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2015 Minerals Yearbook

GALLIUM [ADVANCE RELEASE]

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

November 2017

Gallium

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Low-grade primary gallium is recovered globally as a byproduct of processing bauxite and zinc ores. No domestic low-grade primary gallium was recovered in 2015, and imports of gallium metal and gallium arsenide (GaAs) wafers continued to account for most of U.S. gallium consumption (metal and gallium in GaAs). Metal imports were 47% lower than those in 2014. The leading sources of imported gallium metal, in descending order, were the United Kingdom, China, Germany, and Ukraine. A significant portion of imports was thought to be low-purity gallium that was refined in the United States and shipped to other countries. Data on refined gallium exports, however, were not available. Doped GaAs wafer (a wafer with intentionally modified electrical properties) imports increased significantly from that of 2014—China was the leading source, accounting for 87% of total imports, followed by Taiwan, Germany, and Japan in descending order of quantity. Undoped GaAs wafer imports decreased by 55% from that of 2014—Taiwan and Japan, in descending order of quantity, were the principal sources. Almost all gallium consumed in the United States was for the production of GaAs and gallium nitride (GaN), which, along with imported wafers, were used in integrated circuits (ICs) and optoelectronic devices [laser diodes, light-emitting diodes (LEDs), photodetectors, and solar cells]. U.S. gallium consumption decreased by 17% from that in 2014 owing to a decline in gallium consumed for the production of digital ICs, laser diodes and LEDs, and photodetectors and solar cells, and a decrease in gallium metal imports.

In 2015, estimated world low-grade primary gallium production was 470 metric tons (t), an increase of 7% from estimated production of 440 t in 2014. China, which accounted for 83% of global low-grade primary gallium capacity (fig. 1), was the leading producer. Germany, Japan, the Republic of Korea, and Ukraine were also significant producers. Additionally, plants in Hungary and Russia recovered gallium. Kazakhstan, previously a significant producer of primary gallium, reported no production in 2015. The estimated worldwide compound annual growth rate (CAGR) of low-grade primary gallium production was 20% from 2005 through 2015 (fig. 2), owing primarily to China's large annual increases in production beginning in 2010. About 180 t of low-grade primary gallium was processed to high-purity refined gallium; the remaining low-purity primary gallium produced in 2015 was most likely stockpiled. High-purity primary refined gallium was produced in China, Japan, the United Kingdom, the United States, and possibly Slovakia. The worldwide CAGR of high-purity primary refined gallium production was 6.4% from 2005 through 2015. World high-purity secondary refined gallium production increased at a CAGR of 10%. World gallium consumption, which increased at a CAGR of 7.2% from 2005 through 2015, was estimated to have been 320 t in 2015.

Production

No domestic production of low-purity primary gallium was reported in 2015. Molycorp Inc. (Greenwood Village, CO) recovered gallium from new scrap materials, predominantly those generated during the production of GaAs ingots and wafers. Molycorp's facility in Blanding, UT, had the capability to produce about 50 metric tons per year (t/yr) of high-purity gallium. The company purchased new scrap and low-purity primary gallium to refine into high-purity gallium. It also refined its customers' scrap into high-purity gallium. Molycorp's other gallium investments included an 80% interest in a gallium trichloride production facility in Quapaw, OK; a 50% interest in a primary gallium facility in Stade, Germany; a gallium recycling facility in Peterborough, Ontario, Canada; and an 80% interest in a new gallium trichloride production facility in the Hyeongok Industrial Zone in the Republic of Korea. Gallium trichloride is a precursor for many gallium compounds, including the organic gallium compounds used in epitaxial layering (Molycorp Inc., 2015, p. 15, 47, 103). In 2015, Molycorp filed for bankruptcy owing to a sharp decrease in the prices of rare earths (Miller and Zheng, 2015).

U.S. Consumption

Gallium consumption data were collected by the U.S. Geological Survey from a voluntary survey of U.S. operations. In 2015, 76% of the canvassed respondents replied to the gallium consumption survey. Data in tables 2 and 3 incorporated estimates for the nonrespondents to reflect full-industry coverage. Many of these estimates were based on company reports submitted to the U.S. Securities and Exchange Commission.

GaAs was used to manufacture ICs and optoelectronic devices. GaN principally was used to manufacture LEDs and laser diodes. ICs accounted for 60% of domestic gallium consumption, and optoelectronic devices accounted for 40% (table 2). Approximately 70% of the gallium consumed in the United States was contained in GaAs and GaN wafers. Gallium metal, trimethylgallium (TMG), and triethylgallium (TEG) used in the epitaxial layering process to fabricate epiwafers for the production of LEDs and ICs accounted for most of the remainder.

U.S. gallium consumption decreased by 17% from that in 2014 owing to a decline in gallium consumed for the production of digital ICs (69%), laser diodes and LEDs (22%), and photodetectors and solar cells (47%). U.S. gallium consumers opening new GaAs wafer production facilities in Asia to be closer to the Asian-dominated optoelectronics industry were thought to be a leading cause for the decrease in U.S. gallium consumption and gallium metal imports. While the increase in imports of doped

GaAs wafers from China in 2015 supports the rationale that gallium metal previously consumed in the United States has been consumed in China, the significant increase in volume of these imported wafers coupled with their unusually low value (table 6) may indicate a reporting error. Consequently, these data have been referred to the U.S. Census Bureau for verification.

Global Consumption

Gallium Arsenide.—The value of GaAs devices consumed worldwide increased by 9% in 2015, to approximately $7.5 billion from $6.9 billion in 2014. Developments in cellular telephone technology, particularly sophisticated third-generation (3G) and fourth-generation (4G) smartphones, continued to drive the GaAs device industry, accounting for more than 50% of the GaAs device market in 2015. Fourth-generation smartphones use up to 10 times more GaAs than second-generation (2G) cellular telephones. Wireless and cellular applications together accounted for approximately 70% of the GaAs device revenue (Higham, 2016; Strategy Analytics Inc., 2016, p. 1).

Worldwide sales of smartphones in 2015 totaled more than 1.4 billion units, an increase of 10% from that of 2014. China, the United States, and India were the principal sources of smartphone growth in 2015, with China accounting for 30% of smartphone sales, the United States accounting for 12% of sales, and India accounting for 8% of sales. India has become one of the fastest growing smartphone markets in the world, and was projected to overtake the United States in sales by 2019, accounting for 13% of the smartphone market (IDC Research, Inc., 2016; Statista Inc., undated).

The value of worldwide GaAs wafers consumed increased by 12% in 2015, to $624 million from $557 million in 2014. Countries within the Asia-Pacific region (East Asia, South Asia, Southeast Asia, and Oceania) dominated the GaAs wafer market, with regional wireless, cellular, and optoelectronics manufacturers consuming about 59% of the GaAs wafers. The three largest GaAs wafer manufacturers in the world—WIN Semiconductors Corp. (Taiwan), Advanced Wireless Semiconductor Company (Taiwan), and Global Communication Semiconductors, LLC (Torrance, CA), in order of market share, have their wafer foundries established in Taiwan. Wireless and cellular manufacturers within North America consumed about 25% of GaAs wafers. Device manufacturers in Europe and the rest of the world consumed about 4% and 12%, respectively, of the remaining GaAs wafers (Technavio, 2016a, p. 33–34).

Gallium Nitride.—Increased demand for GaN devices, namely opto semiconductors (LEDs and laser diodes) and power semiconductors [pure power devices and radio frequency (RF) devices], provided significant growth for advanced GaN-based products. In 2015, the estimated value of the worldwide GaN devices market was $871 million, an increase of 81% from $482 million in 2014. GaN opto semiconductors accounted for approximately 64% of the total market, driven primarily by the widespread adoption of LEDs; GaN pure power and RF devices accounted for the remaining 36% of the market (Transparency Market Research, 2016; Yole Développement, 2015, 2016).

In 2015, the GaN RF device market increased by nearly 50% in value to approximately $300 million owing to an increase in wireless infrastructure applications, driven by widespread deployment of long term evolution (LTE) base-station power amplifier networks in China. LTE is a standard for high-speed wireless communication for cellular telephones and data terminals. Wireless infrastructure and defense use, at 55% and 37%, respectively, were the two dominant applications in the GaN RF device market. Cable television (CATV) was also a significant application (Yole Développement, 2016).

GaN power devices operate at higher voltages, power densities, and switching frequencies, and offer greater power efficiency than existing GaAs and silicon devices. Increased demand from the military for enhanced battlefield performance stimulated demand for GaN power devices. The main application of GaN in the military is in discrete high electron mobility transistors (HEMT), which allow for high-frequency operations used in radar and electronic warfare systems (Transparency Market Research, 2015).

North America and Europe were the leading consumers of GaN devices in 2015, primarily owing to North American military and defense applications and European space and telecommunications applications. Prior to construction of the GaN devices, GaN substrates, where GaN is grown epitaxially on sapphire, silicon, or silicon carbide wafers, or to a lesser extent, on GaN wafers, were mostly produced and consumed in the Asia-Pacific region. China, Japan, and the Republic of Korea accounted for more than 80% of world production. It was reported that the cost of the gallium material and fabrication were lower in China than elsewhere, and the country has attracted an increasing number of GaN substrate manufacturers (Semiconductor Today, 2015; Transparency Market Research, 2016).

Light-Emitting Diodes.—Gallium is a main component of many LEDs. Various gallium compounds, including GaAs, GaN, gallium phosphide, aluminum gallium indium phosphide, and gallium arsenide phosphide, produce variously colored light when exposed to an electric current. Worldwide LED consumption continued to increase in 2015. Shipments of high-brightness LEDs were estimated to have increased by more than 30% from that of 2014. Despite increased consumption, the packaged LED market decreased by 2% in value to $15.3 billion owing mainly to a significant oversupply in the market and price decreases of up to 40% from 2014. Significant LED capacity expansion began in 2011, brought about mostly by the creation of Government-subsidized LED companies in China. The LED market has been in surplus since 2012, and prices for packaged LEDs have decreased continually since then (Lin, 2015; Wright, 2016).

The Asia-Pacific region was the leading consumer of LED material, followed by North America and Europe. The demand for LED material in the Asia-Pacific region was driven mainly by the large number of LED manufacturing facilities located in China, the Republic of Korea, and Taiwan. China has the largest LED industry in the world and accounts for about 30% of LED production (Semiconductor Today, 2016; Persistence Market Research, undated).

LEDs for general lighting applications remained the largest segment of the LED market and, according to research and consulting firm Technavio, accounted for about 40% of LED sales, an increase from 34% of sales in 2014. Other LED markets in 2015, in decreasing order of market share, included cellular telephone, computer notebook, tablet, television, and monitor backlighting, 29%; automotive, 13%; and other uses, 18% (Semiconductor Today, 2016).

Packaged LEDs also account for the largest end use of all GaN devices. GaN dominates key LED applications, such as computer monitors, notebook computers, tablet computers, televisions, and has been increasingly in demand for general lighting applications. In 2015, Technavio ranked the packaged GaN LED applications as general lighting, 44%; other lighting, 23%; television, 21%; digital signage, 8%; and cellular telephone, 4%. The Asia-Pacific region consumed 76% of all packaged GaN LEDs, whereas Europe consumed 14%, and North America consumed the remaining 10% (Technavio, 2016c, p. 17, 22).

As LED demand increased beginning in 2010, producers began expanding capacity for TMG, the metal-organic chemical used to fabricate the GaN epitaxial layer on LED epiwafers. When TMG and nitrogen gas are fed into the metal-organic chemical vapor deposition (MOCVD) reactor and heated, a GaN layer is formed on the epiwafer. TMG's purity and quality determine an LED's brightness and reliability. There are five major TMG producers worldwide. Akzo Nobel N.V. (Netherlands) manufactures TMG in Texas; Albemarle Corp. (Baton Rouge, LA) manufactures TMG in the Republic of Korea; the Dow Chemical Co. (Midland, MI) manufactures TMG in Massachusetts and the Republic of Korea; Jiangsu Nata Opto-electronic Material Co., Ltd. (China) manufactures TMG in Jiangsu Province, China; and SAFC Hitech (a subsidiary of Sigma Aldrich, St. Louis, MO) manufactures TMG in Taiwan and the United Kingdom (QYR Chemical and Materials Research Center, 2016, p. 22).

In 2015, an estimated 61 t of TMG was produced worldwide, a 7% increase from 57 t in 2014. The estimated value of global production was $116 million, and the average price was estimated to be $1,905 per kilogram. TMG production share by company was Akzo Nobel, 36%; Dow, 35%; SAFC, 10%; Jiangsu Nata, 8%; Albemarle, 4%; and other producers, 7%. Reported worldwide TMG production capacity was 195 t/yr. Dow had the most production capacity at 70 t/yr; Akzo Nobel, 60 t/yr; Jiangsu Nata, 30 t/yr; SAFC, 18 t/yr; Albemarle, 5 t/yr; and other producers, 12 t/yr. An estimated 61 t of TMG was consumed worldwide in 2015. China consumed 38%; the Republic of Korea, 21%; Taiwan, 19%; the United States, 10%; Europe, 6%; and other countries, 6% (QYR Chemical and Materials Research Center, 2016, p. 15, 17–19, 28, 31, 36).

Solar Cells.—The solar cell market continued to be dominated by crystalline silicon solar cells, which accounted for about 90% of the market (Benson, 2015, p. 12). In 2008, industry experts had thought that copper-indium-gallium-selenide (CIGS) technology would eventually be able to compete with conventional silicon-based photovoltaic technology. CIGS technology, however, has been slow to enter the commercial market owing to a decline in prices of silicon-based solar cells, a complicated manufacturing process that has impeded commercial mass production of CIGS panels, and financial instability among many of the research-based startup CIGS companies. To keep CIGS technology competitive, CIGS manufacturers have trimmed production costs, increased production capacities, improved module conversion efficiencies, and increased CIGS adoption in commercial rooftops. Several large corporations acquired select small startup companies and increased utilization of their production capacities. Japan's Solar Frontier K.K. was thought to be the only mass producer of CIGS solar cells. In December, scientists from Solar Frontier, in partnership with Japan's New Energy and Industrial Technology Development Organization announced they had achieved a record 22.3% efficiency for a CIGS solar cell in a laboratory setting (Gifford, 2015).

Prices

Since 2002, producer prices for gallium have not been quoted in trade journals. From U.S. Census Bureau data, the average annual value for imported low-grade gallium in 2015 was estimated to be $188 per kilogram, about 21% less than that in 2014 (table 4). The estimated average annual import value for high-grade (≥99.9999%-pure) gallium decreased by 13% to $317 per kilogram. Import data reported by the U.S. Census Bureau do not specify purity, and the estimated price distinction between gallium grades was based on the average customs value of the material and the country of origin.

According to Argus Media group Metal-Pages, gallium prices also decreased in China during 2015. At the beginning of 2015, the low-grade (≤99.99%-pure) gallium price in China was reported to be about $200 per kilogram (a decrease of 13% from that in January 2014), as significant increases in China's low-grade gallium production continued to exceed increases in worldwide consumption. By July, the price had decreased to about $160 per kilogram, and by December, the price decreased to about $130 per kilogram, a 35% decrease from the beginning of the year.

Foreign Trade

In 2015, U.S. gallium metal imports were 47% lower than those in 2014 (table 5), primarily owing to U.S.-based gallium consumers shifting a significant portion of their GaAs wafer production from the United States to Asia to be closer to the Asian-dominated optoelectronics industry, and also, perhaps, to import and consume less costly Asian-produced GaAs wafers. The United Kingdom (35%), China (33%), Germany (14%), and Ukraine (13%) were the leading sources of imported gallium metal. Nonaggregated data of U.S. gallium exports were not available.

In addition to gallium metal, GaAs wafers were imported into the United States (table 6). Undoped GaAs wafer imports were 55% less than those in 2014. Doped GaAs wafer imports increased 750% from that of 2014, with China as the leading source, accounting for 87% of total imports. Doped GaAs wafers imported from China were valued at $50 per kilogram in 2015, 87% less expensive than imported doped wafers from the rest of the world, which were valued at $385 per kilogram. While the increase in imports of doped GaAs wafers from China in 2015 supported the rationale that gallium metal previously consumed in the United States had been consumed in China, the significant increase in the volume of these imported wafers coupled with their unusually low value may indicate a reporting error. Consequently, these data have been referred to the U.S. Census Bureau for verification. The data listed in table 6 may include some packaging material weight and, as a result, the quantities reported for 2015 may be higher than the actual total weight of imported wafers.

World Review

Imports of gallium into Japan and the United States, two leading consuming countries, and an updated gallium production estimate for China were used as the basis for estimating world gallium production. China reportedly increased its production of low-grade primary gallium in 2015 by 13% (Shen, 2016) and was estimated to account for more than 90% of worldwide production. Estimated worldwide low-grade primary gallium production was 470 t in 2015. Principal world producers were China, Germany, Japan, the Republic of Korea, and Ukraine. Gallium also was recovered in Hungary and Russia. Kazakhstan, which had been a leading producer in 2012, ceased production beginning in 2013, most likely owing to the worldwide surplus. Production of high-purity primary refined gallium in 2015 was estimated to be about 180 t, 62% less than low-purity primary production. China, Japan, Slovakia, the United Kingdom, and the United States refined high-purity gallium from low-purity primary material.

Worldwide gallium consumption was estimated to be about 320 t in 2015, an increase of approximately 6% from that of 2014. Approximately 40% to 45% of total consumption was estimated to come from recycled material (Spicer, 2013). Therefore, about 180 t of high-purity primary refined gallium and 140 t of recycled gallium were estimated to have been consumed in 2015. Gallium was recycled from new scrap in Canada, Germany, Japan, the United Kingdom, and the United States. By 2020, Roskill expected worldwide gallium consumption to increase to approximately 420 t, with LED general lighting applications accounting for 33% of consumption (Roskill Information Services Ltd., 2014).

Canada.—Orbite Technologies Inc. (formerly Orbite Aluminae Inc.) announced that construction of its high-purity alumina plant in Cap-Chat, Quebec, continued to experience delays in 2015. The plant was expected to begin cold commissioning in the first quarter of 2016. A separation facility was to be built at the alumina plant to recover 4N purity (99.99%) gallium and other rare metals and rare-earth elements (Orbite Aluminae Inc., 2012; Orbite Technologies Inc., 2015).

China.—China, which was reported to have produced 440 t of low-grade primary gallium in 2015, increased its low-grade primary gallium manufacturing capacity to 600 t/yr in 2015 from 550 t/yr in 2014 (Asian Metal Inc., 2016). China was estimated to have consumed about 70 t of low-grade gallium in 2015, approximately 22% of worldwide consumption, and had an estimated 400 t of low-grade primary gallium stockpiled (Shen, 2016). China's share of worldwide consumption was forecast to increase to 35% in 2020 owing to the rapid growth of the country's LED industry (Merchant Research & Consulting, Ltd., 2016).

China's low-grade primary gallium producers included Aluminum Corporation of China Ltd. (Beijing); Beijing JiYa Semiconductor Material Co., Ltd. (Beijing); East Hope Mianchi Gallium Industry Co., Ltd. (Shanghai); Shanxi Jiahua Tianhe Electronic Materials (Shanxi Province); Shanxi Zhaofeng Gallium Industry Co. (Shanxi); Xiaoyi Xingan Gallium Co., Ltd. (Guangxi Zhuang Autonomous Region); and Zhuhai Fangyuan Inc. (Guangdong Province) (Huy and Liedtke, 2016, p. 34). China's high-purity primary refined gallium producers included Beijing JiYa Semiconductor Material Co., Ltd.; 5N Plus Inc. (Shenzhen, Guangdong Province); Nanjing Jingmei Gallium (Nanjing, Jiangsu Province); and Zhuzhou Keneng New Material Co., Ltd. (Zhuzhou, Hunan Province) (Shen, 2015).

Japan.—DOWA Electronics Materials reported that Japan's gallium supply in 2015 totaled 162 t, a slight increase from 159 t in 2014, with 51% of the gallium supply sourced from imports, 46% from recovered scrap, and 3% from low-purity primary gallium produced in Japan as a byproduct of zinc refining. Of Japan's 82 t of imported gallium, 61% came from China (Industrial Rare Metals, 2015). Metal-Pages (2016) estimated that Japan remained the leading gallium-consuming country and consumed 153 t of gallium in 2015, approximately 48% of worldwide consumption. Japan's share of worldwide consumption was forecast to decrease to 41% in 2020 owing to competition from China's LED industry. Japan was the leading producer of commercial GaN wafers, accounting for approximately 85% of worldwide production (Compound Semiconductor, 2014).

Outlook

Smartphones are a fundamental structural shift in mobile communications, offering services not available on standard cellular telephones, such as Internet access, video streaming, computer program applications ("apps"), and global positioning systems. Smartphones, which use up to 10 times the amount of GaAs-rich RF content than 2G cellular telephones, are expected to account for 76% of all worldwide handset sales by 2016 and 89% of all worldwide handset sales by 2020 (Scarsella and Stofega, 2016a, b). Installation of 3G and 4G mobile networks in India and the Republic of Korea is expected to further increase sales of smartphones. Additional increases in GaAs demand will also result from new Wi-Fi® applications, such as point-to-point communications, smart meters, and tablet personal computer technologies. Market research firm Strategy Analytics Inc. forecast that while commercial GaAs device sales would increase by less than 5% per year through 2018, military GaAs device sales are expected to increase by approximately 13% per year through 2018 owing to increasing use of GaAs technologies in radar, electronic warfare, communications, and other military applications. The largest use of military GaAs devices is expected to come from radar applications, accounting for approximately 60% of GaAs military market revenue (Semiconductor Today, 2014).

Yole Développement forecast that the RF GaN device market would increase by 14% per year between 2016 and 2022 owing to increased adoption of GaN technology in wireless infrastructure and defense applications, as well as implementation of new fifth generation (5G) networks beginning around 2019. High-frequency RF applications over 3.5 gigahertz, including military radar and electronic warfare systems, commercial wireless telecommunications, and CATV applications, require the high voltage and high power capabilities of GaN devices. GaAs and silicon devices cannot operate at such high frequencies (Yole Développement, 2016).

Owing to significant expansion of LED manufacturing capacity, reduced prices, and Government incentives, the global LED market is expected to increase by 17% per year between 2016 and 2020. General lighting is expected to remain the largest segment of the LED market for the rest of the decade, followed by backlighting and automotive lighting. The Asia-Pacific region is expected to remain the leading consumer of LED material owing to rapid construction in many Asian countries, Government incentives to encourage use of energy-efficient lighting, and the presence of the majority of the LED industry (Technavio, 2016b).

Annual production of TMG was forecast to remain level at 61 t from 2015 to 2020 and to increase slightly to 64 t by 2022. The average price of TMG was forecast to decrease about 20% by 2022 to $1,547 per kilogram from $1,905 per kilogram in 2015 (QYR Chemical and Materials Research Center, 2016, p. 31, 91, 95).

References Cited

Asian Metal Inc., 2016, AM statistics—Chinese gallium metal output amounts to 444t in 2015: Asian Metal Inc., January 25. (Accessed November 3, 2016, via http://www.asianmetal.com.)

Benson, Michael, 2015, How new applications will impact demand for electronic metals: Minor Metals Trade Association's International Minor Metals Conference, Toronto, Ontario, Canada, April 27–29, presentation, 27 p.

Compound Semiconductor, 2014, Bulk GaN—Too little, too late?: Compound Semiconductor, January 21. (Accessed January 28, 2014, at http://www.compoundsemiconductor.net/csc/indepth-details/19737048/Bulk-GaN:-too-little,-too-late.html.)

Gifford, Jonathan, 2015, Solar Frontier hits 22.3% on CIGS cell: pv magazine, December 8. (Accessed January 18, 2016, at https://www.pv-magazine.com /2015/12/08/solar-frontier-hits-22-3-on-cigs-cell_100022342/.)

Higham, Eric, 2016, Is the GaAs device market running out of gas?: Boston, MA, Strategy Analytics Inc., Advanced Semiconductors blog, September 30. (Accessed October 20, 2016, at https://www.strategyanalytics.com/strategy-analytics/blogs/advanced-semiconductors/2016/09/30/is-the-gaas-device-market-running-out-of-gas.)

Huy, Dieter, and Liedtke, Maren, 2016, Supply and demand of lithium and gallium: Hannover, Germany, Bundesanstalt für Geowissenschaften und Rohstoffe, May, 50 p. (Accessed October 12, 2016, at http://www.bgr.bund.de/EN/Themen/Min_rohstoffe/Downloads/studie_Li_Ga_en.html.)

IDC Research, Inc., 2016, Apple, Huawei, and Xiaomi finish 2015 with above average year-over-year growth, as worldwide smartphone shipments surpass 1.4 billion for the year, according to IDC: Framingham, MA, IDC Research, Inc. press release, January 27. (Accessed June 15, 2016, at https://www.idc.com/getdoc.jsp?containerId=prUS40980416.)

Industrial Rare Metals, 2015, Annual review 2015: Tokyo, Japan, Arumu Publishing Co.

Lin, Jessie, 2015, High-brightness LED market trends and forecast, 2015: Taipei, Taiwan, Digitimes Research press release, March 16. (Accessed January 19, 2016, at http://digitimes.com/news/a20150316RS400.html.)

Merchant Research & Consulting, Ltd., 2016, Gallium demand to rise rapidly through 2020, states Merchant Research & Consulting in its report available at MarketPublishers.com: London, United Kingdom, Business Wire, Inc. press release, October 24. (Accessed October 25, 2016, at http://www.businesswire.com/news/home/20161024005618/en/Gallium-Demand-Rise-Rapidly-2020-States-Merchant.)

Metal-Pages, 2016, Japanese gallium demand to increase in long term: Argus Media group Metal-Pages, December 1. (Accessed December 6, 2016, via http://www.metal-pages.com/.)

Miller, J.W., and Zheng, Anjie, 2015, Molycorp files for bankruptcy protection: The Wall Street Journal, June 25. (Accessed June 30, 2015, at http://www.wsj.com/articles/SB10907564710791284872504581069270334872848.)

Molycorp, Inc., 2015, Annual report—2014: Greenwood Village, CO, Molycorp, Inc., 149 p.

Orbite Aluminae Inc., 2012, Orbite adds gallium and scandium separation facility at the HPA plant: Montreal, Quebec, Canada, Orbite Aluminae Inc. press release, October 22. (Accessed November 4, 2012, at http://www.marketwired.com/press-release/orbite-adds-gallium-and-scandium-separation-facility-at-the-hpa-plant-tsx-ort-1716404.htm.)

Orbite Technologies Inc., 2015, Orbite provides HPA construction update: Montreal, Quebec, Canada, Orbite Technologies Inc. press release, December 15. (Accessed October 20, 2016, at http://www.orbitetech.com/English/investors/news/news-details/2015/Orbite-Provides-HPA-Construction-Update/default.aspx.)

Persistence Market Research, [undated], LED materials market—Global industry analysis and forecast to 2020: New York, NY, Persistence Market Research report primer. (Accessed August 14, 2015, at http://www.persistencemarketresearch.com/market-research/led-materials-market.asp.)

QYR Chemical and Materials Research Center, 2016, Global trimethylgallium (TMG) industry 2016 market research report: Beijing, China, QYR Chemical and Materials Research Center, November, 102 p.

Roskill Information Services Ltd., 2014, Roskill—Gallium market to benefit as GaN-based LED lighting comes of age: PRNewswire news release, May 12. (Accessed May 13, 2014, at http://www.prnewswire.com/news-releases/roskill-gallium-market-to-benefit-as-gan-based-led-lighting-comes-of-age-258928021.html.)

Scarsella, Anthony, and Stofega, William, 2016a, Worldwide mobile phone forecast, 2016–2020: Framingham, MA, IDC Research, Inc., March. (Accessed June 15, 2016, at https://www.idc.com/getdoc.jsp?containerId=US41084116.)

Scarsella, Anthony, and Stofega, William, 2016b, Worldwide smartphone forecast, 2016–2020: Framingham, MA, IDC Research, Inc., March. (Accessed June 15, 2016, at https://www.idc.com/getdoc.jsp?containerId=US41084216.)

Semiconductor Today, 2014, Military GaAs device market to grow at CAGR of 13% to over $0.5bn by 2018: Semiconductor Today, October 16. (Accessed October 29, 2014, at http://www.semiconductor-today.com/news_items/2014/OCT/STRATEGY-ANALYTICS_161014.shtml.)

Semiconductor Today, 2015, Demand for larger diameters to boost GaN substrate market from $2.2bn in 2014 to $4bn by 2020: Semiconductor Today, September 3. (Accessed January 20, 2016, at http://www.semiconductor-today.com/news_items/2015/sep/industryarc_030915.shtml.)

Semiconductor Today, 2016, LED market to grow at CAGR of nearly 17% until 2020: Semiconductor Today, May 27. (Accessed July 15, 2016, at http://www.semiconductor-today.com/news_items/2016/may/technavio_270516.shtml.)

Shen, Daisy, 2015, Chinese 6N gallium market flat, business slow: Metal-Pages, July 8. (Accessed September 17, 2015, via http://www.metal-pages.com/.)

Shen, Daisy, 2016, China electronic metal prices to fall more—CNIA: Argus Media group Metal-Pages, May 9. (Accessed July 12, 2016, via http://www.metal-pages.com/.)

Spicer, Andi, 2013, ESM13—Most specialty and minor metals lost in the copper recycling process–PPM: Metal-Pages, September 11. (Accessed September 11, 2013, via http://www.metal-pages.com/.)

Statista Inc., [undated], Statistics and facts about the U.S. smartphone market: New York, NY, Statista Inc. (Accessed October 20, 2016, at https://www.statista.com/topics/2711/us-smartphone-market/.)

Strategy Analytics Inc., 2016, GaAs device forecast and outlook—2015–2020: Boston, MA, Strategy Analytics Inc., September 30, 24 p. (Accessed October 20, 2016, at https://www.strategyanalytics.com/access-services/components/advanced-semiconductors/reports/report-detail/gaas-device-forecast-and-outlook-2015---2020.)

Technavio, 2016a, Global gallium arsenide wafer market, 2016–2020: Elmhurst, IL, Technavio, August, 70 p.

Technavio, 2016b, Global LED market, 2016–2020: Elmhurst, IL, Technavio press release, May 13. (Accessed July 11, 2016, at http://www.technavio.com/report/global-semiconductor-equipment-led-market.)

Technavio, 2016c, Global packaged GaN LED market, 2016–2020: Elmhurst, IL, Technavio, February, 42 p.

Transparency Market Research, 2015, GaN industrial devices market to be propelled due to increase in demand from defense sector for enhanced battlefield performance: Albany, NY, Transparency Market Research press release, June 11. (Accessed November 24, 2015, at http://www.transparencymarketresearch.com/article/gan-industrial-devices-market.htm.)
Transparency Market Research, 2016, GaN semiconductor devices market—Global industry analysis, size, share, growth, trends, and forecast 2016–2024: Albany, NY, Transparency Market Research press release, August 29. (Accessed October 20, 2016, at http://www.transparencymarketresearch.com/gallium-nitride.html.)
Yole Développement, 2015, As GaN power devices are now poised for rapid market adoption, a strong IP position is essential for companies to grow their business: Lyon, France, Yole Développement press release, September 8. (Accessed November 11, 2015, at http://www.yole.fr/iso_upload/News/2015/PR_PowerGaN_PatentInvestigration_YOLE_KNOWMADE_Sep2015.pdf.)
Yole Développement, 2016, The GaN RF market enjoyed a healthy increase in 2015: Lyon, France, Yole Développement press release, March 23. (Accessed October 20, 2016, at http://www.yole.fr/GaNRF_Market.aspx.)
Wright, Maury, 2016, Strategies Unlimited reports packaged LED revenue has been stymied by oversupply: LEDs Magazine, March 3. (Accessed June 21, 2016, at http://www.ledsmagazine.com/articles/2016/03/strategies-unlimited-reports-packaged-led-revenue-has-been-stymied-by-oversupply.html.)

GENERAL SOURCES OF INFORMATION

U.S. Geological Survey Publications

Gallium. Ch. in Mineral Commodity Summaries, annual.
Gallium (Ga). Ch. in Metal Prices in the United States Through 2010, Scientific Investigations Report 2012–5188, 2013.
Gallium, Germanium, and Indium. Ch. in United States Mineral Resources, Professional Paper 820, 1973.
Historical Statistics for Mineral and Material Commodities in the United States. Data Series 140.

Other

Gallium. Ch. in Mineral Facts and Problems, U.S. Bureau of Mines Bulletin 675, 1985.
Gallium and Gallium Arsenide—Supply, Technology, and Uses. U.S. Bureau of Mines Information Circular 9208, 1988.
Gallium—Global Industry Markets & Outlook (8th ed.). Roskill Information Services, Ltd., 2011.

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

(Kilograms unless otherwise specified)

	2011	2012	2013	2014	2015
Production, primary crude	--	--	--	--	--
Imports for consumption	85,700	58,200	35,400	53,900	28,600
Consumption	35,300	34,400	37,800	35,800	29,700
Price,[2] dollars per kilogram	688	529	502	363	317

-- 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 CONTAINED GALLIUM, BY END USE[1, 2]

(Kilograms)

End use	2014	2015
Optoelectronic devices:		
Laser diodes and light-emitting diodes	14,500	11,400
Photodetectors and solar cells	732	391
Integrated circuits:		
Analog	14,700	16,000
Digital	5,620	1,720
Research and development	182	160
Total	35,800	29,700

[1]Data are rounded to no more than three significant digits; may not add to totals shown.
[2]Includes gallium metal and gallium contained in compounds produced domestically.

TABLE 3
STOCKS, NET RECEIPTS, AND CONSUMPTION OF GALLIUM METAL, BY GRADE[1, 2]

(Kilograms)

Purity	Beginning stocks	Net receipts	Consumption	Ending stocks
2014:				
99.99% to 99.999%	4,200	-1,280 [3]	--	2,910
99.9999%	786	10	36	760
99.99999% to 99.999999%	491	559	748	302
Total	5,470	-713 [3]	784	3,980
2015:				
97% to 99.9%	--	1	--	1
99.99% to 99.999%	2,910	-458 [3]	--	2,460
99.9999%	760	-190 [3]	32	538
99.99999% to 99.999999%	302	546	559	289
Total	3,980	-102 [3]	591	3,280

-- Zero.
[1]Consumers only.
[2]Data are rounded to no more than three significant digits; may not add to totals shown.
[3]Reshipments exceeded receipts.

TABLE 4
ESTIMATED AVERAGE GALLIUM PRICES

(Dollars per kilogram)

Gallium metal	2014	2015
Purity ≥ 99.9999%; average value of U.S. imports	363	317
Purity ≤ 99.99%; average value of U.S. imports	239	188

Source: U.S. Census Bureau.

TABLE 5
U.S. IMPORTS FOR CONSUMPTION OF UNWROUGHT GALLIUM AND GALLIUM POWDERS, BY COUNTRY[1]

Country	2014 Quantity (kilograms)	2014 Value[2]	2015 Quantity (kilograms)	2015 Value[2]
Belgium	--	--	131	$223,000
Canada	66	$16,900	--	--
China	17,700	3,860,000	9,330	1,850,000
France	404	199,000	1,110	745,000
Germany	9,320	2,690,000	4,070	1,140,000
Hong Kong	--	--	24	4,080
Japan	1,360	394,000	180	97,900
Poland	33	14,000	--	--
Taiwan	258	57,000	--	--
Ukraine	10,200	2,170,000	3,800	751,000
United Kingdom	14,500	4,240,000	9,980	2,310,000
Total	53,900	13,600,000	28,600	7,120,000

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

Material and country	2014 Quantity (kilograms)	2014 Value[2]	2015 Quantity (kilograms)	2015 Value[2]
Undoped:				
Austria	84	$32,600	85	$30,700
Canada	14,100	63,700	2,850	24,700
China	--	--	2,240	8,600
Japan	6	12,400	7,750	15,300
Taiwan	65,800	451,000	22,900	83,300
United Kingdom	9	10,400	2	10,000
Other	1 r	4,500 r	36	10,100
Total	80,000	575,000 r	35,900	183,000
Doped:				
Austria	637	41,500	1,260	152,000
Belarus	8,050	2,140,000	9,010	1,810,000
Belgium	476	631,000	1,110	1,170,000
China	50,700	27,800,000	2,320,000	116,000,000
Finland	6,840	5,110,000	6,280	4,520,000
France	2,940	2,710,000	4,860	5,270,000
Germany	51,400	23,800,000	69,000	14,600,000
Hong Kong	29,200	4,870,000	7,320	1,200,000
Italy	2,260	241,000	470	150,000
Japan	71,000 r	36,400,000 r	58,700	31,400,000
Korea, Republic of	14,500	5,470,000	6,350	1,410,000
Malaysia	2,290	305,000	778	132,000
Netherlands	649	23,000	160	34,000
Poland	172	144,000	205	268,000
Singapore	5,590	1,670,000	7,850	781,000
Taiwan	59,300	72,400,000	158,000	62,400,000
United Kingdom	4,380	1,950,000	1,320	2,310,000
Other	932 r	1,050,000	432	786,000
Total	311,000	187,000,000	2,660,000	245,000,000

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, 2015[1]

(Metric tons)

Country	Capacity
China	600
Germany	40
Hungary	8
Japan	10
Kazakhstan	25
Korea, Republic of	16
Russia	10
Ukraine	15
Total	724

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

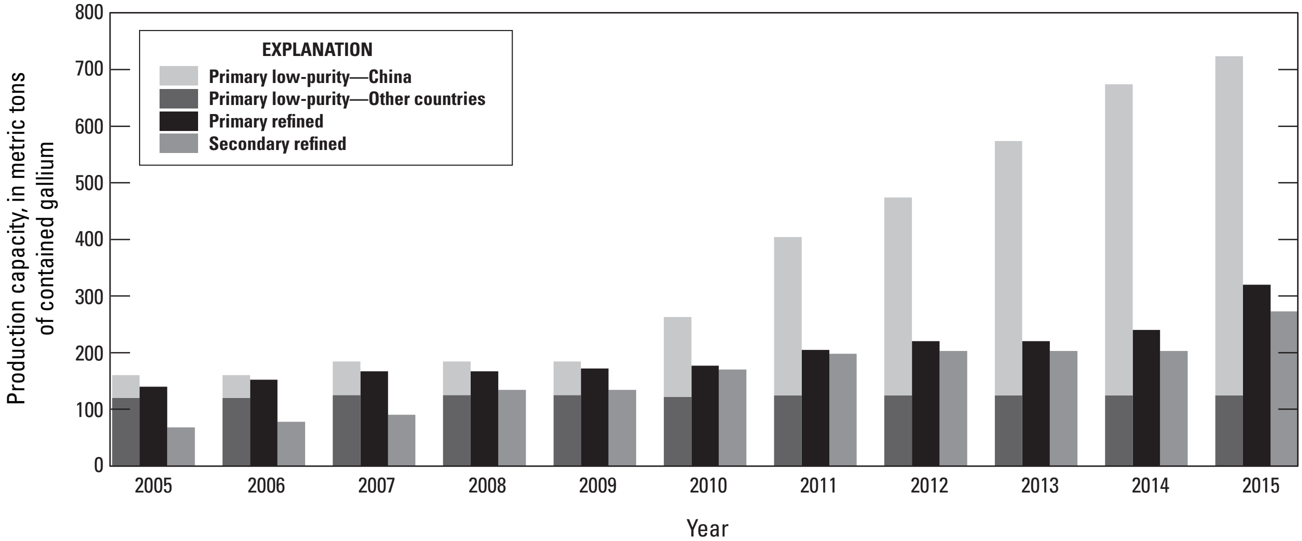

Figure 1. Estimated worldwide gallium production capacity from 2005 through 2015. Source: U.S. Geological Survey.

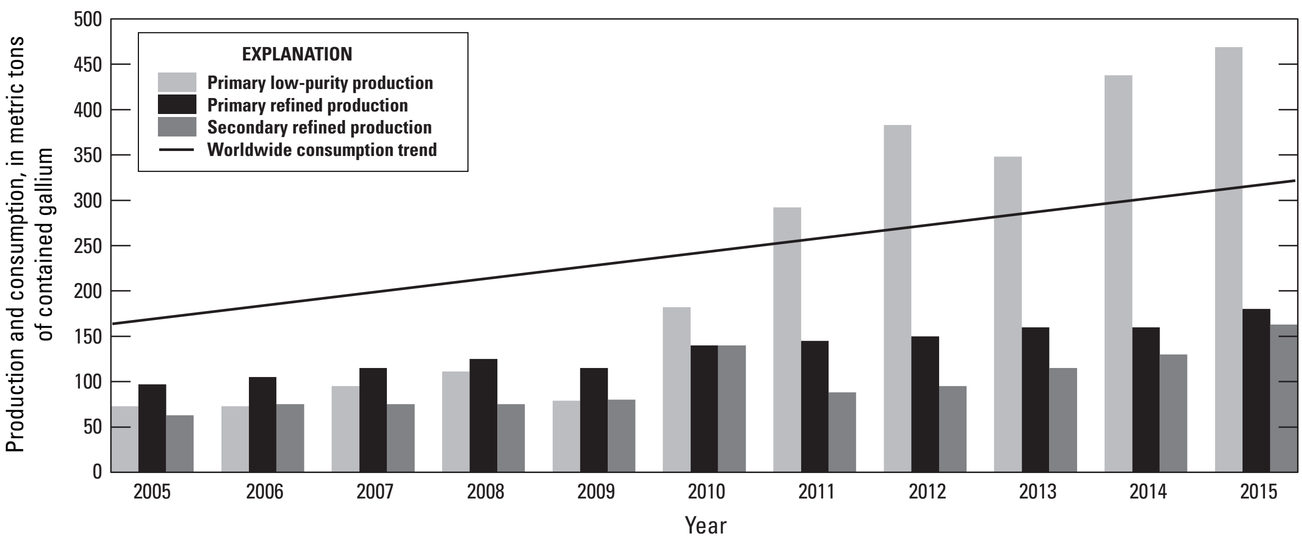

Figure 2. Estimated worldwide gallium production and consumption from 2005 through 2015. Source: U.S. Geological Survey.