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2006 Minerals Yearbook

GALLIUM

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GALLIUM

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Gallium metal and gallium arsenide (GaAs) wafer imports continued to account for most of the U.S. gallium consumption. Metal imports were 71% higher than those in 2005, with China, Ukraine, and Germany, in descending order, as the leading sources of imported gallium. Undoped GaAs wafer imports were 18% lower than those in 2005; China and Taiwan were the principal sources. Almost all the gallium consumed in the United States was in the form of GaAs and gallium nitride (GaN) and was used in integrated circuits (ICs) and optoelectronic devices [laser diodes, light-emitting diodes (LEDs), photodetectors, and solar cells]. Gallium consumption increased by 8% from that in 2005. The increase in consumption was significantly less than the increase in imports because a large portion of the U.S. imports was estimated to be low-purity material that was refined in the United States and shipped to other countries.

In 2006, estimated world crude gallium production was 72 metric tons (t), slightly higher than that in 2005. Principal producers were China, Germany, Japan, Kazakhstan, and Ukraine. Plants in Hungary, Russia, and Slovakia also recovered gallium. Refined gallium production was estimated to be about 105 t, which included some new scrap refining. Refined gallium was produced in France, Japan, and the United States.

Legislation and Government Programs

In June, the U.S. Department of Energy (DOE) awarded $7 million for five cost-shared projects for solid-state lighting (SSL) product development. These projects continued DOE's public-private partnership to advance state-of-the-art SSL used for general lighting applications. Three of these projects involve improvements in LEDs. Color Kinetics Inc.'s and General Electric Global Research's goals are to create LED lamps to replace incandescent bulbs. Osram Sylvania Development Inc.'s proposal seeks to increase the quantity of light that escapes from an LED (U.S. Department of Energy, 2006). In October, the DOE began a commercial product testing program under the SSL project. This program was intended to assist the introduction of LED-base lighting products into the commercial marketplace. The program also will provide unbiased, reliable product performance information to the public, helping buyers have confidence that new SSL products will perform as claimed.

Also in October, the DOE selected a National Laboratory Center for Solid-State Lighting Research and Development. The National Laboratory Center will provide technical administrative support for SSL research projects in nanotechnology, and will be run by the Center for Integrated Nanotechnologies, jointly operated by Sandia National Laboratories and Los Alamos National Laboratories. The DOE also announced that it will provide $5 million for seven research projects in solid-state lighting including two at Sandia to develop improved GaN material (LEDs Magazine, 2006a).

In February, EMCORE Corp. signed a subcontract to participate in the Defense Advanced Research Projects Agency's (DARPA) Very High Efficiency Solar Cell Program. This program was expected to increase the efficiency of terrestrial solar cells to at least 50% within 50 months; the highest efficiency for EMCORE's triple-junction solar cells was about 36%. In connection with this award, EMCORE also has joined a consortium formed by the University of Delaware to succeed in meeting DARPA's program requirements for a high-efficiency and low-cost terrestrial solar product. The program will provide up to $53 million in funding, which will be awarded to program participants in various phases over the next several years (Compound Semiconductor, 2006b).

Bandwidth Semiconductor LLC (a subsidiary of Spire Corp.) was awarded a small business innovation research grant from the National Aeronautics and Space Administration (NASA) to develop a new type of thermophotovoltaic (TPV) power cell that produces electricity from heat. The cells are similar to solar cells that convert visible photons to electricity, but the semiconductor material is adjusted to convert long-wavelength or thermal photons to electricity. The project has potential applications for NASA in long-duration space missions to generate electricity from heat generated by long-life radioisotope sources; the power generated by conventional solar cells is limited because of the large distance from the sun. Potential commercial applications of TPV cells include electricity cogeneration using heat from wood or propane combustion (Spire Corp., 2006). Bandwidth Semiconductor also began offering custom GaAs-base concentrator solar cells for terrestrial power generation in May.

The NanoPower Research Laboratories at Rochester Institute of Technology were awarded a $0.85 million contract from the U.S. Department of Defense to develop high-efficiency solar cells containing quantum dots. The dots will be added to the central GaAs-base layer of triple junction solar cells and produce an enhancement in short-circuit current and an increase in overall efficiency (Compound Semiconductor.net, 2006k).

Production

No domestic production of primary gallium was reported in 2006 (table 1). 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 produce about 40 metric tons per year (t/yr) of high-purity gallium. The company recovered gallium from its customers' scrap on a fee basis and purchased scrap and low-purity gallium for processing into high-purity material.

Additional drilling continued at Gold Canyon Resources Inc.'s Cordero gallium property in Humboldt County, NV. In April, the company initially reported indicated resources containing

337,360 kilograms (kg) of gallium and inferred resources containing 384,640 kg. Gold Canyon had drilled additional holes before the end of 2006 and was awaiting analytical results (Gold Canyon Resources Inc., 2006).

Consumption

Gallium consumption data were collected by the U.S. Geological Survey from a voluntary survey of U.S. operations. In 2006, there were nine responses to the consumption of gallium survey, representing 47% of the total canvassed. Data in tables 2 and 3 were adjusted by incorporating estimates to reflect full industry coverage. Many of these estimates were based on the companies' 2006 10-K reports submitted to the Securities and Exchange Commission.

More than 95% of the gallium consumed in the United States was in the form of GaAs or GaN. GaAs was used to manufacture optoelectronic devices (laser diodes, LEDs, photodetectors, and solar cells) and ICs. ICs accounted for 66% of domestic consumption, optoelectronic devices accounted for 20%, and 14% was used in research and development and other applications (table 2). GaN principally was manufactured into LEDs and laser diodes.

According to industry analysts, in 2006, the global consumption of GaAs ICs rose sharply to about 75% of total available production capacity from about 50% in 2005. Global production capacity is estimated to be about 800,000 6-inch GaAs wafer equivalents. The additional demand for GaAs was because of the more complex requirements of multimode and multiband cell phone handsets. One analyst predicted that between 150 million and 170 million of these complex handsets would be sold in 2007 and that demand for GaAs would remain balanced with the available supply (Hatcher, 2007).

Gallium Arsenide.—RF Micro Devices Inc. (RFMD) planned to increase GaAs wafer manufacturing capacity at its Greensboro, NC, facility by 40% with an investment of $80 million. This would be the company's fifth expansion in its 15-year history. The expansion was expected to reduce RFMD's cost per wafer and provide available capacity to increase internal production of GaAs pseudo-high electron mobility transistors (pHEMTs). Having already begun the expansion through an investment in additional processing equipment at its existing cleanroom facilities, RFMD expected volume production to begin in late 2006. The increase in manufacturing capacity was expected to supply rising demand for power amplifiers, which are used widely in mobile handsets (Compound Semiconductor, 2006j).

In July, EMCORE agreed to sell its Electronic Materials & Device Division to IQE plc for $16 million. The sale included the inventory, fixed assets (including a facility in Somerset, NJ), and intellectual property of the division. IQE, based in Wales, United, Kingdom, with United States operations in Bethlehem, PA, planned to continue to operate the New Jersey facility (EMCORE Corp., 2006a). In August, EMCORE sold its 49% interest in GELcore LLC to the lighting operations of GE Consumer & Industrial [a division of General Electric Corp. (GE)] for $100 million in cash. GE owned a 51% interest in GELcore prior to acquiring the remaining 49% from EMCORE (EMCORE Corp., 2006b). EMCORE sold off these interests to concentrate on its terrestrial solar cell operations.

AXT Inc. increased GaAs wafer production capacity in China in 2006 and planned additional capacity increases in 2007. During the second quarter, AXT increased its capacity for 6-inch substrates by 50% and was planning to add another 40% by the end of the first quarter of 2007. The company cited increased sales of substrates for LED and radio-frequency integrated circuit (RFIC) applications and expectations of continued strong demand as the reasons for the capacity increases (Compound Semiconductor.net, 2006u).

Kopin Corp. began volume production of gallium arsenide indium nitride (GaAsInN) material designed to be used in cell-phone handset power amplifiers. The company has worked on the development of the advanced technology with power amplifier supplier Skyworks Solutions Inc. According to Kopin, the new material improves power amplifier reliability compared with conventional indium gallium phosphide (InGaP) heterojunction bipolar transistors (HBTs). Other advantages compared with InGaP include a base layer that allows good power amplifier performance across a wider temperature range and potentially higher power efficiency. To aid in ease of processing, the GaAsInN material can simply be dropped into the wafer processing line in place of the InGaP wafers previously used (Compound Semiconductor, 2006g). Kopin also planned to increase its HBT manufacturing capacity by 50% by 2008. The company planned to install additional metal-organic chemical vapor deposition (MOCVD) systems to increase 4-inch and 6-inch wafer capacity. Projected increased demand for cellular telephone handsets was cited as the reason for the increase (Compound Semiconductor, 2006f).

In April, Mimix Broadband Inc. agreed to sell its Santa Clara, CA, GaAs wafer facility to semiconductor services provider Universal Semiconductor Technology Inc. (USTI) based in San Jose, CA. With the sale, Mimix no longer will have GaAs production capability. Mimix and USTI signed a multiyear GaAs wafer supply and noncompetition agreement under which Mimix will gain nonexclusive foundry services including GaAs metal-semiconductor field-effect transistor (MESFET), pHEMT, and HBT processes. Mimix had acquired the facility in June 2005 when it bought the remaining assets of now-defunct Celeritek Inc. (Compound Semiconductor.net, 2006f).

WJ Communications Inc., a manufacturer of RFICs for wireless infrastructure applications, planned to close its Fremont, CA, GaAs wafer manufacturing facility in 2007. The firm had acquired the GaAs facility in June 2004 when it bought EiC Corp.'s wireless infrastructure business. Since March, Torrance, CA-based Global Communication Semiconductors Inc. had been acting as a second-source supplier for WJ Communications for InGaP HBT and GaAs material, but will become its main supplier after the closure (Compound Semiconductor, 2006l).

Optoelectronic component manufacturer Advanced Photonix Inc. was consolidating its wafer manufacturing facilities in Camarillo, CA, and Dodgeville, WI, to a single facility in Ann Arbor, MI (the company's headquarters). The company makes silicon-, GaAs- and indium phosphide (InP)-base avalanche photodiodes and positive-intrinsic-negative detectors for use primarily in nondestructive testing applications. The consolidation was expected to be completed in 2007 (Compound Semiconductor.net, 2006a).

In September, Freescale Semiconductor Inc. announced that it had entered into a merger agreement to be acquired by a private equity consortium for $17.6 billion. The consortium is led by The Blackstone Group and includes The Carlyle Group, Permira Funds, and Texas Pacific Group. Rated as the world's ninth-biggest semiconductor manufacturer, Freescale operated a manufacturing facility for 150-millimeter GaAs wafers in Tempe, AZ (Compound Semiconductor.net, 2006s). The merger was finalized in December.

Freescale Semiconductor claims to have developed a commercially viable GaAs device that can be scaled in much the same way as complementary metal-oxide semiconductor (CMOS) silicon devices. If it does prove viable, the development could pave the way for a GaAs equivalent of Moore's Law, where the speed and size of transistors can be advanced rapidly through standard processes. According to the company, the crucial breakthrough was the development of a feasible gate oxide that is also compatible with GaAs; silicon has silicon dioxide as a native gate oxide. Because of this gate oxide problem, the semiconductor industry has been unable to apply its standard processes and manufacturing equipment to GaAs (Hatcher, 2006).

In August, Teledyne Technologies Inc. completed its $167.5 million cash acquisition of compound semiconductor foundry Rockwell Scientific Co. LLC. Rockwell specialized in advanced semiconductor applications including GaAs and silicon germanium (SiGe) for mixed signal ICs. The company operates a GaAs foundry where it makes pHEMTs and monolithic microwave integrated circuits (MMICs) for low-noise amplifier and power amplifier applications. Rockwell's technological expertise also included GaN-base HEMTs (Compound Semiconductor, 2006k). Teledyne Technologies produced electronic components primarily for aerospace and defense applications.

Gallium Nitride.—Companies continued to try to improve the substrate material on which GaN is grown to improve the quality of the GaN material. In February, Group4 Labs LLC released GaN-on-diamond wafers that the company claimed would offer unprecedented high temperature resilience. The new wafers were based on chemical vapor deposition diamond, which has a thermal conductivity 3 to 30 times greater than that of conventional semiconductors; this enables the chip to dissipate heat more effectively (Compound Semiconductor.net, 2006g). In August, engineers at the U.S. Air Force Research Laboratory announced that they created the world's first GaN-on-diamond transistor using epitaxial material from EMCORE attached to a diamond substrate by Group4 Labs (Compound Semiconductor.net, 2006y).

In March, Kyma Technologies Inc. announced that it developed a new range of nonpolar and semipolar GaN substrates that should lead to higher performance devices. In devices grown on top of nonpolar GaN, the usual electric fields that are generated were eliminated, while in semipolar material they were reduced. This means that GaN-base optoelectronic devices can operate at higher efficiencies (Compound Semiconductor.net, 2006n).

Researchers from the École Polytechnique Fédérale de Lausanne in Switzerland announced that they have grown high-quality GaN-on-sapphire templates by hydride vapor-phase epitaxy (HVPE) that have a GaN thickness of just 8 micrometers (μm). This compares with values of 20 to more than 300 μm for GaN films for other GaN-on-sapphire templates. The new process could cut the cost of GaN templates used to produce lasers and transistors because of a reduction in GaN material deposited and the removal of an MOCVD growth step that is typically used prior to HVPE deposition (Compound Semiconductor.net, 2006b).

Arrowhead Research Corp. announced that its majority-owned subsidiary, Aonex Technologies Inc., and Aonex's partner, Sandia, demonstrated the growth of GaN structures on proprietary sapphire substrates that are composed of a thin layer of single crystal sapphire that is bonded to a polycrystalline aluminum nitride support substrate. These substrates have a coefficient of thermal expansion that is nearly identical to GaN with an industry-standard sapphire growth surface suitable for MOCVD and HVPE growth; this reduces bowing in the substrate during the growth process (Compound Semiconductor.net, 2006h).

In November, BluGlass Ltd. of Sydney, Australia, demonstrated its GaN-on-glass production technology on 4-inch substrates, double the diameter of the 2-inch industry standard. BluGlass was spun off in June 2005 from research conducted at Macquarie University in New South Wales, Australia, and, in September 2006, the company raised $7.7 million in an initial public offering. In October, BluGlass signed an 18-month joint development agreement to work with France's Saint-Gobain Recherche to develop specifically engineered specialty glass substrates. BluGlass claimed that its growth process is less costly than conventional MOCVD growth because it operates at lower temperatures (500° to 700° C, compared with 950° C for current commercial MOCVD techniques) and uses cheaper substrates. BluGlass planned to develop commercial manufacturing equipment in 2007 (Semiconductor Today, 2006).

In the battle among manufacturers of DVD players to agree on a standard format [high definition (HD) or Blu-ray] for the next generation of DVD players, which use GaN-base laser diodes, Ricoh Co. Ltd. announced that it developed an optical component that can be used to read both disks. Blu-ray disks operate with a wider beam and also have a data layer that is much nearer to the disc surface than the HD-DVD format. Ricoh said that it could overcome this problem by altering the depth of the laser's focal point. The company planned to commercialize the technology by the end of 2007 (Compound Semiconductor.net, 2006i).

Low yields of GaN-base laser diodes from semiconductor wafers appear to be behind the decision by Sony Corp. to delay its introduction of the PlayStation 3 game console in Europe. The PlayStation 3 launch dates in Japan and the United States were November 11 and November 17, respectively, but in Europe and other locations, the system was scheduled to be launched in March 2007. Blue laser diode manufacturers have encountered yield problems with the technology in the past, which primarily is because of the lattice mismatch between the substrate and active layers of the devices resulting in a high number of defects (Compound Semiconductor.net, 2006p).

Despite problems with manufacturing blue GaN-base laser diodes, Matushita Electric Industrial Co. Ltd. (manufacturer of products under the Panasonic brand name) and Sony both launched Blu-ray disc recorders before the end of 2006. Blu-ray recorders were expected to be manufactured in much smaller quantities than the PlayStation 3, meaning that enough blue lasers can be made to meet the demand (Compound Semiconductor.net, 2006t). In addition, Philips introduced its Blu-ray disc player in June. The player included a trio of laser sources to enable playback of CD, DVD, and Blu-ray content. Philips Blu-ray player was expected to retail for $999 (Compound Semiconductor.net, 2006j).

The Missile Defense Agency (MDA) (an agency of the U.S. Department of Defense) awarded several contracts to firms to develop improved substrates for GaN-base devices. Kyma won funding under two new projects sponsored by the MDA. These programs are looking at the development of GaN materials and devices for next-generation military radar systems, including X-band applications. Kyma planned to increase GaN substrate sizes and improve the material quality of its semi-insulating GaN through the new projects. In addition, diamond wafer specialist sp3 Inc., in collaboration with GaN wafer and component developers at Nitronex Inc. and TriQuint Semiconductor Inc., planned to use a separate MDA contract to deliver GaN on silicon-on-diamond technology. The key advantage with diamond is its very high thermal conductivity—10 times that of silicon and more than twice that of silicon carbide, the most commonly used substrate for GaN electronics (Compound Semiconductor, 2006h; Compound Semiconductor.net, 2006o). The company also signed a cooperative research and development agreement with the U.S. Navy to develop GaN field-effect transistors for advanced military radar applications.

Engineers at Technologies and Devices International Inc. claim to have developed the first hydride vapor phase epitaxy (HVPE) process that can be used to produce very thin layers of GaN and aluminum gallium nitride (AlGaN) quantum wells. The technique, which traditionally deposits material much faster than either molecular beam epitaxy (MBE) or MOCVD processes, had only been suitable for growing very thick semiconductor layers. The company says that a new HVPE machine is able to slow down from its normal deposition rate of around 1 μm per minute by more than two orders of magnitude (Compound Semiconductor, 2006e).

Matsushita Electric researchers claim to have developed the world's first vertical GaN transistor that can be used in high-power switching devices. According to the company, the new design dramatically reduces the surface area of the devices compared with the traditional arrangement, potentially allowing many more transistors to be produced on a single wafer. To produce the vertical transistor, Matsushita developed a new epitaxial growth pattern that uses indium aluminum gallium nitride (InAlGaN) in the contact layer, which the company claims results in 33% lower than normal contact resistance (Compound Semiconductor.net, 2006r).

Researchers at Mitsubishi Electric Corp. fabricated GaN HEMT's with an additional 3-nanometer-thick aluminum layer between the AlGaN barrier layer and the gate contact. The company claims that the aluminum layer results in significantly improved capacitance-voltage characteristics and a reduction in gate leakage current. Mitsubishi planned to continue to investigate the lifetime of these devices (Compound Semiconductor, 2006a).

Researchers at Georgia State University developed a GaN-base detector that is sensitive to both ultraviolet and near-infrared light. This detector could be used by firefighters to determine the fire source material by looking at the emission spectrum for specific ultraviolet radiation patterns. Although all fires emit infrared radiation, they also can emit ultraviolet radiation. Two source examples would be coal and hydrogen, which emit vastly different intensities at ultraviolet and infrared wavelengths. The detector also could be used in military and forensics applications, such as checking for blood stains or gunshot residue (Cartwright, 2006).

***Light-Emitting Diodes.*—**Many LED manufacturers introduced new LEDs based on GaAs and GaN technology that offer improvements from currently produced LEDs. In many cases, the new LEDs are brighter, last longer, and/or can be used in new applications. These new products have applications that include automotive lighting, cellular telephones, entertainment and decorative lighting, and signage.

Koninklijke Philips Electronics N.V. (the owner of Lumileds LLC) announced that it would set up a wafer manufacturing facility in Singapore where it will manufacture power LEDs for emerging lighting applications. The new facility was expected to begin initial production in the first quarter of 2007 and be fully operational by the end of the year, at which point it will have doubled the company's total power LED production capacity. Lumileds manufactured LEDs at its facility in San Jose, CA, and production was expected to continue at this facility, but the company did not have enough capacity to meet the anticipated demand. Philips expected the devices to be used in automotive lighting, camera phone flash components, and large LCD backlights (Compound Semiconductor, 2006i).

Avago Technologies Ltd. entered the high-power LED market with the first in a series of emitters that was designed for use in applications such as outdoor lighting and display backlights. The indium gallium nitride (InGaN)-base LEDs are available in blue, green, and when coupled with a color-converting phosphor, white. Previously, Avago had concentrated on lower power LED products and had not competed directly with companies such as Lumileds, Nichia Corp., and Cree Inc. in high-power products (Compound Semiconductor.net, 2006c).

Shimei Semiconductor Co. Ltd., a startup company based in Kyoto, Japan, is reported to have developed a blue LED using GaN-on-silicon epitaxy. Shimei was planning to begin shipping samples of the technology in April 2007 and planned to build a facility capable of manufacturing 3 million units per month. Blue LEDs are normally fabricated on either silicon carbide or sapphire wafers for volume applications. Although silicon would provide a cheaper, conducting, nonnative substrate and be available in very large diameters, the problem is that it is opaque in the blue spectrum. To get around the opacity, Shimei reportedly developed a way to deposit a reflecting layer within the device structure so that all the light is emitted out of the top of the LED (Compound Semiconductor.net, 2006m).

Researchers at the National Institute of Standards and Technology (NIST) made GaAs-base LEDs more than seven times brighter by etching nanoscale grooves in a surrounding cavity to guide scattered light in one direction. LEDs typically emit only about 2% of the light in the desired direction—perpendicular to the diode surface. The NIST nanostructured cavity increased useful LED emission to about 41% and may be cheaper and more effective for some applications than conventional post-processing LED shaping and packaging methods that attempt to redirect light. The NIST team fabricated their own infrared LEDs consisting of GaAs packed with quantum dots of assorted sizes made of indium gallium arsenide (InGaAs). The new devices may have applications in areas such as in biomedical imaging where LED brightness is crucial (LEDs Magazine, 2006c).

Solar Cells.—Sustained high energy prices have sparked renewed interest in solar energy. Most of the solar cells that are being manufactured for terrestrial applications are multijunction cells, with a substrate of germanium and layers of InGaAs and other gallium compounds.

In August, Spectrolab Inc. (a subsidiary of The Boeing Co.) announced that it signed a multimillion dollar contract to supply concentrator photovoltaic cell assemblies to an Australian company that produces renewable solar energy. The assemblies will be based on GaAs multijunction solar cells. Under the contract with Solar Systems Pty. Ltd. of Hawthorn, Victoria, Spectolab would deliver 500,000 concentrator solar cell assemblies for use at power stations that generate renewable energy for small remote Australian communities. The solar cell assemblies for Solar Systems will be capable of providing more than 11 megawatts (MW) of electricity generating capacity (Spectrolab Inc., 2006b).

Spectrolab also signed a 12-month contract to provide 600,000 solar concentrator cells to SolFocus Inc., a California-based renewable energy company that is developing renewable terrestrial energy alternatives. The cells produced for SolFocus would be capable of generating more than 10 MW of electricity. Earlier in the year, SolFocus formed a partnership with the Palo Alto Research Center, which was contributing core patents and long-term technology development support for current and next-generation product lines in exchange for royalties and equity in SolFocus (Compound Semiconductor.net, 2006x).

In December, Spectrolab announced that it had achieved a new world record in terrestrial concentrator solar cell efficiency. Using concentrated sunlight, Spectrolab demonstrated the ability of a photovoltaic cell to convert 40.7% of the sun's energy into electricity (Spectrolab Inc., 2006a).

In November, EMCORE received a $41 million order for several hundred thousand multijunction solar cells from a U.S. communications satellite manufacturer, which was an extension to an existing purchase order that the satellite maker had signed previously. The cells will be used in 10 geosynchronous satellites. Production of these cells at EMCORE's Albuquerque, NM, plant, which houses eight MOCVD reactors, was scheduled to begin in January 2007 and will continue for 3 years (Compound Semiconductor.net, 2006e).

EMCORE also announced that it would invest $18 million in WorldWater and Power Corp., which specializes in solar-powered water pump technology. This would give EMCORE a 31% equity share in WorldWater, and a separate supply agreement would mean that EMCORE would be WorldWater's exclusive supplier of high-efficiency multijunction solar cells, assemblies, and concentrator subsystems. EMCORE has valued the supply agreement to be worth up to $100 million for the next 3 years. WorldWater produced specialized electrical drives that are used to pump water for utility companies and to irrigate farmland; the solar cells will be used to power the drives (Compound Semiconductor, 2006c). Because of the new contracts, EMCORE planned to purchase additional MOCVD reactors to increase its production capacity sometime in 2007.

A startup firm, Nanosolar Inc., announced that it selected two sites—one in San Jose and the other in Berlin, Germany—to manufacture solar cells and panels. The company planned to use its proprietary nanoparticle ink and fast roll-printing technology that it claims will dramatically improve the cost efficiency, yield, and throughput of the production of thin-film solar cells. Commercial production was scheduled to begin in 2007 (Nanosolar Inc., 2006).

In November, Sharp Corp. announced that it would begin shipping GaAs-base concentrator photovoltaic systems for terrestrial electricity generation in 2007 to customers in Europe. GaAs-base solar cells used in the systems are grown on a germanium substrate and have a photovoltaic conversion efficiency of more than 37%. Previously, Sharp's commercial sales of solar energy systems have not included concentrator photovoltaics based on compound semiconductors (Compound Semiconductor.net, 2006v).

A new joint-venture company, RSL Energy in Phoenix, AZ (50%-owned by Sumitomo Chemical Co. Ltd. and 50%-owned by RoseStreet Laboratories LLC), received a license to commercialize InGaN multijunction solar cell designs. This technology was developed through a collaboration between Lawrence Berkley National Laboratories and Cornell University. The company believed that the InGaN approach could produce solar cells with practical efficiencies of more than 48%. Sumika Electronic Materials Inc. (a subsidiary of Sumitomo Chemical), also located in Phoenix, was expected to be the source of the InGaN feedstock. RSL Energy will perform research and development and product development during 2007 and expected to have its first prototypes for field testing in 2008 (Compound Semiconductor.net, 2006w).

Prices

Since 2002, producer prices for gallium have not been quoted in trade journals. Data in table 4 represent the average customs value of gallium imported into the United States. Reports in Mining Journal indicated that low-grade gallium prices fell slightly during 2006. At the beginning of the year, the low-grade gallium price was reported to be about $350 per kilogram. By June, the price had fallen to about $300 per kilogram, where it remained throughout the rest of the year.

From U.S. Census Bureau import data, the annual average value for low-grade gallium was estimated to be $285 per kilogram, almost 17% higher than the estimated average value for 2005. For high-grade gallium, the annual average estimated value fell to $443 per kilogram, about 18% lower than that in 2005. Import data reported by the U.S. Census Bureau do not specify purity, so the values listed in table 4 are estimated based on the average value of the material imported and the country of origin.

Foreign Trade

In 2006, U.S. gallium imports were 71% higher than those in 2005 (table 5). China (21%), Ukraine (20%), and Germany (17%) were the leading sources of imported gallium. One reason for the increase in gallium imports was that after Recapture Metals and Mining & Chemical Products Ltd. (MCP) purchased the gallium recovery facility in Germany, some of the gallium produced in Germany was refined in the United States rather than in France, where it had been normally refined.

Although no data for exports were available, Japan reported a substantial quantity of gallium imported from the United States in 2004 (8,700 kg) and 2005 (11,000 kg), so although imports increased significantly between 2005 and 2006, it was estimated that a larger quantity than normal was shipped to Japan. This would account for a smaller percentage increase in U.S. consumption than in U.S. imports.

In addition to gallium metal, GaAs wafers were imported into the United States (table 6). In 2006, 3,550 kilograms (kg) of undoped GaAs wafers and 185,000 kg of doped GaAs wafers were imported. The data listed in table 6 may include some packaging material and, as a result, may be higher than the actual total weight of imported wafers.

World Review

Imports of gallium into Japan and the United States, the two leading consuming countries, have been used as the basis for estimating world gallium production. Estimated crude gallium production was 72 t in 2006. Principal world producers were China, Germany, Japan, Kazakhstan, and Ukraine. Gallium also was recovered in Hungary, Russia, and Slovakia. Refined gallium production was estimated to be about 105 t; this included some new scrap refining. France was the leading 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.

China.—In August, MCP, based in the United Kingdom, completed a new gallium refining facility in Shenzhen, Guangdong Province. After its purchase of the Stade, Germany, gallium recovery plant (along with United States-based Recapture Metals) earlier in 2006, MCP needed additional refining capacity; MCP, however, did not specify the capacity of the new plant. MCP planned to market the upgraded gallium to manufacturers of LEDs and telecommunications equipment in Asia (Shaw, 2006).

Germany.—MCP and Recapture Metals purchased the Stade gallium production facility from Geo Gallium S.A. in May. The Stade facility will operate as a joint venture with each of the owners receiving one-half of the plant's output. Current production at the plant was estimated to be 12 t/yr, but the companies planned to increase production to 24 t/yr. MCP operated refining facilities in the United Kingdom, and Recapture Metals had refining operations in the United States. Geo Gallium's refining operations in France were not included in the purchase (Platts Metals Week, 2006). The Salindres, France, purification facility was subsequently closed, and Geo Gallium's Pinjarra, Australia, recovery plant that had been idle for years was sold and renamed Anascot Pty. Ltd. At yearend, Geo Specialty Metals Inc. no longer operated its Geo Gallium subsidiary.

Japan.—In 2006, Japan's virgin gallium production was estimated to be 8 t, gallium recovered from scrap was reported to be 90 t, and gallium imports were reported to be 42 t, for a total supply of 141 t. The United States (26%), Taiwan (21%), and France (18%) were estimated to be the principal sources of gallium imported into Japan (Roskill's Letters from Japan, 2006).

Showa Denko K.K. announced that it would increase its aluminum gallium indium phosphide (AlGaInP) chip capacity with a $13 million investment. Showa Denko's upgrade will include an expansion of MOCVD capability to make more epitaxial wafers, with the company planning to increase chip production to 100 million units per month from 30 million per month. The expansion work was expected to begin in February 2007, with completion scheduled for the third quarter. Showa Denko expected that large-area display backlighting and automotive applications for the LEDs would continue to grow rapidly (Compound Semiconductor.net, 2006q).

Taiwan.—Consolidation continued among Taiwan's LED suppliers. In 2005, Epistar Corp. merged with United Epitaxy Co. Ltd., creating the leading LED chip maker in Taiwan, and two smaller firms, Epitech Technology Corp. and South Epitaxy Corp., also merged. In September 2006, Epistar announced that it would merge with both Epitech and Highlink Technology Corp. Epistar and Epitech both produced GaN- and AlGaInP-base LED chips, and Highlink was a specialized producer of GaN-base devices. Epitech and Highlink together have a significant capacity for blue and green InGaN-base chips. Combined, the three companies have a huge capacity for the growth of epitaxial LED wafers. Epistar, Epitech, and Highlink have about 80, 60, and 20 MOCVD epitaxial systems, respectively (LEDs Magazine, 2006b). Prior to its merger with Epistar, Highlink had purchased two MOCVD reactors that increased its wafer processing capacity significantly.

United Kingdom.—In June, Filtronic plc, one of RFMD's principal GaAs suppliers, announced that it would invest $83 million in a capacity expansion program to be funded by Filtronic's sale of its wireless infrastructure division, which had accounted for 80% of its revenues from $83 million. In August, the company reduced the investment to about $28 million. The company operated a GaAs manufacturing facility in Newton Aycliffe (Compound Semiconductor, 2006d).

In December, IQE agreed to acquire MBE Technology Pte. Ltd., a Singapore-based manufacturer of compound epitaxial wafers, for about $14.9 million. The acquisition was expected to provide IQE with a strong presence in Asia, which it intended to use to sell into the Pacific Rim wireless industry. With the acquisition, IQE will have a dual-source manufacturing capability for all its wireless products, with facilities in Singapore, the United Kingdom, and the United States qualified for the production of wafers for RF components (Compound Semiconductor.net, 2006l).

Outlook

Strategy Analytics Inc. predicted that the worldwide market for GaAs devices would grow from $3 billion in 2006 to more than $5 billion by 2011. The company forecast that cellular handsets would remain the largest market for GaAs devices, with Wi-Fi (high-frequency wireless local area network technology) emerging from the remaining group of applications to claim a clear second place in 2007 and beyond. It also forecast that overall wireless applications will account for 79% of GaAs MMIC demand in 2011. The company also predicted that despite the positive outlook for GaAs components in wireless applications, the competition for silicon-base components in other markets is very real. Silicon-germanium could take market share away from GaAs in fiber-optics and automotive radar applications (Compound Semiconductor.net, 2007a).

In a separate report, Strategy Analytics predicted that GaN would be the underlying compound semiconductor technology used in military applications like electronic warfare and advanced radar from 2010 onward. According to another of Strategy Anlaytics' market reports, GaAs device demand from the defense sector would increase at a year-on-year rate of 9% in 2006 and continue at roughly the same rate of growth through the end of the current decade (Compound Semiconductor.net, 2006d).

According to a report by Strategies Unlimited (a unit of PennWell Corp.), the total market for high-brightness LEDs used in lighting applications in 2005 was $205 million, and this was forecast to grow at a compound annual growth rate of 36.9% to reach approximately $1 billion by 2011. The leading application for LEDs was architectural lighting, followed by channel letter/contour lighting and consumer portable electronics. In the past, the growth of the LED lighting market has been driven mainly by the use of color (red, green, and blue); however, during the next 5 years, white LEDs were expected to capture an increasing share of the market as use of LEDs in general illumination applications increases (LEDs Magazine, 2007).

Strategy Analytics predicted that the revenue from LEDs used in the camera flash in cellular handsets will increase at a compound annual growth rate of 23% between 2006 and 2011. Overall LED sales to the cell phone market, however, were expected to decline during this period, because of a drop in LED backlight revenue. By 2011, the backlighting application will be worth only 63% of LED sales for handsets. The company also projected that by 2011, 82% of all handsets shipped will include a camera (Compound Semiconductor.net, 2007b.).

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

(Kilograms unless otherwise specified)

		2002	2003	2004	2005	2006
Production		--	--	--	--	--
Imports for consumption		13,100	14,300	19,400	15,800	26,900
Consumption		18,600	20,100	21,500	18,700	20,300
Price[2]	dollars per kilogram	530	411	550	538	443

-- Zero.

[1]Data are rounded to no more than three significant digits.

[2]Estimate based on average value of U.S. imports of high-purity gallium.

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

(Kilograms)

End use	2005	2006
Optoelectronic devices:		
Laser diodes and light-emitting diodes	3,880	3,670
Photodetectors and solar cells	219	303
Integrated circuits:		
Analog	11,700	12,000
Digital	115	1,400
Research and development	2,800	2,840
Other	76	77
Total	18,700	20,300

[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
2005:				
99.99% to 99.999%	456	59	12	503
99.9999%	1,120	3,390	3,350	1,160
99.99999% to 99.999999%	137	139	140	136
Total	1,720	3,590	3,500	1,800
2006:				
99.99% to 99.999%	503	131	--	634
99.9999%	1,160	2,970	2,900	1,230
99.99999% to 99.999999%	136	496	602	30
Total	1,800	3,590	3,500	1,890

-- Zero.

[1]Consumers only.

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

TABLE 4
ESTIMATED AVERAGE GALLIUM PRICES

(Dollars per kilogram)

Gallium metal	2005	2006
Purity ≥ 99.9999%; average value of U.S. imports	538	443
Purity ≤ 99.99%; average value of U.S. imports	244	285

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

	2005		2006	
Country	Quantity (kilograms)	Value[2]	Quantity (kilograms)	Value[2]
Canada	1,090	$269,000	2,410	$593,000
China	1,530	624,000	5,780	1,820,000
France	1,520	775,000	1,120	593,000
Germany	26	22,800	4,600	1,380,000
Hungary	2,100	535,000	2,200	676,000
Japan	4,290	814,000	1,960	584,000
Russia	2,480	695,000	718	187,000
Slovakia	77	50,900	1,710	671,000
Ukraine	2,000	540,000	5,380	1,450,000
United Kingdom	215	103,000	387	133,000
Other	436 [r]	470,000 [r]	652	116,000
Total	15,800	4,900,000	26,900	8,210,000

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

Source: U.S. Census Bureau.

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

Material and country	2005 Quantity (kilograms)	2005 Value[2]	2006 Quantity (kilograms)	2006 Value[2]
Undoped:				
China	2,000	$530,000	1,140	$354,000
Germany	1,200	50,300	--	--
Hungary	--	--	200	60,000
Russia	498	124,000	--	--
Taiwan	--	--	2,160	260,000
Ukraine	620	133,000	--	--
Other	38 r	12,700 r	50	36,400
Total	4,350	850,000	3,550	711,000
Doped:				
China	8,900	14,000,000	19,500	20,000,000
Finland	8,270	13,200,000	11,000	6,470,000
France	4,940	9,760,000	12,600	28,400,000
Germany	25,400	27,900,000	36,500	40,200,000
Japan	50,900	47,200,000	53,500	61,300,000
Korea, Republic of	44,500	27,500,000	26,400	24,100,000
Singapore	3,290	4,860,000	5,400	6,810,000
Taiwan	17,500	9,470,000	8,730	10,900,000
United Kingdom	26,800	4,540,000	1,050	799,000
Other	9,100 r	3,630,000 r	10,400	2,310,000
Total	200,000	162,000,000	185,000	201,000,000

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

Source: U.S. Census Bureau.

TABLE 7
ESTIMATED WORLD ANNUAL PRIMARY GALLIUM
PRODUCTION CAPACITY, DECEMBER 31, 2006[1]

(Metric tons)

Country	Capacity
China	59
Germany	35
Hungary	8
Japan	20
Kazakhstan	25
Russia	19
Slovakia	8
Ukraine	10
Total	184

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