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# 2005 Minerals Yearbook

## GALLIUM

U.S. Department of the Interior
U.S. Geological Survey

July 2006

# Gallium

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Gallium metal and gallium arsenide (GaAs) wafer imports continued to supply most of the U.S. gallium demand. Metal imports were 19% lower than those in 2004, with Hungary, Japan, Russia, and Ukraine as the principal import sources. Undoped GaAs wafer imports were 22% higher than those in 2004; China and Germany 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 fell by about 13% from that in 2004, reflecting the continuing shift of device manufacturing from the United States to other countries.

In 2005, estimated world crude gallium production was 70 metric tons (t), about the same as that in 2004. Principal producers were China, Germany, Japan, and Ukraine. Plants in Hungary, Kazakhstan, Russia, and Slovakia also recovered gallium. Refined gallium production was estimated to be about 97 t, which included some new scrap refining. Refined gallium was produced in France, Japan, and the United States.

### Legislation and Government Programs

On August 8, the President signed the Energy Policy Act of 2005 (Public Law 109-58). Title IX (Research and Development) of the Act directed the Secretary of Energy to carry out a Next Generation Lighting Initiative (NGLI) to support research, development, demonstration, and commercial application activities for solid-state lighting. The Energy Policy Act authorizes $50 million to the NGLI for each of the fiscal years 2007 through 2009, with extended authorization to allocate $50 million for each of the fiscal years 2010 to 2013 (U.S. Department of Energy, 2005§[1]). Many of the projects funded under NGLI are aimed at improving GaN technology and GaN-base LED performance.

TriQuint Semiconductor Inc. is the prime contractor in a $15.8 million military-funded project to develop GaN-base, high-power, wide-band amplifiers and packaging technology. The project, which is funded by the Defense Advanced Research Projects Agency (DARPA), also includes BAE Systems Inc., EMCORE Corp., II-VI Corp., Lockheed Martin Corp., and Nitronex Corp. If the development is successful, then GaN high-electron-mobility transistors could be used in high-power phased array radar systems, electronic warfare, and communications links. In addition, the DARPA awarded Northrop Grumman Corp. an initial $16.5 million to transition GaN microelectronics from development to production. The aim of this initiative is to develop GaN components for military communications, radar, and intelligence applications. Northrop Grumman began developing GaN technology in 2002 under a $5.1 million phase I contract with the DARPA (Hatcher, 2005).

### Production

No domestic production of primary gallium was reported in 2005 (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.

Metallurgical studies by ChelaTech Inc. reported recoveries of greater than 90% of the contained gallium from mineralized rock at Gold Canyon Resources Inc.'s Cordero gallium project in Humboldt County, NV. Actual recovery ranged from 91.6% to 96.8% of the total gallium contained in mineralization at Cordero. The process developed to recover gallium was a multistep acid leach process using commonly available acids and reagents, which is similar to the acid leach process used to treat copper oxide ores (Gold Canyon Resources Inc., 2005§).

### Consumption

Gallium consumption data were collected by the U.S. Geological Survey from a voluntary survey of U.S. operations. In 2005, there were eight responses to the consumption of gallium survey, representing 38% 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' 2005 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 63% of domestic consumption, optoelectronic devices accounted for 22%, and 15% was used in research and development and other applications (table 2). GaN principally was manufactured into LEDs and laser diodes.

***Gallium Arsenide.***—In January, RF Micro Devices Inc. (RFMD) and the United Kingdom's Filtronic plc signed a supply agreement whereby Filtronic will become RFMD's leading supplier of GaAs-base pseudomorphic high-electron-mobility transistors (pHEMTs). Filtronic will manufacture the components at its 6-inch wafer processing facility in Newton Aycliffe, United Kingdom. The pHEMTs will be incorporated into RFMD modules for cell phone handset and wireless local area network (LAN) applications (Compound Semiconductor, 2005e). As a result of the contract, Filtronic increased the

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

operating rate at its United Kingdom facility to 24 hours per day, 7 days per week.

In April, EMCORE announced plans to close its solar panel operations in City of Industry, CA, and consolidate into a facility in Albuquerque, NM. In August, however, EMCORE received an $8.0 million contract for solar panels for a new communications satellite. This contract also contained options for several additional sets of solar panels with deliveries through early 2007. As a result of this award and an accelerated delivery schedule, EMCORE decided to keep its California facility open until contract deliveries were completed. Production at the facility was expected to be discontinued during 2006 and the plant to be completely closed by March 2007 (Compound Semiconductor, 2005b).

Sumika Electronic Materials Inc. added GaAs pHEMT epitaxial wafer manufacturing capability at its Phoenix, AZ, facility. The company (owned by Japan's Sumitomo Chemical Co. Ltd.) already makes GaAs heterojunction bipolar transistor (HBT) epitaxial wafers in Phoenix. The addition of two new metal-oxide chemical vapor deposition (MOCVD) systems means that Sumika now has two production sites for both pHEMT and HBT epitaxial wafers—the other is in Chiba, Japan (Compound Semiconductor, 2005l).

Koninklijke Philips Electronics N.V. announced that it would buy Agilent Technologies Inc.'s 47% share in LED manufacturer Lumileds Lighting for $948 million in cash. The deal, which would give Philips 96.5% ownership of Lumileds, was part of Aglient's plan to sell off its entire semiconductor business unit, which also included GaAs IC, fiber-optic component, and low-brightness LED manufacturing facilities. Lumileds was Hewlett-Packard Co.'s optoelectronics division, and that division became part of Agilent Technologies when Hewlett-Packard split into two businesses in 1999 (Compound Semiconductor, 2005i). In December, private equity firms Kohlberg Kravis Roberts & Co. and Silver Lake Partners took control of Agilent's remaining semiconductor business in a deal worth about $2.66 billion. These firms renamed the business Avago Technologies Ltd. (LEDs Magazine, 2005a§).

In June, Mimix Broadband Inc., a supplier of microwave and millimeter-wave GaAs semiconductors, acquired the remaining assets of Celeritek Inc. for $2.8 million. The GaAs component operation that Mimix acquired included such products as low-noise amplifiers, gain blocks, and power amplifier modules for both commercial and defense applications. In September 2003, Celeritek had exited the cell phone handset power amplifier business and had decided to concentrate on defense markets. Shortly afterwards, Anadigics Inc. acquired the Tavanza handset power amplifier design business from Celeritek, and in July 2004, Teledyne Technologies Inc. purchased Celeritek's defense electronics business (Compound Semiconductor, 2005h).

In September, Goodrich Corp., a supplier of systems and services to aerospace, defense, and homeland security markets, announced that it would acquire Sensors Unlimited Inc. for $60 million. Sensors Unlimited produced indium gallium arsenide (InGaAs) imaging technology and had in-house manufacturing capabilities for advanced infrared cameras and short-wave infrared and near-infrared focal plane arrays. Sensors Unlimited's products were used in commercial, industrial, military, security, and telecommunications applications, such as covert surveillance, health and safety protocols, historical art inspection, and night vision (Goodrich Corp., 2005§). In September, Sensors Unlimited was awarded a $4.5 million contract from the DARPA to develop an InGaAs focal plane array, which will form the basis of an uncooled dual-wavelength camera that is sensitive between 0.4 and 1.7 micrometers (µm) and capable of night vision imaging. The goal of the focal plane array will be to identify a human target at a distance of 100 meters under no-moon conditions (Compound Semiconductor.net, 2005h§).

In January, Endwave Defense Systems (a wholly owned subsidiary of Endwave Corp.) announced that it was awarded a $518,000 contract with a major U.S. prime defense contractor to design and deliver prototype low-power GaAs-base amplifiers for use in the back-fit of an airborne defense system in the 20-plus-year-old North Atlantic Treaty Organization aircraft fleet. Prototype deliveries were expected to start during the fourth quarter of 2005. Upon successful field qualification testing, production was expected to begin in 2006 and last 2 to 4 years (Compound Semiconductor, 2005d).

U.S. defense contractor Raytheon Corp. won a $580 million contract to produce GaAs-base radars for use in fighter aircraft used by the U.S. Navy. Under the 5-year production contract, Raytheon will deliver 190 active electronically scanned array APG-79 radar systems to Boeing Corp. to be installed on the F-15 Eagle and F/A-18 Super Hornet. The new system also has the potential to be used in unmanned aircraft. The APG-79 system will allow the aircraft to track other aircraft at longer ranges, provide higher resolution synthetic aperture radar maps, and allow near-simultaneous air-to-air and air-to-ground sensing. The first system was delivered to Boeing Integrated Defense Systems in January (Compound Semiconductor, 2005k).

***Gallium Nitride.***—Picogiga International (a division of the Soitec Group) adapted its silicon-on-insulator technology to produce 2-inch diameter GaN-on-insulator substrates; this represents the first single-crystal GaN-on-insulator substrate. The new technology could lead to improvements in the performance of GaN-base devices, such as blue and white LEDs and high-power microwave components. Picogiga has produced only 2-inch diameter GaN-on-insulator wafers, but says that the technique will be suitable for larger substrates as soon as these become available. However, production quantities of GaN-on-insulator wafers will not be available until bulk GaN substrates become more affordable and widely used, with Picogiga not expecting commercialization until 2006 or 2007 (Compound Semiconductor, 2005f).

In July, Veeco Instruments Inc. and Picogiga announced that they would set up a development program to create the first industrial molecular beam epitaxy (MBE) reactor set up specifically for Picogiga's patented GaN-on-silicon manufacturing process. Once it has been built, Veeco will deliver and install the reactor at Picogiga's Les Ulis production facility in France, where it will be used to fabricate GaN-on-silicon epitaxial wafers of up to 6 inches in diameter (Compound Semiconductor, 2005n).

EMCORE decided to spin off a new company, Velox Semiconductor Corp., to commercialize its fast, high-voltage GaN diodes for high-power electrical supply applications. EMCORE holds a 20% stake in Velox, which has raised $6 million from three venture capital partnerships. According to EMCORE, the formation of the new company will reduce operating expenses and allow EMCORE to benefit from the technology with its 20% ownership (Compound Semiconductor, 2005c).

The battle among manufacturers of DVD players to agree on a standard format (high definition or Blu-ray) for the next generation of DVD players, which use GaN-base laser diodes, continued in 2005. Toshiba Corp. reportedly developed a triple-layer version of its high-definition DVD disc that holds up to 45 gigabytes of data. The disc, which would be read by an optical head with a GaN-base blue laser diode, could record 12 hours of high-definition movies. Toshiba also announced that it has a novel disc technology that would allow consumers to view standard DVD content using existing players as well as high-definition content with next-generation technology. Matsushita Electric Industrial Co. Ltd. (manufacturer of products under the Panasonic brand name), however, planned to start operating a pilot-production line for Blu-ray disc replication in Torrance, CA, in May, with full production expected to begin in January 2006 (Compound Semiconductor, 2005m). In October, Toshiba and Matsushita each announced that they would mass-produce drives for desktop and notebook personal computers—Toshiba would manufacture discs with the high-definition format, and Panasonic would use the Blu-ray format. These would be available in early 2006 (Compound Semiconductor, 2005a).

***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.

According to a new report by Strategies Unlimited (a research unit of PennWell Corp.), more than 100 companies now produce high-brightness (HB) LEDs at various levels of the vertical supply chain. Out of a total of 30 companies selling epitaxial wafers and/or HB-LED chips in 2004, the top 3 suppliers accounted for more than one-half of the sales of these materials. Asia was the dominant supplier, accounting for 76% of the packaged HB-LED market and 57% of epitaxial wafer and chip sales in 2004 (Compound Semiconductor.net, 2005c§).

In February, Kopin Corp. announced that it would form a joint venture company to spin off its indium gallium nitride (InGaN) LED technology to a low-cost manufacturing operation in Asia. As a result, Kopin would stop manufacturing LEDs in the United States and concentrate its efforts on the manufacture of GaAs HBT epitaxial wafers. Taiwan-based Bright LED Electronics Corp. was one of the other partners in the joint venture, which was named KoBrite Corp. In November, the joint venture's production facility in Dongguan, China, opened, although the epitaxial growth stage in the chip fabrication process will take place in Taiwan (Compound Semiconductor.net, 2005f§).

Light Waves Concept Inc. (a New York, NY-based LED product manufacturer) was working with the U.S. Department of Defense on an evacuation system using LED technology. The system is made up of LED rope lights that line hallways within buildings and are connected to a controller. In the event of an emergency, the controllers will illuminate the ropes in a series of different flashing patterns and colors. The colors used will be those of a traffic light and will send the same signals to the evacuees—red for stop, green for go, and yellow for move cautiously. Biochemical, motion, and temperature sensors will feed data to the controllers based on the nature and severity of the emergency. The project is a new use for LED rope lights, which have been used mainly to highlight signage boards and buildings (LEDs Magazine, 2005g§).

III-N Technology Inc., a spin-off from Kansas State University, developed single-chip power LED lamps that can be plugged directly into standard power outlets or lamp sockets without power conversion. Normally, standard power LEDs operate from a direct current (DC) supply with a voltage of around 3.5 volts (V) (for blue devices); the new chips are capable of operating directly from an alternating current (AC) supply with a voltage of 110 V or 220 V. The new technology eliminates the need for an AC-DC power converter, which is expected to lead to significant cost savings. The main advantage, however, is the compatibility with the existing lighting and electricity infrastructure. The company has applied for patent protection covering its invention (LEDs Magazine, 2005j§).

Showa Denko K.K. has developed two new GaN-base LED chips that it planned to produce in large volumes. Showa Denko's proprietary near-ultraviolet and green LED chips were aimed at applications in general lighting and backlighting of large liquid crystal display (LCD) screens. The company had previously commercialized blue LEDs based on similar structures and has the capacity to produce 30 million GaN-base chips per month at its plant in Chiba, Japan (Compound Semiconductor.net, 2005i§).

A U.S. team conducted what is believed to be the first demonstration of a flow-through water purification module that uses ultraviolet LEDs. In collaboration with microbiologists at the University of Maine, Hydro-Photon Inc. developed a bench-level prototype flowing water treatment module that uses 10 aluminum gallium nitride (AlGaN) LEDs made by Sensor Electronic Technology Inc. In tests using sterile tap water contaminated with E. coli at a concentration of 10,000 microbes/milliliter, the ultraviolet LEDs destroyed at least 95.5% of the bacteria. Such purification modules, which would be far smaller and more convenient than those that use mercury lamps to kill bacteria, could become a high-volume market for ultraviolet LEDs in the future. Later in 2005, Hydro-Photon demonstrated water purification at flow rates close to those required for individual water treatment applications by using more powerful LEDs. Hydro-Photon's chamber reduced the level of E coli in water flowing at 150 milliliters per minute (mL/min) and 300 mL/min by 99.99% and 99.0%, respectively. Individual water treatment systems would typically require a flow rate of 500 mL/min (Compound Semiconductor.net, 2005a§). Sensor Electronic Technology also supplied LEDs to a firm that has built a prototype to treat raw sewage. Ohio-based start-up company Oh! Technology LLC (OHT) claimed to have reduced bacteria levels in flowing raw sewage by 60% using ultraviolet LEDs. OHT's first battery of tests, which began in February, analyzed the effect of a prototype module containing 16 AlGaN LEDs on raw fecal sewage at a local wastewater treatment facility (Compound Semiconductor, 2005g).

Permlight Products Inc. incorporated LEDs from Osram Opto Semiconductors GmbH into a new system that prevents the use of digital camcorders in cinemas. Permlight's line of antipiracy products uses Osram's recently introduced thin-film infrared power LED technology to transmit a harmless signal that is invisible to humans. The signal is directed towards movie audiences in cinema theaters and will wash out digital camcorders, preventing signals from being recorded. The system sells for between $1,200 and $5,000, depending on the size of the movie screen (LEDs Magazine, 2005i§).

The Diamond Vision LED screen, which was installed during a renovation of Turner Field in Atlanta, GA, is said to be the world's largest outdoor high-definition display. The 520-square-meter ($m^2$) (5,600-square-foot) Mitsubishi Electric Diamond Vision screen, which was recognized by Guinness World Records, is 21.6 meters (m) tall and 24.1 m wide and weighs 45 t. It consists of 266 panels that contain 20 lighting units each, resulting in a screen with almost 5.2 million LED modules that can reproduce 1 billion colors and be clearly seen from almost any viewing angle. Diamond Vision is a division of Mitsubishi Electric Power Products Inc. (a U.S. subsidiary of Mitsubishi Electric Corp. of Japan) (LEDs Magazine, 2005e§).

## 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 gallium prices rose slightly during 2005. At the beginning of the year, low-grade gallium prices were reported to be about $300 per kilogram. By April, the price increased to $330 to $350 per kilogram and then increased to about $400 per kilogram in June. By yearend, the price had decreased to $330 to $380 per kilogram. Metal-Pages reported similar price movements for the low-purity material. For high-purity gallium, Metal-Pages reported that prices early in 2006 were about $400 per kilogram, but increased to $617 per kilogram by midyear.

From U.S. Census Bureau import data, the annual average value for low-grade gallium was estimated to be $244 per kilogram, almost 30% higher than the revised average value in 2004. For high-grade gallium, the annual average estimated value fell to $538 per kilogram from a revised figure of $550 per kilogram. 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 2005, U.S. gallium imports were 19% lower than those in 2004 (table 5). Japan (27%), Russia (16%), Hungary (13%), and Ukraine (13%) were the leading sources of imported gallium. U.S. consumption of gallium metal has diminished mainly because a significant portion of the GaAs manufacturing capacity has moved to other countries, such as China and Taiwan. Gallium metal imports, therefore, are not expected to be as large as they have been in the past several years.

In addition to gallium metal, GaAs wafers were imported into the United States (table 6). In 2005, 4,350 kilograms (kg) of undoped GaAs wafers and 200,000 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 70 t in 2005. Principal world producers were China, Germany, Japan, and Ukraine. Gallium also was recovered in Hungary, Kazakhstan, Russia, and Slovakia. Refined gallium production was estimated to be about 97 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.***—A newly discovered coal deposit in China's Inner Mongolia Autonomous Region was reported to contain 875,000 t of gallium (Metal-Pages, 2005a§).

***Germany.***—Jenoptik Diode Lab GmbH planned to increase production of its GaAs laser diode chips in early 2006. The small company, which was set up in 2002 as a spinoff of the Ferdinand Braun Institute for High Frequency Technology, will build a new facility in Berlin-Adlershof to manufacture the chips. The complex will include 500 $m^2$ of clean rooms for 3-inch GaAs production, as well as in-house research and development laboratories and offices. Diode Lab principally will be manufacturing lasers for its parent company Jenoptik Laserdiode GmbH, with the lasers destined for applications in materials processing, medicine, and displays (Compound Semiconductor.net, 2005d§)

***Japan.***—In 2005, Japan's virgin gallium production was estimated to be 9 t, gallium recovered from scrap was reported to be 83 t, and gallium imports were reported to be 45 t, for a total supply of 136 t. China (29%), Taiwan (17%), and the United States (20%) were estimated to be the principal sources of gallium imported into Japan (Roskill's Letters from Japan, 2005).

***Kazakhstan.***—Production of gallium in Kazakhstan in 2005 was reported to be 6,245 kg (Metal-Pages, 2006§).

***Russia.***—In October, Fosagro AG announced that it would construct two nepheline concentrate processing plants—one at Kirov and the other at Murmansk—at a cost of $1 billion each. In conjunction with the new facilities, Fosagro planned to install 30 t of gallium recovery capacity at each plant. The first plant was scheduled to be completed within 3 to 4 years (Metal-Pages, 2005b§).

***Taiwan.***—The LED production industry continued to consolidate in 2005. In August, Epistar Corp. announced that it would acquire United Epitaxy Co. Ltd. through a share swap to create the nation's leading LED manufacturer. The new company will retain the Epistar name and will combine two complementary technologies—Epistar's high-luminance blue LEDs, and United Epitaxy's AlGaInP LEDs (Taiwan's leading supplier). In

February, South Epitaxy Corp., which supplies LED epitaxial wafers and chips, announced that it would acquire Epitech Technology Corp. through a share-swap transaction (Taipei Times, 2005§). A review of Taiwan's gallium manufacturing industry was published in January (III-Vs Review, 2005§).

Everlight Electronics Co. Ltd. planned to invest $14.9 million in an LED production capacity expansion in 2006. The expansion will increase Everlight's total monthly LED capacity to 650 million units from 372 million units by the end of 2006. Most of Everlight's LEDs are used in handset applications, while future growth will be driven by the automotive market and by the adoption of white LEDs as backlights for small LCD panels (LEDs Magazine, 2005b§).

***Ukraine.***—Rusal Ltd. announced that it would increase gallium production capacity at its Nikolaev Alumina Refinery to 12 t in 2006 from 10.5 t in 2005. Gallium production at the plant has been increasing steadily since 2003. In 2003, the plant produced 4 t of gallium, and in 2004, 10 t (Metals and Mining Weekly, 2005).

## Current Research and Technology

In September, Princeton Lightwave Inc. (PLI) introduced a new InGaAs-indium phosphide (InP) single photon avalanche diode that it claimed to be the first commercially available device designed and optimized specifically for applications where extremely low light levels require the capability to detect single photons. These applications include quantum information processing, long-range light detection and ranging (LIDAR), long-range terrestrial and satellite free-space communications, scientific instrumentation, and quantum cryptography for secure communications. Early in 2006, PLI planned to introduce products for quantum cryptography applications that use these avalanche photodetectors combined with technology licensed from IBM Corp. By combining the two technologies, PLI believes that it can become the first commercial supplier of single-photon detectors for quantum cryptography systems. Invented in 1984, quantum cryptography takes advantage of the quantum physics of light. In theory, it allows two users to communicate securely over a normally insecure channel, such as a regular optical fiber (Compound Semiconductor, 2005j).

Toshiba developed a fluorescent converter material that allows white LEDs to produce light that is close in appearance to sunlight. The newly developed material transforms blue LED light into various colors ranging from blue to yellow and orange and is designed to be used in combination with an additional fluorescent material that converts blue to red. Conventional white LEDs use a fluorescent material that converts blue to yellow, resulting in artificial white light containing no green or orange. As a result, red and green objects appear dark with poor color rendering. Products containing the material could be available in 2 or 3 years (LEDs Magazine, 2005h§).

Scientists at the Lighting Research Center at Rensselaer Polytechnic Institute have developed a method to get significantly more light from white LEDs without requiring more energy. Commercially available white LEDs combine a light-emitting semiconductor with a phosphor to produce visible white light. However, more than one-half of the light produced by the phosphor is diverted back toward the LED where much of it is lost because of absorption, which reduces the LED's overall light output. The scientists developed a method to extract the backscattered photons by moving the phosphor away from the semiconductor and reshaping the LED lens geometry. The researchers claim that compared to commercial white LEDs, prototypes of the new LED technology produced 30% to 60% more light output and lumens per watt of electricity. The research was funded by the U.S. Department of Energy's Building Technologies Program (Rensselaer Polytechnic Institute, 2005§).

In a different method to produce more efficient LEDs, a team of scientists at Los Alamos National Laboratory and Sandia National Laboratory developed the first completely inorganic, multicolor LED based on colloidal quantum dots encapsulated in a GaN semiconductor. The devices, which have cadmium selenide nanocrystals incorporated within a GaN-base light-emitting region, circumvent the inefficiencies of using phosphors to convert blue emission into yellow light, which include losses associated with light capture of the phosphor, nonradiative carrier losses during the reemission process, and losses because of reabsorption of the color-converted photons by the phosphor. Standard GaN deposition methods could not be used because the high temperatures would have degraded the nanocrystals. Instead, the researchers used a new lower temperature technique, which they call energetic neutral atom beam lithography/epitaxy (ENABLE). With this, they created films said to be as good as those produced by MOCVD (Compound Semiconductor.net, 2005j§).

Two additional groups of scientists were trying to increase the efficiency of white LEDs by capturing the light that is lost. Researchers from Meijo University, Japan, claimed that they have doubled the efficiency of white LEDs. Instead of using blue-emitting devices and color-converting yellow phosphors, the researchers use a purple-emitting LED combined with a "structured" silicon carbide (SiC) substrate that converts this emission into white light. The Japanese researchers have submitted patent applications for the structure of the SiC substrate (Compound Semiconductor.net, 2005e§). Scientists at Seoul National University, Republic of Korea, reportedly have more than doubled the output power of blue GaN-base LEDs with a holographic process that etches a two-dimensional photonic crystal into the device (Compound Semiconductor.net, 2005g§).

Research groups at the University of California at Santa Barbara, the University of Tsukuba [Japan], and the Tokyo University of Science [Japan] reportedly developed a new class of GaN semiconductor thin films, which are used to make blue and green LED chips. The new materials are known as semipolar and nonpolar GaN. The researchers demonstrated that the optical output power of LEDs fabricated using nonpolar and semipolar GaN saturates at much higher drive currents than for conventional LEDs, which is promising for high-brightness applications, such as automobile headlights. Semipolar and nonpolar GaN films have a different crystal structure from conventional GaN, with reduced or zero built-in electric fields. This makes it easier for the process leading to light emission to happen (LEDs Magazine, 2005c§).

Collaborators from National Aeronautics and Space Administration's Jet Propulsion Laboratory and IQE plc claim to have produced the world's first four-band infrared camera.

Based on quantum-well infrared photodetector (QWIP) technology, the camera is suitable for applications including weather prediction and remote sensing of pollution, such as the detection of nitrous oxide in smog. It has already been used as part of an international project investigating the environmental impact of vegetation burning and related ecological effects in Africa. It also has the potential to assist with monitoring crop health, tropical rainforest deforestation, and industrial pollutants. The new QWIP camera can see up to 15.5 µm, and its focal plane can be compared to the retina of an eye. The QWIP camera contains GaAs-base material that was grown at IQE's U.S. facility in Bethlehem, PA (Stevenson, 2005).

## Outlook

A report from Strategy Analytics Inc. forecast that 1 billion cell-phone handsets would be shipped worldwide in 2006. If this is correct, then the growth, largely fueled by strong sales from Nokia Group and caused by robust demand in emerging markets like India, would represent a 22% increase compared with the 2005 figure of 817 million shipments. Cell phone manufacturer Nokia, however, predicted an industry growth rate of about 15% in 2006. As phones become more complex, multiple power amplifiers manufactured from GaAs-base components are needed in the handset (Compound Semiconductor.net, 2006§). In response to these forecasts, GaAs manufacturing firms are either bringing idled capacity onstream or are announcing capacity increases. If these forecasts are overoptimistic, however, there could be a repeat of the same situation that happened in 2000-02. Gallium supplies were tight and prices skyrocketed in 2000 as companies increased their GaAs production to meet a predicted high demand for cell phone components. As the economy stagnated, the anticipated cell phone demand did not materialize, leaving cell phone manufacturers with excess inventory. The gallium market remained depressed, prices fell, and GaAs manufacturing firms closed some of their capacity until the excess inventory was sold.

Although the market for power amplifiers in cell phones was expected to increase, two market research firms predicted that the market for HB-LEDs in cell phones would either decrease or grow at a much slower rate than in the past. iSuppli Corp. predicted that the backlighting of LCD displays in mobile phones would start to slow as shipments of wireless handsets begin to decelerate and that many of the new lighting applications for the next generation of ultrahigh-brightness LEDs have not been commercialized yet, which would slow near-term growth (LEDs Magazine, 2005f§). Strategy Analytics expected that the introduction of brighter LEDs and more efficient backlighting schemes would cause a net reduction in the average number of LEDs used in both the LCD and keypad backlighting segments of the market. This loss, however, would be offset by strong growth in the emerging camera flash segment. By 2009, revenues from the growing camera flash function would represent 36% of the total handset LED market demand (LEDs Magazine, 2005d§).

Strategy Analytics also predicted that the global semi-insulating (SI) GaAs substrate market will grow in area by 43% by 2009. Sales of SI GaAs substrates were predicted to rise from 14 million square inches in 2004 to 20 million square inches in 2009, and worldwide SI GaAs revenue was expected to increase by 9% to 10% per year. In general, average selling prices were continuing to decline by at least 5% year-on-year. The decline in the price of 6-inch wafers, however, has slowed, partly because of an increase in the cost of raw gallium. Although by 2003 companies had been expected to switch to 6-inch from 4-inch substrates, sales of 4-inch substrates still accounted for 50% of the total (Compound Semiconductor.net, 2005b§).

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

(Kilograms unless otherwise specified)

| | | 2001 | 2002 | 2003 | 2004 | 2005 |
|---|---|---|---|---|---|---|
| Production | | -- | -- | -- | -- | -- |
| Imports for consumption | | 27,100 | 13,100 | 14,300 | 19,400 | 15,800 |
| Consumption | | 27,700 | 18,600 | 20,100 | 21,500 | 18,700 |
| Price | dollars per kilogram | 640 [2] | 530 [3] | 411 [3] | 550 [r, 3] | 538 [3] |

[r]Revised. -- Zero.
[1]Data are rounded to no more than three significant digits.
[2]Source: American Metal Market.
[3]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 | 2004 | 2005 |
|---|---|---|
| Optoelectronic devices: | | |
| Laser diodes and light-emitting diodes | 6,930 | 3,880 |
| Photodetectors and solar cells | 809 | 219 |
| Integrated circuits: | | |
| Analog | 9,890 | 11,700 |
| Digital | 63 | 115 |
| Research and development | 3,690 | 2,800 |
| Other | 111 | 76 |
| Total | 21,500 | 18,700 |

[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 |
|---|---|---|---|---|
| 2004: | | | | |
| 99.99% to 99.999% | 340 | 151 | 35 | 456 |
| 99.999% | 729 | 5,720 | 5,330 | 1,120 |
| 99.99999% to 99.999999% | 126 | 608 r | 507 | 137 r |
| Total | 1,200 | 6,480 r | 5,870 | 1,720 r |
| 2005: | | | | |
| 99.99% to 99.999% | 456 | 59 | 12 | 503 |
| 99.999% | 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 |

[r]Revised.

[1]Consumers only.

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

TABLE 4
ESTIMATED YEAREND GALLIUM PRICES

(Dollars per kilogram)

| Gallium metal | 2004 r | 2005 |
|---|---|---|
| 99.9999%-pure, average value of U.S. imports | 550 | 538 |
| 99.99%-pure, average value of U.S. imports | 188 | 244 |

[r]Revised.

TABLE 5

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

| Country | 2004 Quantity (kilograms) | 2004 Value[2] | 2005 Quantity (kilograms) | 2005 Value[2] |
|---|---|---|---|---|
| Canada | 763 | $151,000 | 1,090 | $269,000 |
| China | 4,740 | 1,050,000 | 1,530 | 624,000 |
| France | 1,170 | 569,000 | 1,520 | 775,000 |
| Germany | 37 | 15,800 | 26 | 22,800 |
| Hungary | 2,300 | 476,000 | 2,100 | 535,000 |
| Japan | 5,380 | 828,000 | 4,290 | 814,000 |
| Russia | 1,740 | 508,000 | 2,480 | 695,000 |
| Ukraine | 3,000 | 420,000 | 2,000 | 540,000 |
| United Kingdom | 182 | 46,700 | 215 | 103,000 |
| Other | 101 r | 62,900 r | 513 | 521,000 |
| Total | 19,400 | 4,130,000 | 15,800 | 4,900,000 |

[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]

| Country | Undoped 2004 Quantity (kilograms) | Undoped 2004 Value[2] | Undoped 2005 Quantity (kilograms) | Undoped 2005 Value[2] | Doped 2004 Quantity (kilograms) | Doped 2004 Value[2] | Doped 2005 Quantity (kilograms) | Doped 2005 Value[2] |
|---|---|---|---|---|---|---|---|---|
| Canada | 2,260 | $28,500 | -- | -- | 25 | $102,000 | 16 | $53,600 |
| China | 27 | 9,380 | 2,000 | $530,000 | 12,000 | 19,700,000 | 8,900 | 14,000,000 |
| Finland | -- | -- | -- | -- | 8,750 | 10,400,000 | 8,270 | 13,200,000 |
| Germany | 103 | 4,960 | 1,200 | 50,300 | 31,500 | 27,600,000 | 25,400 | 27,900,000 |
| Japan | 111 | 92,900 | 7 | 8,110 | 80,500 | 50,800,000 | 50,900 | 47,200,000 |
| Korea, Republic of | 14 | 10,200 | -- | -- | 64,500 | 23,800,000 | 44,500 | 27,500,000 |
| Russia | 502 | 182,000 | 498 | 124,000 | 88 | 215,000 | 391 | 580,000 |
| Singapore | 557 | 116,000 | -- | -- | 257 | 692,000 | 3,290 | 4,860,000 |
| Taiwan | 3 | 14,900 | -- | -- | 22,200 | 12,500,000 | 17,500 | 9,470,000 |
| Ukraine | -- | -- | 620 | 133,000 | -- | -- | 3 | 23,300 |
| United Kingdom | 2 | 17,700 | 31 | 4,540 | 164 | 451,000 | 26,800 | 4,540,000 |
| Other | 6 | 4,590 | -- | -- | 6,440 | 7,300,000 | 13,600 | 12,700,000 |
| Total | 3,580 | 481,000 | 4,350 | 850,000 | 226,000 | 153,000,000 | 200,000 | 162,000,000 |

-- 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, 2005[1]

(Metric tons)

| Country | Capacity |
|---|---|
| China | 59 |
| Germany | 35 |
| Hungary | 8 |
| Japan | 20 |
| Kazakhstan | 20 |
| Russia | 19 |
| Slovakia | 8 |
| Ukraine | 10 |
| Total | 179 |

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