdom (8%) were the principal sources of imported gallium. The drop in gallium imports resulted from the decline in gallium requirements for wireless communications applications. In addition to gallium metal, GaAs wafers were imported into the United States. In 2001, 42,200 kilograms (kg) of undoped GaAs wafers was imported, slight increase from that in 2000. Japan (61%) and Slovakia (38%) were the principal sources. Japan (39%), Finland (16%), the Philippines (11%), and Germany (9%) were the main import sources for doped GaAs wafers, totaling 93,700 kg during the year, a decrease of 68% from that in 2000. 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 81 t in 2001. Principal world producers were China, Germany, Japan, Kazakhstan, and Russia. Hungary, Slovakia, and Ukraine also recovered gallium. Refined gallium production was estimated to be about 107 t; this included some new scrap refining. France was the largest producer of refined gallium using gallium produced in Germany as feed material. Japan and the United States also refined gallium. Gallium was recycled from new scrap in Germany, Japan, the United Kingdom, and the United States.

Australia.—GEO Gallium Group postponed the startup of its new \$40 million, 100-t/yr gallium extraction plant in Pinjarra, Western Australia, until the fourth quarter of 2002; the originally scheduled date was the second quarter of 2002. The delay in plant startup was attributed to poor market conditions, but when the plant does begin producing gallium, it will produce 99.99%-pure material. This gallium most likely will be shipped to GEO Gallium's purification plant in Salindres, France, where it will be purified to 99.9999%- and 99.99999%-pure gallium before being shipped to customers. Completion of the plant will bring GEO Gallium's total gallium extraction capacity to about 133 t/yr, making it the largest gallium producer in the world. In December, the company reached a contract with Alcoa of Australia Ltd. for Alcoa to provide feedstock for the new plant, which would consist of a bleed stream of the caustic leach solution from Alcoa's Bayer alumina extraction plant nearby (Chemical Market Reporter, 2001).

China.—Sumitomo Chemical Co. was forming a joint venture in Shanghai to produce high-purity gallium, beginning in the fall of 2001. The refining facility will have a capacity of 40 t/yr, and the other partners in the joint venture are Inabata & Co. Ltd., a Japanese trading firm, with 15%, and the U.S. firm Technical Sourcing International Group (which was founded in part by Inabata), also with 15%; Sumitomo Chemical will own the remaining 70%. The new joint-venture company will be called Shanghai Sumika High Purity Metal Ltd., and the gallium produced will be supplied to Sumitomo (Compound Semiconductor, 2001o). The company also has licensed its gallium recovery technology to China's Great Wall Aluminium

Co., which planned to increase its capacity to 15 t/yr from its current level of 8 t/yr. In addition, the other large gallium producer in China, Guizhou Aluminium Smelter, planned to increase its production capacity by 12 t/yr with a second production line that was scheduled to be completed in the second half of 2001. The capacity increase would bring the operation's total production capacity to 20 t/yr (China Council for the Promotion of International Trade, 2001§).

Japan.—Furukawa Co. Ltd. announce that it was developing technology to recover gallium and arsenic from the GaAs semiconductors that are used in cellular telephone applications. The company expected to use the recovered materials in its gallium phosphide (GaP) polycrystals, used in LED applications. Furukawa is the world's largest producer of high-purity arsenic, and also announced that it was increasing high-purity arsenic production capacity at its Iwaki plant to 15 t/yr from 9 t/yr by yearend to meet the growing demand for GaAs production (Compound Semiconductor, 2001b).

Taiwan.—In spite of the overall downturn in the demand for GaAs in wireless applications, Taiwanese companies continued to announce plans to build new wafer production lines. In September, Giga Epitaxy Technology Corp. completed construction of a new facility in Yangmei for production of 6-inch GaAs epitaxial wafers targeted at the wireless telecommunications market. The new facility has 2,200 m² of cleanroom space, and initial production at the new plant is expected to be 2,000 wafers per month in the first quarter of 2002, increasing to 3,000 wafers per month by the second quarter. Total capacity could be increased to 12,000 wafers per month, depending on demand. Giga Epitaxy is 51%-owned by Japan's Hitachi Cable Ltd., which also produces epitaxial GaAs wafers and substrates. Hitachi Cable signed agreements to transfer the technology for many of its manufacturing processes to Giga Epitaxy (Compound Semiconductor, 2001e).

A new firm that was founded in 2000, Suntek Compound Semiconductor Co., completed construction of a 4-inch GaAs wafer fabrication facility in April. Mass production began in October at a rate of 1,000 wafers per month. This number was projected to rise until it reaches the plant's full capacity of 5,000 wafers per month. The initial products will be AlGaAs and InGaP HBTs. Suntek planned to build a 6-inch line to produce GaAs HBTs and pseudo-HEMTs by the end of 2002. In total, the company plans to increase capacity to the equivalent of 21,100 6-inch wafers by 2004 (Whitaker, 2001). Suntek's shareholders include Japan's Mitsubishi Electric Corp. and Taiwan's Procomp Informatics Ltd. The U.S. firm Celeritek Inc. also invested in Suntek.

Another new firm, Compound Semiconductor Manufacturing Corp., that was founded in 2000 planned to begin mass production in June 2001 and expand its cleanroom capacity from 800 m² to 2,500 m² by yearend. The company also planned to have 10 fabrication lines in place by 2003, with a total capacity of 16,000 4- and 6-inch wafers per month (Whitaker, 2001).

Transcom Inc. announced that it began production of 3- and 4-inch GaAs wafers at a new plant in Hsinchu Industrial Park for field effect transistor (FET) applications in the telecommunications market. The initial capacity of the plant is 15,000 wafers per year, but the company hoped to expand to

35,000 wafers per year (LePedus, 2001§). Transcom was founded by former executives from Celeritek and Hewlett-Packard Co. A new small firm established in January 2001, Millennium Communication Co. Ltd., began producing GaAs-based epitaxial wafers at a 1,200-m² plant in Hsinchu Industrial Park at a production rate of 100 to 200 wafers per month, most of which are exported to North America. The company's products are mainly focused on the laser diode and photodiode markets (Compound Semiconductor, 2001i).

Running contrary to announcements from other firms, Advanced Wireless Semiconductor Co. (AWSC) delayed plans to install a 6-inch GaAs manufacturing line. Originally scheduled to be operational by early 2001, AWSC has decreased the size of the line to 4-inch wafers and has pushed back the completion date until 2003 (Whitaker, 2001).

If all the proposed GaAs projects in Taiwan were completed (including those announced by WIN Semiconductors Corp. in 2000), the country's total GaAs production capacity would be greater than 1 million 6-inch-wafer equivalents by 2005. Most analysts predict that only one or two of these projects would be completed, and the rest would either be delayed indefinitely or canceled.

Ukraine.—In January, the Nikolayev Alumina Plant began operating the first line of its new gallium extraction plant, which, when fully commissioned, will increase gallium capacity from 1.8 t/yr to 10 t/yr. Nikolayev Alumina only expected to increase production capacity to 3 t/yr by the end of 2001, with the timetable to start up the remaining capacity uncertain (Metal Bulletin, 2001).

United Kingdom.—Filtronic plc, a designer and manufacturer of customized microwave electronic subsystems, signed agreements with two international companies for additional use of its facility at Newton Aycliffe in County Durham. Filtronic signed one agreement with M/A-COM Inc. (a unit of Tyco International Ltd.) to supply large quantities of GaAs products on 6-inch wafers for the mobile handset, cable communications, and microwave tagging markets. Filtronic has been working with M/A-Com for more than 6 months processing and qualifying its epitaxial wafers. The two companies will also jointly develop new products. A second agreement was signed with BAE Systems Avionics Ltd. in which Filtronic has granted BAE Systems a sole licence to use its design and process technology for compound semiconductors for defense applications. In addition, Filtronic will supply BAE Systems with related semiconductor devices. The combined effect of these two agreements will be to reduce the losses of the Newton Aycliffe operation significantly, which had been losing about £1 million per month (Cameron, 2001§).

Current Research and Technology

In September, scientists at Motorola Inc. announced that they had developed a method of growing compound semiconductor materials, specifically GaAs, on silicon substrates. Although the idea of growing GaAs on silicon is not new, previous attempts to do this had not been able to overcome the problems that were created by the difference in the lattice constants of GaAs and silicon. A key mechanical issue relates to the fact that silicon and such materials as GaAs have different

crystalline structures, and it is impossible to grow a structure of one crystalline material on top of another unless they have very similar lattice constants (the distance between the atoms in the structure). If the two crystalline materials have less than a 2% mismatch in their lattice constants, then very thin layers of one material can be grown on the other material. However, the strain caused by the mismatch becomes too great when thicker layers are grown or when the lattice constant exceeds 2%, causing dislocations or “cracks” in the material. So, while researchers have been trying to combine silicon and GaAs for years, none has succeeded until now because silicon and GaAs have a mismatch of 4.1%.

In 1999, Motorola demonstrated the world’s thinnest functional transistor by growing a strontium titanate (STO) crystalline material on silicon substrate. The STO worked, but as thicker layers were grown, oxygen molecules diffused through the layer and began to bond with the silicon below, creating an amorphous interface layer between the silicon and the STO. Initially, that layer appeared to be a problem, and researchers focused on thinning or eliminating it. Then the scientists discovered that the amorphous layer allowed the STO to completely relax to its own natural crystal lattice constant, allowing the successful growth of a GaAs layer. The main value of the technology is its potential to reduce substrate cost, increase the substrate size, and reduce processing cost for III-V compound wafer manufacturing. Currently, there is no commercially practical way to produce GaAs wafers larger than 6 inches in diameter or InP wafers larger than 4 inches in diameter. However, this technology has already enabled the production of 8-inch and 12-inch GaAs on silicon wafers (Motorola Inc., 2001§). Motorola has applied for numerous patents on the technology and its potential applications. Combining GaAs and silicon on the same wafer potentially could produce wafers that have the best properties of both materials—the sturdiness and cost efficiency of silicon with the high speed and optical capabilities of GaAs.

Researchers at Japan’s National Research Institute for Metals and the University of Tokyo developed a way to make large numbers of GaAs quantum dots of uniform size and shape. Each dot is 5 to 20 nm in diameter and is created by a method called liquid-droplet epitaxy. Starting with an AlGaAs thin film on GaAs, liquid gallium is sprayed on the surface, creating a number of gallium droplets. Then arsenic is sprayed over the wafer, creating the dots. The GaAs quantum dots have the potential for semiconductor lasers that emit light at one-hundredth the current of existing devices and may offer potential for quantum computers that operate at extremely fast speeds (Compound Semiconductor, 2001c).

Researchers from Thales Corporate Research in France developed a GaAs-based quantum cascade laser that operates at room temperature. Since their development in 1995, quantum cascade lasers have found applications in gas sensing and infrared spectroscopy. GaAs-based devices had been limited to operation at cryogenic temperatures because of heat generated during operation, but the researchers found that mounting the device upside-down improved thermal dissipation. The new lasers lased at temperatures up to 287 K (Photonics Spectra, 2001).

Researchers at Osram Opto Semiconductors GmbH

developed a new wafer-bonding technique to produce a aluminum gallium indium phosphide (AlGaInP) LED reaching luminous efficacies of more than 50 lumens per watt at a wavelength of 615 nm, surpassing the standard efficacy of 25 to 30 lumens per watt. Normally, AlGaInP LEDs are created by epitaxially depositing the active layer on a GaAs substrate, but the GaAs substrate absorbs some of the light, thereby lowering the amount that can be transmitted. Engineers at Osram used advanced thin-film technology to solve this problem. The so-called substrateless LED still uses the GaAs substrate for crystal growth, but afterwards the LED functions without the base material. With this new technology, the upper side of the LED is coated with a metal layer after the epitaxy process, then it is bound onto a new, thin carrier. The original GaAs substrate can then be removed, leaving behind just the thin, light-generating layer. The intermediate metal film is partially alloyed, allowing the alloyed part to act as an electrical contact and the nonalloyed part as a highly reflective mirror. This technique allows more light to be emitted than conventional LED designs (Compound Semiconductor, 2001k).

Japan’s Nitride Semiconductors Co. Ltd., formed in 2000 as a spinoff from Tokushima University, announced the development of a GaN-based 350-nm ultraviolet LED with enough light output for commercialization. Sample products, grown on sapphire, have a light output of 0.1 milliwatt, but the company says that the technology can support light outputs of up to 1 milliwatt. Because they have short wavelengths and are easily focused, the new LEDs are expected to be useful to detect microscopic quantities of chemical substances as well as for light sources for medical devices (Compound Semiconductor, 2001j).

Technologies & Devices International Inc. (TDI) produced bulk single-crystal GaN substrates and then produced polished 1.5-inch diameter GaN wafers from the bulk material. Bulk GaN is difficult to grow, and commercial GaN-based devices are normally grown on sapphire or silicon carbide substrates. Even after the normal substrates are removed leaving a GaN layer, the GaN has a high number of dislocations caused by the relaxation of stresses on the crystal structure after the substrate is removed. According to TDI, the production of GaN wafers from a bulk substrate yields a wafer with a reduction in dislocation density of several orders of magnitude compared to the epitaxially grown GaN. TDI planned to have pilot quantities of the wafers available by mid-2002 and was in discussions with potential partners to commercialize their proprietary crystal-growth and wafer-fabrication technologies (Compound Semiconductor, 2001p).

Cree Inc. announced that its GaN HEMT microwave devices and GaN HEMT epitaxial wafer materials were successfully installed aboard the International Space Station after being launched into space by the space shuttle Discovery. The GaN HEMT transistors and material were being evaluated to determine their radiation hardness compared to existing semiconductor materials for future satellite applications. The materials and devices were incorporated into the Materials International Space Station Experiment (MISSE) for the purpose of determining how various materials endure the space environment. The Discovery delivered the MISSE to the International Space Station after it was launched on August 10,

2001. The experiment was mounted onto the outside of the space station's airlock during the first spacewalk of the mission on August 16, 2001. After long-term exposure to space conditions, the MISSE will be retrieved and returned to Earth on a future shuttle mission for testing and evaluation (Compound Semiconductor, 2001a).

UOE announced a long-term collaborative project, called UV Florida, with three of Florida's leading research universities—the University of Florida, the University of South Florida, and the University of Central Florida—to accelerate UOE's development of ultraviolet LEDs. The initial goal of the project will be the development of 350- to 400-nm aluminum gallium indium nitride (AlGaInN)-based LED devices. According to UOE, ultraviolet LEDs, when packaged with a tricolored phosphor, generate a brighter, purer, and more efficient white LED device than the current method of packaging a high-brightness blue LED with yellow phosphor. The University of Florida will focus on epitaxial growth and processing of the devices, and the Universities of South and Central Florida will provide structural determination and electrical and optical characterization, respectively. Potential markets for the high-brightness ultraviolet LEDs include solid-state white lighting, medical diagnosis, optical storage, and compact sensing devices in the biological, chemical, and environmental markets (Compound Semiconductor, 2001s). UOE also completed expansion of its epitaxial growth facility in Tampa, FL, in July, including the purchase of three MOCVD reactors for that will be used to manufacture blue and green high-brightness LEDs; this expansion brings the total number of MOCVD reactors at the facility to six (Compound Semiconductor, 2001r).

Cermet Inc. received a contract from the U.S. Department of Defense's (DOD) Ballistic Missile Defense Organization to develop bulk GaN crystal growth and substrate technology. The term of the contract will be 2 years and is valued at approximately \$770,000. During the term of the contract, Cermet will demonstrate a 2-inch diameter GaN crystal growth technology. The DOD is pursuing bulk nitride technology to incorporate into advanced detectors and high-power, high-frequency electronic devices and optoelectronic devices (Cermet Inc., 2001§).

As part of a collaboration with the National Aeronautics and Space Administration (NASA), JX Crystals Inc. and Tecstar, Inc. (acquired by EMCORE in 2002), demonstrated solar cells with an efficiency of 33.4%. The solar cells are a combination of Tecstar's InGaP-GaAs dual front cell with JX Crystal's gallium antimonide (GaSb) bottom cell. The solar cells were developed as a Small Business Innovative Research Program that has as one of its goals to produce cells with solar efficiencies greater than 30% for aerospace applications, such as for the ultralight Stretched Lens Array that NASA wants to use for power (Compound Semiconductor, 2001h). In addition, Tecstar is a principal contract holder with NASA's Glen Research Center to develop a solar cell with 40% efficiency. The design for this type of cell consists of a four-junction cell; an InGaP-GaAs dual-junction cell on top combined with an indium gallium arsenide phosphide-indium gallium arsenide (InGaAsP-InGaAs) dual-junction cell on the bottom. The practical efficiency of the

top cell is estimated to be 30.3% and that of the bottom cell, 9.5% (Compound Semiconductor, 2001i).

Under a \$6.4 million contract from the U.S. Space and Naval Warfare Systems Center, Rockwell Scientific Co., and the University of California at Santa Barbara will collaborate on antimony-based compound semiconductors to provide high-speed low-noise circuits. The principal system being investigated will be indium arsenide-aluminum gallium arsenide antimonide (InAs-AlGaAsSb) to produce HEMTs and HBTs for defense and space applications. The objective of the 3- to 4-year project would be to produce devices that operate at a voltage up to four times lower than that of comparable GaAs devices and at a higher cutoff frequency and lower voltage than InP devices (Compound Semiconductor, 2001n).

Outlook

According to Strategies Unlimited, the worldwide market for high-brightness LEDs in 2001 was flat compared to 2000, with total revenues of around \$1.2 billion. In spite of a flat 2001, the company estimates that this market will grow by around 15% in 2002, and by 20% to 30% thereafter, with the market projected to reach \$3 billion by 2006. Although LED unit sales increased throughout 2001, this increase was offset by a drop in average selling prices, resulting in zero revenue growth. While the overall economic recession was the main cause for the lack of growth, the declining value of the Japanese yen had an additional effect, because Japan supplies over one-half the high-brightness LEDs worldwide. High-brightness LEDs continued to penetrate existing markets and find their way into new applications. Major market sectors for these products included signs that use monochromatic displays for moving messages and highway information; full-color displays for large video screens; interior and exterior lighting applications in cars, trucks, and buses; and traffic signals. Overall, there was a large variation in the growth rates for these applications in 2001, with high growth rates for traffic signals and interior automotive lighting applications. In 2001, the largest market for high-brightness LEDs became backlighting, which makes up 30% of the total. Automotive applications and applications in signs and displays, each with 26% of the total, were the second-largest uses for high-brightness LEDs. Sales of InGaN LEDs accounted for about two-thirds of the total market. The market for AlInGaP LEDs in 2001 was around 28% of the total, and AlGaAs LEDs lost market share and dropped to about 6% of the total (Dixon, 2002).

According to its research reports on the wireless communications market, CIBC World Markets predicted that this industry is expected to have a 14.4% compound annual growth rate from 2001 to 2004. The main driver for the high growth rate is expected to be existing subscribers acquiring replacement handsets with new features and services, such as color screens and data capability. If handset shipments pick up to the extent that CIBC has predicted, then GaAs components should have growth exceeding 15% during 2002, because the new platforms are more complex and require additional GaAs content per phone (Whitaker, 2002).

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TABLE 1
SALIENT U.S. GALLIUM STATISTICS 1/

(Kilograms, unless otherwise specified)

	1997	1998	1999	2000	2001
Production	--	--	--	--	--
Imports for consumption	19,100	26,300	24,100	39,400	27,100
Consumption	23,600	26,900	29,800	39,900	27,700
Price per kilogram	\$595	\$595	\$640	\$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	2000	2001
Optoelectronic devices:		
Laser diodes and light-emitting diodes	12,600	8,710
Photodetectors and solar cells	267	598
Integrated circuits:		
Analog	25,200	16,800
Digital	1,130	1,230
Research and development	701	242
Other	95	95
Total	39,900	27,700

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
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
2001:				
99.99% to 99.999%	478	--	190	288
99.9999%	341	9,360	9,550	154
99.99999% to 99.999999%	136	18,000	18,000	136
Total	955	27,300	27,700	578

-- 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)

	2000	2001
Gallium metal, 99.9999%-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/

Country	2000		2001	
	Quantity (kilograms)	Value	Quantity (kilograms)	Value
China	685	\$368,000	7,710	\$7,280,000
France	24,800	9,510,000	10,600	8,050,000
Germany	731	207,000	890	1,320,000
Hungary	1,470	601,000	879	904,000
Japan	898	746,000	742	877,000
Kazakhstan	4,840	2,490,000	--	--
Korea, Republic of	1,200	1,430,000	200	318,000
Russia	2,100	1,590,000	2,990	2,620,000
United Kingdom	1,940	1,040,000	2,170	2,360,000
Other	672	450,000	858	448,000
Total	39,400	18,400,000	27,100	24,200,000

-- 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, 2001 1/

(Metric tons)

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

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

2/ Standby capacity as of December 31, 2001.