Byproduct Metals and Rare-Earth Elements Used In the Production of Light-Emitting Diodes—Overview of Principal Sources of Supply and Material Requirements for Selected Markets

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By David R. Wilburn

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Conversion Factors

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Mass	
ton, metric (t)	1.102	ton, short (2,000 lb)
	Energy	
joule (J)	0.0000002	kilowatthour (kWh)

Acronyms

$(Ce,La)CO_3(F,OH)$	bastnäsite
$(Ce,La,Nd,Th)PO_4$	monazite
Al_2O_3	alumina
As_2S_3	orpiment
AsS	realgar
Ce	cerium
CFL	compact fluorescent light
DOE	U.S. Department of Energy
Eu	europium
GaAs	gallium arsenide
GaAsP	gallium arsenide phosphide
GaN	gallium nitride
GaP	gallium phosphide
HB	high brightness
InGaN	indium gallium nitride
La	lanthanum
LCD	liquid crystal display
LED	light-emitting diode
lm/W	lumens of visible light per watt of electricity consumed
mÅ	milliangstrom
MOCVD	metal-organic chemical vapor deposition
nm	nanometers
OLED	organic light-emitting diode
REE	rare-earth element
SiC	silicon carbide
Tb	terbium
UNEP	United Nations Environmental Programme
Y	yttrium
YAG	yttrium aluminum garnet

Byproduct Metals and Rare-Earth Elements Used in the Production of Light-Emitting Diodes—Overview of Principal Sources of Supply and Material Requirements for Selected Markets

By David R. Wilburn

Abstract

The use of light-emitting diodes (LEDs) is expanding because of environmental issues and the efficiency and cost savings achieved compared with use of traditional incandescent lighting. The longer life and reduced power consumption of some LEDs have led to annual energy savings, reduced maintenance costs, and lower emissions of carbon dioxide, sulfur dioxide, and nitrogen oxides from powerplants because of the resulting decrease in energy consumption required for lighting applications when LEDs are used to replace less-energy-efficient sources.

Metals such as arsenic, gallium, indium, and the rare-earth elements (REEs) cerium, europium, gadolinium, lanthanum, terbium, and yttrium are important mineral materials used in LED semiconductor technology. Most of the world's supply of these materials is produced as byproducts from the production of aluminum, copper, lead, and zinc. Most of the rare earths required for LED production in 2011 came from China, and most LED production facilities were located in Asia.

The LED manufacturing process is complex and is undergoing much change with the growth of the industry and the changes in demand patterns of associated commodities. In many respects, the continued growth of the LED industry, particularly in the general lighting sector, is tied to its ability to increase LED efficiency and color uniformity while decreasing the costs of producing, purchasing, and operating LEDs. Research is supported by governments of China, the European Union, Japan, the Republic of Korea, and the United States. Because of the volume of ongoing research in this sector, it is likely that the material requirements of future LEDs may be quite different than LEDs currently (2011) in use as industry attempts to cut costs by reducing material requirements of expensive heavy rare-earth phosphors and increasing the sizes of wafers for economies of scale. Improved LED performance will allow customers to reduce the number of LEDs in automotive, electronic, and lighting applications, which could reduce the overall demand for material components.

Non-Chinese sources for rare earths are being developed, and some of these new sources are likely to be operational in time to meet increasing demand for rare earths from the LED sector. Because most LED component production and manufacturing occurs in Asia and many LED producers have established supply contracts with Chinese producers of rare earths, a significant amount of the metallic gallium, indium, and the rare earths used for LED production will likely continue to come from Chinese sources at least for the next 5 years; however, a greater amount of these materials are now being processed in Japan, the Republic of Korea, and Taiwan. As non-Chinese sources of rare earths come into production, these new mines are likely to be sources of light REEs, but China will likely remain the leading source of supply for the heavy REEs suitable for use as LED dopants and phosphors at least for the next few years. Increased research in the development of phosphors that use smaller amounts of or different REEs is intended to reduce dependence on rare earths from China. Supply disruption of rare earths and other specialty metals could take place if China's specialty metal exports are redirected to domestic markets.

The cost of recovery is high and the lifespan for LEDs is comparatively long; thus, the LED waste volume was low in 2010, and few LEDs were recycled. The minute metal content of LEDs leads to a high cost for recovery, so recycling of LEDs outside of electronic waste is unlikely in the near term, although some LED producers are evaluating recycling options. Recycling of metals from LEDs in electronic waste is possible if the costs of recovering metals are justified by demand and metal prices.

Introduction

Light-emitting diode (LED) use is increasing in automotive, electronics, and lighting display applications and is expected to increase in general lighting applications in response to U.S. Government regulation, growing demand, and technological improvements. An adequate and reliable supply of raw materials is essential to meet this increasing demand for LEDs. Goals of increasing domestic and global energy independence, minimizing the economic effects of rising fossil fuel costs, and reducing greenhouse global gas emissions have contributed to government policy decisions placing greater emphasis on the development and implementation of devices that are more energy efficient. Currently (2011), the traditional incandescent light bulb typically produces 15 lumens of visible light per watt of electricity consumed (lm/W), and only about 5 percent of the electrical energy that goes into the bulb is converted to visible light (a measure of efficiency). The incandescent light bulb has a relatively short life span of 750 to 2,000 hours. Thus, it requires more energy and is more expensive to operate than newer types of lighting, such as halogen incandescent bulbs, compact fluorescent lights (CFLs), LEDs, or organic light-emitting diodes (OLEDs) (Humphries, 2008; U.S. Department of Energy, 2011a, b). Regulations restricting the sale of incandescent bulbs in Australia, Brazil, the European Union, and other areas began to be implemented in 2005. The United States enacted regulations halting the manufacture or export of incandescent bulbs in 2007. The Energy Independence and Security Act of 2007 (Public Law 110–140) set standards for increasing the energy efficiency of light bulbs by 30 percent. This would phase out most traditional incandescent light bulbs by 2012 or 2014. China, the world's leading producer of energy-efficient light bulbs, announced plans in 2011 to replace the 1 billion traditional incandescent bulbs it uses annually with more energy efficient types within 5 years (Branigan, 2011).

The U.S. Department of Energy (DOE) is legally required to ensure that manufacturers comply with the standards set by the U.S. legislation. Industry has responded by investing $120 million in LED research and development for lighting. LEDs, one type of solid-state lighting technology, consume less energy per lumen than traditional incandescent lighting. In an effort to reduce the cost of LED lighting, the DOE has been authorized by the U.S. Congress to invest up to $37 million for in manufacturing research and development on solid-state lighting, including high-brightness (HB) LEDs (U.S. Department of Energy, 2010b).

Although CFL technology provides an interim replacement device for incandescent bulbs in the general lighting market because of the lower cost, longer life (8,000 hours), and improved energy efficiency (typically 63 lm/W in 2010) of CFLs (U.S. Department of Energy, 2011a,b), CFLs contain mercury; LEDs do not and have in addition a broader range of applications than CFLs. As of 2009, a cool (more than 4,000 degrees kelvin (K)) white LED typically produced 60 to 92 lm/W, and a warm (less than 4,000 K) white LED typically produced 27 to 54 lm/W over an estimated useful life of 25,000 to 50,000 hours (U.S. Department of Energy, 2009a,b). The potential for LED technology to produce high-quality white light with a very high energy efficiency is being evaluated by much research and development.

LEDs are semiconductor devices that emit light when an electric current passes through the semiconductor chip in a single direction, converting 20 to 30 percent of the power into visible light. Figure 1 shows the generalized structure of an LED. Diodes in general are made up of thin layers of semiconductor material; one layer will have an excess of electrons (n-layer), and the subsequent layer will have a deficit of electrons, or "holes" (p-layer). When an electrical current is applied to a diode, electrons (negative) flow one way across the diode, and holes (positive) flow in the opposite direction across the diode. The holes exist at a lower energy level than the electrons, so when an electron falls, it loses energy, which is emitted as a light photon. The distance of the gap determines the energy level and wavelength frequency. Conventional LEDs are constructed using a variety of inorganic materials in groups IIIA, IIIB, IVA, and VA of the periodic table (fig. 2). Combinations of these materials are selected to produce light of a characteristic wavelength and color. The elements used most for LEDs include aluminum, arsenic, gallium, indium, and phosphorus.

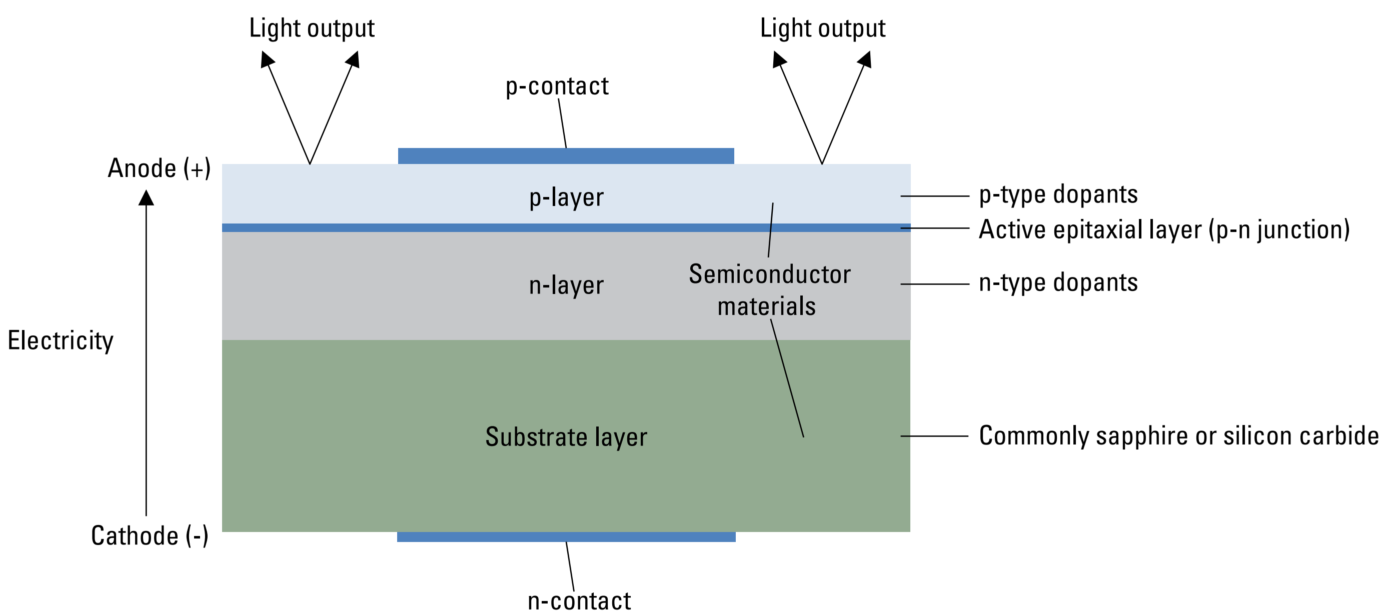

Figure 1. Structure of a light-emitting diode chip.

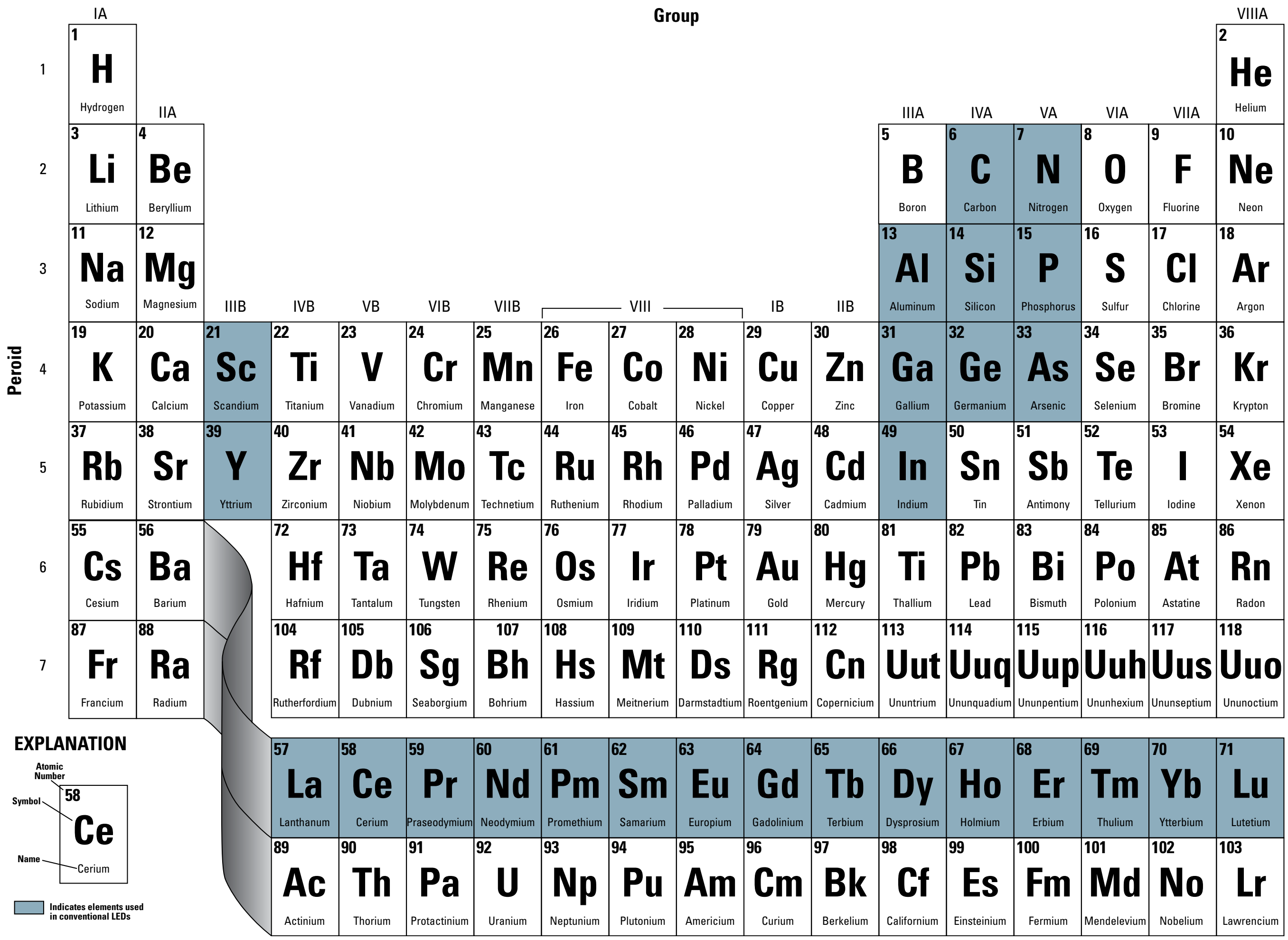

Figure 2. Periodic table of elements; modified from Dragoset and others (2011). The highlighted elements (in blue) in groups IIIA, IIIB, IVA, and VA indicate the principal materials used in the manufacture of conventional light-emitting diodes.

Different semiconductor materials (called substrates) and different impurities (dopants) introduced into the LED manufacture create the required electron density to generate the desired color produced by the LED (Casiday and Frey, 2007).

Historically, low-power LEDs of the through-hole design (fig. 3*A*) have been the most widely used type of LED. This type of low-brightness LED typically has a chip width of 0.25 millimeter (mm) and is generally used in indicator lamps for automobiles and electronic devices, signage, low-intensity lighting applications, and low-power, focused-light applications, such as in the backlighting of portable electronic devices (Perkins, 2009). More recently, surface-mounted high-power LED chips with a width ranging from 0.1 to 3 mm and a wider emitted light angle (fig. 3*B*) are used in HB lighting applications in which individual LEDs are connected together in a bar, grid, or string assembly, such as that used in automobile dashboard lighting and large lighting displays. LEDs are often produced to conform to individual customer specifications, so electrical specifications, component materials, and LED sizes vary considerably based on application and customer needs.

The components of the most widely used types of LEDs (fig. 3) consist of the semiconductor chip, a metallic frame on which the chip is mounted, and the plastic encapsulation material surrounding the chip assembly. Semiconductor materials commonly used in LEDs include gallium arsenide (GaAs) or gallium arsenide phosphide (GaAsP), gallium nitride (GaN), indium gallium nitride (InGaN), gallium phosphide (GaP), and (or) silicon carbide (SiC). Metals commonly found in the frame for the LED chip include aluminum, chromium, copper, iron, lead, nickel, and (or) zinc. Gold and silver are often used in the metal contacts of the LED (How Products Are Made!, 2011).

Low-brightness (with a wavelength ranging from 0.00001 to 0.002 nanometer (nm), or 1 to 20 milliangstrom (mÅ)), colored LEDs have been produced since the 1960s. The development of blue LEDs in the 1990s enabled the development of the first white LEDs made by coating blue LEDs with a phosphor. Other white LEDs were developed in the late 1990s by combining blue, red, and yellow-green LEDs. Medium-brightness LEDs (0.002 to 0.01 nm (20 to 100 mÅ)) were developed within the past decade for use in light panels, emergency

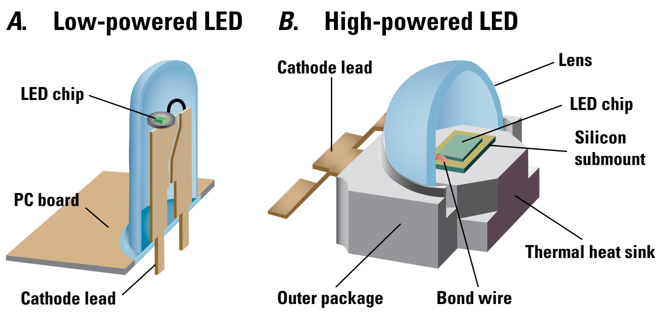

Figure 3. Principal components of *A*, low-power and *B*, high-power light-emitting diodes (LEDs); modified from Energy Star (undated).

lighting, and automobile taillights; HB LEDs (0.01 to 0.1 nm (100 mÅ to 1 angstrom (Å))) are used primarily in televisions and cellular and mobile electronic devices. As of 2009, based on a global market value of $5.7 billion, the principal markets for all types of LEDs were signage, displays, and signals (38 percent), cellular and mobile applications (32 percent), general lighting (18 percent), automotive (9 percent) and televisions and backlighting (3 percent). Short-term growth in LED use by 2015 is expected to be in backlighting and solid-state lighting sectors (Young and Low, 2009).

The LED industry uses a wide and growing range of phosphor materials to convert the light emitted from LED chips into different wavelengths of the lighting spectrum. Unlike dopants, phosphors are coatings that are applied to the LED chip during the packaging process. LED manufacturers rely on their supply of phosphor materials as a crucial aspect of the production process. The most common use is the combination of a blue LED chip with one or more phosphors to create a white LED. Many of the phosphors used in LEDs contain rare-earth elements (REEs), although the purity of REEs in LED phosphors is reported to be about 10 times less than phosphors used in cold-cathode fluorescent lamps (CCFLs) and liquid-crystal display (LCD) televisions (Bruce Hillman, Intematix Corporation, oral commun., November 18, 2011).

Because impurities can distort the color characteristics of phosphors, REEs used in phosphors must be 99.999 percent pure (U.S. Department of Energy, 2010c). In order to achieve such high purity, the processing of REEs intended for use as phosphors requires more processing stages than phosphors for other markets and increases the cost of producing REEs for this application.

OLED technologies are a flat light-emitting technology created by placing a series of organic thin films between two conductors. Light is emitted when electrical current is applied. Because OLEDs emit light, they do not require a backlight, so they are brighter, more energy efficient (consume less power), and thinner than LCDs, which require a white backlight. This technology has been used principally in television screens, computer monitors, and small electronic devices, such as cell phones and PDAs (OLED-Info, 2011). OLEDs typically emit less light per area than inorganic solid-state LEDs, which are often designed for point source lighting. Development of efficient OLED systems for a broad range of applications will likely lag LED systems by about 5 years (Whitaker, 2011b). Because the byproduct materials used in OLEDs are similar to those used in LEDs and because the use of OLEDs in a broad array of applications will not likely occur before 2020, this report does not include a separate treatment of OLED materials use.

Sources and Supplies of Selected Mineral Commodities Used in Light-Emitting Diodes

LEDs are made up of a variety of primary metals and minerals produced as byproducts from the production of other metals. Metals such as aluminum, chromium, copper, gold, iron, lead, nickel, silver, and zinc and organic components are excluded from this analysis because production is widespread and published literature on the sources and supply of these metals is readily available. This report describes the sources of supply of several mineral commodities that are not widely produced or produced in limited quantities but considered critical for the production of LEDs and LED phosphors. It also provides general estimates of material requirements based on reported or anticipated LED demand. Byproduct materials used in LEDs evaluated in this study include arsenic, gallium, and indium, as well as the REEs cerium, europium, gadolinium, lanthanum, terbium, and yttrium.

Arsenic

Arsenic is found in low concentrations in most soils and in higher concentrations associated with copper, lead, and zinc ores. Because of the health implications to humans and the environment, the extraction, recovery and processing, use, and disposal of arsenic are highly regulated. The United States was a leading producer of arsenic metal until 1985, when the Asarco Incorporated copper smelter in the State of Washington was closed (Bleiwas, 2000). In China, Peru, and the Philippines, arsenic is recovered from the minerals orpiment and realgar. Arsenic is also produced from deposits in Chile and Morocco by the reduction of arsenic trioxide obtained from flue dusts derived from smelting copper, gold, lead, and silver. In 2010, commercial-grade (99 percent pure) arsenic metal was produced from arsenic trioxide in China (47 percent), Chile (21 percent), Morocco (15 percent), and Peru (8.5 percent), with minor amounts from seven other countries. There has been no production of arsenic trioxide or arsenic metal in the United States since 1985, although the Nation remained the world's leading consumer of these products in 2010 (Brooks, 2011). The United States imports arsenic trioxide primarily from China and Morocco and high-purity (99.9999 percent pure) arsenic metal from China and Japan for use in the manufacture of chemicals, semiconductors, and pressure-treated wood products.

High-purity arsenic metal is used to produce GaAs, InGaN, or GaAsP semiconductors. The GaAsP semiconductor is commonly used to produce red, orange, and yellow LEDs used in indicator lamps, automotive applications, signage, and traffic signals.

Because arsenic concentration in LEDs is reportedly lower than what is required by Federal and State guidelines, arsenic in LEDs does not pose a safety hazard. A supply disruption is not anticipated unless regulations governing arsenic production and processing facilities in China and other producing countries are modified, delaying production or increasing its cost enough to impair the production of LEDs. The recycling of electronic waste is a potential source of secondary arsenic and many other materials. Close monitoring of metal recovery facilities will ensure that some of the metals potentially recoverable do not become environmental hazards or pose risks to human health. U.S. and foreign mineral processing companies prefer to process electronic scrap where the precious metal content is high and the risk for emission or exposure to deleterious elements such as arsenic is low; higher risk waste material is often shipped overseas for processing (Bleiwas and Kelly, 2001).

Gallium

Most of the world's supply of gallium originates as an impure byproduct recovered during the aluminum production process. Where gallium has replaced aluminum in rock-forming silicates, such as bauxite, its concentration typically ranges from 10 to 160 parts per million. Gallium is recovered primarily from deposits in Australia (33 percent), China (19 percent), Brazil (15 percent), and India (8.5 percent) (Bray, 2011). A small amount of gallium is recovered in Japan during the zinc refining process. No primary gallium recovery was reported in the United States in 2010. In 2011, the estimated production capacity of gallium metal refined from ores worldwide was about 180 metric tons per year (t/yr), with China producing an estimated 93 metric tons (t) in 2011 (Brian Jaskula, gallium commodity specialist, U.S. Geological Survey, oral commun., October 31, 2011). Other leading producers of gallium metal are Germany, Kazakhstan, the United Kingdom, and Ukraine. Some low-grade gallium metal is refined onsite, but much of it is sold and processed into gallium metal alloys of varying purities elsewhere. Gallium is recovered from new scrap from the gallium arsenide production process.

The recycling capacity of gallium worldwide is about 200 t from GaAs semiconductors and optoelectronic devices (laser diodes, LEDs, photo detectors, and solar cells) primarily in Japan, Canada, and the United States. The amount of potentially recoverable gallium is larger than the amount actually recovered because, where gallium concentration is too low to be economically recoverable, it is disposed of as waste during aluminum processing.

More than 97 percent of the gallium consumed in the United States in 2010 was in the form of GaAs or GaN. Optoelectronic devices accounted for 30 percent of the GaN consumption in the United States in 2010. The United States imported 166 t of doped [1] GaAs wafers and 63 t of undoped wafers for use in LEDs in 2010 (Brian Jaskula, gallium commodity specialist, U.S. Geological Survey, oral commun., October 31, 2011). Consumption of gallium for LEDs in the United States in 2010 (based on data on imports of wafers reported by the U.S. International Trade Commission (2011) increased by 64 percent from 2009 owing to the growth of the LED market. Supply of gallium and indium used as precursor materials in the metal-organic chemical vapor deposition (MOCVD) process commonly used to produce LED wafers was reported during the second half of 2010 (Hatcher, 2010), and capacity expansions for facilities that produce LED wafers using the MOCVD process are in progress (Cooke, 2010). An increase in gallium demand beyond the current (2011) capacity can be satisfied by further expansion of recovery circuits at existing alumina facilities and (or) increased recycling of GaAs wafers.

Indium

Approximately 570 t of indium metal produced worldwide in 2010 came from primary sources (Tolcin, 2011b). Most of the world's supply of indium originates as a byproduct of the processing of zinc ores mined in China, Peru, Canada, Australia, and the United States (in decreasing order of quantity of indium recovered). Indium can also be recovered as a byproduct of mining copper, lead, tin, and precious metals in many countries, but production of indium from these sources is minor. Indium metal is produced primarily in Canada, China, Japan, and the Republic of Korea. China produces about 52 percent of the world's refined indium, primarily from domestic sources. The Republic of Korea produces 14 percent of the world's refined indium from imported concentrates, Japan produces 12 percent from imported concentrates, and Canada produces about 6 percent from domestic sources and from imports from the United States (Tolcin, 2011a).

Raw indium materials are often extracted in one country and processed at a second location, and final products containing indium, such as LEDs, are manufactured at a third location because few companies that produce indium operate fully integrated mining, processing, and manufacturing facilities. Japan Energy Corporation is the largest integrated indium producer in the world and produces indium metal of varying grades from zinc refining operations as well as indium phosphide for use in LED semiconductors. Hunan Nonferrous Metals Corporation Limited is the largest integrated metals producer in China, and Umicore S.A. of Belgium produces high-purity indium products for the semiconductor industry from internal and purchased sources. Most mining companies produce

[1]Doping refers to the process of introducing impurities in the material to generate the desired electrical characteristics and wavelength (color).

indium metal compounds of lower purity that are further upgraded at specialty refineries in China, Japan, the Republic of Korea, and the United States.

The principal use of indium is in the production of flat-panel LCD televisions. The use of LEDs in backlit LCD televisions is growing, so consumption for indium in LCD televisions is expected to increase at a rate greater than the 5 percent growth rate in consumption of indium from 2009 to 2010 (Tolcin, 2011b). With the increase in the demand for indium, exploration of deposits containing high amounts of indium has become more attractive for development, supply is being increased by adding or expanding additional recovery circuits, and recovery of indium from tailings and slags and recycling of indium from flat-panel LCD televisions is also increasing. Increased demand in 2010 for precursor materials such as indium in MOCVD production led to a short-term supply shortage that year; this shortage was expected to be resolved by the end of 2011 as new capacity was expected to come into production (Cooke, 2010; Hatcher, 2010). Because LCD televisions are a relatively new consumer product and the life of an LCD television and most of its components is reported to be more than 15 years, little, if any, recycling of indium from LCD televisions occurred in 2010. Research patents have been issued for technology to recycle indium from zinc tailings and slag and to recover indium from LCD televisions.

The United Nations Environmental Programme has called for rapid improvements in the recycling rates of a group of metals that include gallium, lithium, and neodymium (United Nations Environmental Programme, 2010). The increase in demand for specialty metals, such as gallium and indium, in LED manufacturing has led to efforts to improve access to these commodities. Short-term concerns over possible gallium and indium shortages for use in critical high-technology industries contributed to Japan setting up a 42-day stockpile of gallium and indium in 2009 (Tolcin, 2011a). The Republic of Korea set up a stockpile for these elements in 2006 and may increase the stockpile by 2016 if warranted. Gallium and indium were among the 10 rare metals that the China's State Bureau of Material Reserve [China] was considering for stockpiling in 2010 (Cooke, 2010).

Based on available data, the supply of indium from 2012 through 2015 will likely be able to meet anticipated industrial demand unless China imposes additional export restrictions on these materials, which are so important to many high-technology industries.

Rare-Earth Elements

The supply chain for REEs generally consists of mining, separating, refining, alloying, and product manufacturing. As of 2010, about 97 percent of mining and concentration of rare earths, 97 percent of separation of REEs from concentrates to oxides, and almost 100 percent of the refining of oxides to metals has taken place in China (Schüler and others, 2011). REEs commonly used in LED phosphors include cerium, europium, lanthanum, terbium, and yttrium. China consumes 80 percent of the world's supply of phosphor raw materials and produces most of the phosphor powders intended for fluorescent bulbs, CFLs, and LEDs used in lighting applications (U.S. Department of Energy, 2010c). Because China is the world's primary source of REEs and has implemented a quota system that limits the export of these unprocessed materials, the future accessibility and supply of rare earths are of concern to industry and governments (Whitaker, 2011a). In an effort to increase domestic consumption of rare earths in its product manufacturing sectors, China's Government has gradually reduced the export quota from about 47,000 t of rare-earth oxide (REO) equivalent in 2000 to 22,500 t in 2010 from domestic producers and traders and 7,700 t from joint ventures of Chinese and foreign companies (Tse, 2011). In 2008, about 9,000 t of REOs was used in phosphor powders (Bade, 2010), but only a small fraction of the total production of phosphor powder is thought to have been used in LEDs. A variety of phosphors are manufactured for use in LEDs; the most common LED phosphor is yttrium aluminum garnet (YAG) doped with cerium (Setlur, 2009b; Snob, 2011). New phosphors are being developed that are less expensive, provide truer colors, and use smaller quantities of REEs. Material alternatives to rare-earth phosphors used in semiconductor applications that are presently being researched include alkali earth hydrides and nitrides, manganese-doped fluorides, or semiconductor nanocrystals (Setlur, 2009a; Erdem and Demir, 2011).

Worldwide, most REEs are located in deposits of the minerals bastnäsite and monazite. Although primary and (or) byproduct bastnäsite has been mined and (or) recovered in China and the United States and byproduct monazite has been mined from deposits in Australia, Brazil, China, India, and Malaysia, more than 95 percent of the global production of REEs in 2010 came from China from bastnäsite, monazite, xenotime ores, and ion-adsorption clay (Schüler and others, 2011). REEs have also been recovered as a byproduct of copper, gold, iron, phosphate, and uranium mining and processing. Resources of rare earths are geographically diverse, but separation of the individual rare earths from the ore requires a sequential series of concentration steps. Only a few Chinese producers have the capability to process REEs into finished materials. Concentrations of individual REEs differ from site to site. Most of the deposits of rare earths contain higher concentrations of light REEs (cerium, europium, gadolinium, lanthanum, neodymium, praseodymium, promethium, and samarium) than heavy REEs (dysprosium, erbium, holmium, lutetium, terbium, thulium, ytterbium, and yttrium). Deposits that contain significant quantities of the light rare earths cerium, europium, and lanthanum and the heavy rare earths gadolinium, lutetium, terbium, and yttrium are those that are most likely to be sources of rare earths for LED production in the near future (Goonan, 2011). Deposits in China produce light and heavy REEs; ion-adsorption clays in China produced all the heavy rare earths used in 2010.

The Molybdenum Corporation of America's (later Molycorp Inc.) Mountain Pass mine in California served as the predominant source of rare earths in the United States from 1965 to 1998. Molycorp ceased mine production in 1998 as a result of regulatory problems with the main wastewater pipeline and low prices for rare earths. The processing facility remained open for the concentration, purification, and sale of previously mined stockpiles through 2002, when processing operations were suspended (U.S. Government Accountability Office, 2010). In 2007, the mine resumed sales of stockpiled materials, and mining recommenced in December 2010. Since 1990, when the United States generated approximately 40 percent of the world's revenue of rare earths, the country has been primarily dependent on foreign sources for REEs and the products containing them (U.S. Department of Energy, 2011b). The announced acquisition of Neo Material Technologies Inc., with downstream rare earth processing facilities in China and Thailand, by Molycorp in 2012 would allow the company to again become an integrated producer of rare-earth products (Molycorp Inc., 2012).

Concerns about possible supply disruptions of rare earths have led to increased exploration for rare earths and stimulated development of several new mining and production facilities outside of China. The Mount Weld mine in Australia began production in 2011 and was expected to reach its full capacity of 10,500 t/yr of total REO equivalent in 2012. A new refinery in Malaysia with an initial annual production capacity of 11,000 t/yr of rare-earth products was under construction and was scheduled to begin production in 2012. By 2013, production of REEs in the United States is expected to reach 19,050 t/yr of REO equivalent when the Mountain Pass mine in California reaches full capacity.

The principal use of REEs in LEDs is in the phosphors used to generate the desired color. Although phosphors accounted for about 6 to 7 percent (8,000 to 9,000 t based on various estimates) of the total demand of 124,000 to 127,500 t of REE in 2010 (Kingsnorth and Cox, 2010; Lynas Corporation Limited, 2011), the total amount of REEs used in LED phosphors in 2010 was estimated to be one to two orders of magnitude lower than the amount required for other sources of lighting, such as CFLs and linear fluorescent lamps, of equivalent light output (U.S. Department of Energy, 2011c). By 2014, total consumption of rare earths used for phosphors in lighting applications is anticipated to be 11,000 to 13,000 t of REEs, still about 7 percent of total consumption of REEs (Kingsnorth and Cox, 2010). However, because of the lower REE content of LED phosphors when compared with some other lighting applications, growth of the LED industry for general lighting is likely to result in reduced consumption of REEs on a unit basis. This is one factor contributing to the increased use of LEDs in lighting (Bruce Hillman, Intematix Corp., oral commun., November 18, 2011).

In 2008, LEDs represented less than 2.4 percent of the global lighting market. However, development has led to a broader use for LEDs in this sector, and one estimate suggests that LEDs will account for about 8 percent of the lighting market in 2013 (Schüler, 2011). The effect of LED growth on REE consumption is expected to be small because LEDs use minute quantities of REEs in the phosphor compared with alternative lighting options (Hykawy and others, 2010).

Light-Emitting Diode Component and Manufacturing Supply Chain

The manufacturing process of LEDs is complex. As the industry grows, the markets change; as technology advances, the manufacturing processes change. An overview of the principal manufacturing steps and sources of key materials required for each step in the manufacturing processes currently (2011) in use are discussed below. Figure 4 summarizes the supply chain for selected byproduct raw materials, manufactured components, and assembly facilities for the LED industry.

Substrate Manufacturing

The manufacture of an LED begins with the growth of the lowest layer on which various semiconductors are grown. This base layer is called a substrate; common substrates include artificially grown sapphire, silicon carbide, and silicon. Most LEDs, particularly those intended to produce white light, use a sapphire substrate. To create the sapphire substrate, alumina is heated in a furnace to form a boule, from which a rod-shaped tube is extracted. Alumina is derived from the mineral bauxite, which is generally processed to high-purity (99.9999 percent) alumina (which in 2010 was processed primarily in Australia, Brazil, China, and India) before being shipped to substrate suppliers (Bray, 2011). Substrate production occurs primarily in Asia (about 67 percent was manufactured in China, Japan, the Republic of Korea, and Taiwan in 2007), Europe (20 percent was in France and Russia in 2007), and the United States (13 percent in 2007) (Semiconductor Today, 2008). Ultra-thin wafers (about 0.25 mm (0.01 inch) thick) ranging from 50 to 200 mm (2 to 8 inches) in diameter are sliced from the tube, polished and packaged, then shipped to customers.

Because high-purity alumina is available only from a limited number of suppliers, increased demand for high-purity alumina in 2010 resulted in a sapphire wafer shortage in 2010. This shortage lasted through 2011 when additional capacity came online. At the end of 2010, consumption (measured in terms of 2-inch-equivalent wafer units) was estimated to be 2,800 million units, while demand in 2011 was projected to be 4,200 million units (China Optical Network, 2011).

Inorganic Semiconductor Manufacturing

Component metals are melted, combined, and extruded in a rod-shaped tube that is sliced into wafers in a process similar to sapphire substrate production. Semiconductor substrates of various compositions are selected based on the wavelength of light and color of LED desired and are then manufactured and layered on the substrate. An infrared light can be produced from a GaP substrate, a GaAsP substrate can generate yellow, orange, or red light of various wavelengths, and a gallium nitride (GaN) substrate can be used to produce blue light. GaN or InGaN substrates are commonly used in white LEDs when a blue LED is combined with a yellow phosphor to generate white light.

Epitaxial Process

The method used to manufacture semiconductors by depositing a series of thin layers of various component materials on a substrate is called epitaxy. The most common technology used to deposit these layers in LED manufacturing is MOCVD, which attaches compounds such as trimethyl gallium or trimethyl aluminum to the sapphire substrate to create the GaN or InGaN precursors for the blue LED, which is used in creating LEDs that emit white light. During this sequential process, minute quantities of dopant are added to create the LED with the specific electrical characteristics and wavelength desired. Currently (2011), the primary source of dopants used in the epitaxial process is China. A single epitaxial rod can then be sliced into wafers, each wafer yielding more than 20,000 individual chips. The electrical contact pattern is then etched on the surface of each chip, and gold or silver contacts are attached.

More than 98 percent of the MOCVD equipment manufactured in 2010 was manufactured by three companies, Veeco Instruments Incorporated (United States, 63 percent of production), Aixtron SE (Germany, 28 percent), and Taiyo Nippon Sanso (Japan, 7 percent), all with manufacturing facilities in Asia (Matsumoto, 2011). Epitaxy production in 2010 took place in the Republic of Korea (31 percent), Japan (29 percent), Taiwan (16 percent), Germany (9 percent), the United States (9 percent), and China (6 percent) (Research in China, 2011). The 50-mm (2-inch)-diameter wafer is currently (2011) the preferred standard unit for LEDs, although new technological advances are making the production of larger wafers more cost effective. By 2012, 100-mm (4-inch)-diameter wafers will likely be the substrate size of choice for LEDs. Larger 150-mm (6-inch)-diameter wafers are also being developed by leading manufacturers (Business Wire, 2011; I-Mícronews, 2011a). Economies of scale make larger wafers and thus LEDs more cost competitive. A single 2-inch-diameter wafer can yield 6,000 to 20,000 chips, while a 6-inch-diameter wafer can yield more than 100,000 chips. Variation in the number of

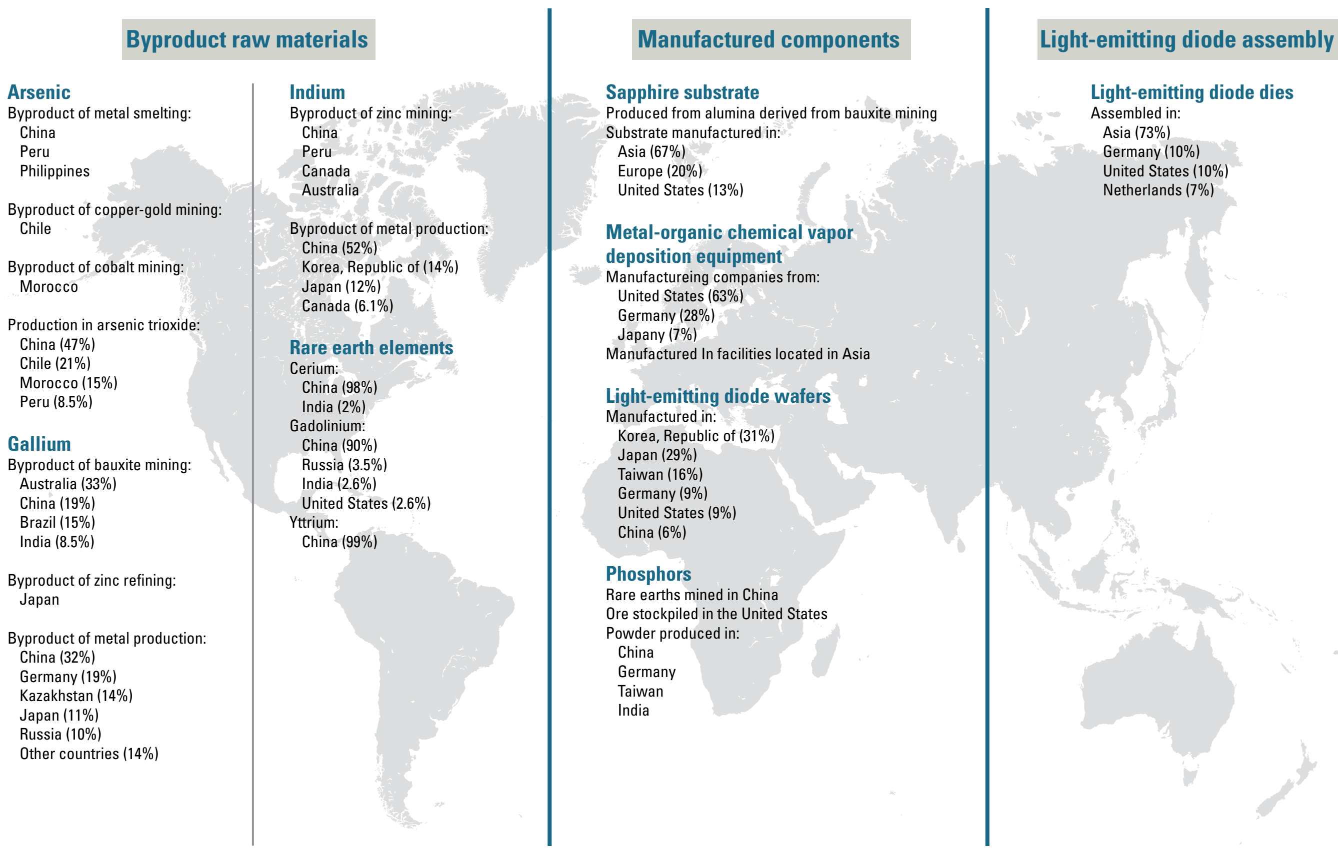

Figure 4. Supply chain for selected byproduct raw materials, key manufactured components, and assembly facilities for the light-emitting diode industry. Data are as of 2009 and are compiled from reports in the U.S. Geological Survey Minerals Yearbook series (reporting for 1995–2010) and available information from trade publications.

chips produced per wafer results from variation in chip quality and breakage rate (How Products Are Made!, 2011).

A number of chemical companies are building or increasing their MOVCD process capacity using trimethyl gallium so that, by 2012, there may be an oversupply of wafers for low-end markets (Cooke, 2010; I-Mícronews, 2011b).

Phosphor Manufacturing

The LED industry uses a wide and growing range of phosphors to convert the light from LED chips into various wavelengths as required by the end-use application. Most of the rare earths used in the manufacture of silicate and oxide powders come from China. The phosphor powders are manufactured primarily in China, Germany, Taiwan, and India. Many of the large LED manufacturers have in-house phosphor manufacturing capability or have supply agreements with small-scale phosphor manufacturers. Manufacturers use patented processes in preparing phosphors with unique compositions for the same base powder, so phosphor composition in LEDs can vary significantly. Consequently, a binning process is used to store LEDs of similar composition and light-emitting characteristics.

LED phosphor manufacturing costs are high at the initial stage of LED development for some applications because of the relatively low demand for LED phosphor powder and LEDs, economy of scale issues, difficulty in achieving a suitable color consistency, and the high cost of REEs used in many phosphors. Medium- and high-purity REEs are necessary for phosphors used in lighting applications, increasing the cost to LED manufacturers. Ores containing multiple REEs must be refined such that each REE that is produced meets the specified purity level, an expensive process that few companies are willing to undertake (U.S. Department of Energy, 2011a). The concentrated rare-earth product is usually shipped to a small number of phosphor manufacturers who further process the metals to ever higher levels of purity and (or) produce phosphor powders of various specifications. Powders are then sold to suppliers for global distribution, or LED manufacturers may create the desired phosphor in-house.

Research is ongoing to develop phosphors that use a smaller quantity of REEs per application. New nitride or silicate compositions are being tested, and phosphors substituting manganese for europium and those using lower amounts of europium are being developed to improve light quality and reduce consumption of rare earths (Setlur, 2009b).

Light-Emitting Diode Assembly and Packaging

LED assembly is completed during the packaging process by companies located in Asia (73 percent), Germany (10 percent), the United States (10 percent), and the Netherlands (7 percent). During this stage of manufacturing, the phosphor is added to the LED, LED optics and wiring are completed, the die is encapsulated in plastic resin, and the LED is packaged for shipment to customers. Packages for high-power applications are created using large single wafers or multiple smaller wafers connected in series (I-Mícronews, 2011a).

Major producers have established sources of supply for raw materials, and new consumers to the market generally rely on smaller producers for their supply of materials and components.

Market and Technology Trends

The packaged LED market is expected to increase at a 28 percent annual growth rate from 2009 through 2015. Initial growth from 2006 through 2008 was stimulated by small display applications, such as cell phones and other handheld devices. Industry growth from 2009 through 2015 will likely be driven by large LCD backlighting and automotive applications. One analyst suggests that the total LED die surface area required for LEDs used in LCD backlighting will increase from 6.3 billion square millimeters in 2009 to 51 billion square millimeters in 2015 (I-Mícronews, 2011b). Large-scale use of LEDs in general lighting applications will most likely take place after 2015. The degree and timing to which LEDs are used in the general lighting market depend on cost, public acceptance, quality, policy, and technology issues.

In 2010, more than 60 companies were involved in the manufacture of GaN-based LEDs, and additional companies began production in 2011. MOCVD tool installations in China are expected to increase from a cumulative total of 323 tools in 2010 to more than 1,000 tools by the end of 2012 (Whitaker, 2011b). The LED epitaxial manufacturing industry was expected to be consolidated by 2013, but production will likely continue primarily in China, Japan, the Republic of Korea, and Taiwan (I-Mícronews, 2011b). Dependence on Chinese rare earths for use in dopants and phosphors will probably continue in the short term; increased production of rare earths from non-Chinese sources and development of phosphors that use fewer REEs will likely reduce dependence on rare earths from China only slightly by 2015.

The DOE has established benchmarks for desired LED efficiency improvements and costs; the efficacy of cool white light bulbs containing LEDs are expected to increase from 134 lm/W in 2010 to 224 lm/W in 2015 and 258 lm/W by 2020. Similarly, the efficacy[2] of warm white light bulbs containing LEDs are targeted to increase from 96 lm/W in 2010 to 202 lm/W in 2015 and 253 lm/W by 2020. The average price of a cool white LED light bulb is targeted to decrease from $13.00 per kilolumen in 2010 to $2.00 per kilolumen in 2015 and $1.00 per kilolumen in 2020. The average price of a warm white LED lamp is targeted to decrease from $18.00 per kilolumen in 2010 to $2.20 per kilolumen in 2015 and $1.00 per kilolumen in 2020 (Wright, 2011).

[2]Efficacy refers to the amount of light produced against the power consumed to produce that amount of light.

Life Cycle Dynamics

If LEDs are to become the principal replacement for the incandescent light bulb, a number of factors must be considered when comparing LEDs with other lighting technologies. Factors include consumer acceptance; energy, material, and cost requirements; environmental and toxicity concerns; government policies and subsidies; and recycling and disposal issues. Although the LED industry is still in the early stage of growth for some applications, several studies provide information on these issues.

A study conducted by Carnegie Mellon University in 2008 suggests that the energy requirement for LED chip manufacture (excluding raw materials production and final light bulb assembly) is 0.02 to 0.08 kilowatthour (kWh) per LED chip or about 1 kWh for the entire LED module to be included in an 'average' retrofit light bulb with a life of 10,000 hours (Matthews and others, 2009). Humphreys (2008) developed estimates of the lifetime cost of ownership for various types of lighting, and key findings from this study are listed in table 1.

Unlike CFLs, lifetime estimates for LEDs are determined by estimating the useful life of an LED based on the length of time a LED maintains a specified level of its initial light output. For general lighting applications, the useful life is most often defined as the length of time it takes an LED to reach 70 percent of its initial light output (L_{70}). For other applications, a useful life of L_{50} (the length of time it takes an LED to reach 50 percent of its initial light output) is often used. When LEDs are to be used as part of a lighting fixture, the effective lifetime is based on the failure of the first component, which often may not be the LED.

LEDs do not contain any mercury, which is found in CFLs, and thus they are not regulated as a hazardous waste by the U.S. Environmental Protection Agency. Some LEDs contain minute but detectable quantities of some metals that can be treated as hazardous waste when they exceed Federal or State regulatory limits (Lim and others, 2010; European Commission, 2011).

Because LEDs are small in size and have a comparatively long lifespan, the LED waste volume is low, and few LEDs are recycled. Because of the minute metal content of individual LEDs, recycling of LEDs is unlikely; however, it is possible that LEDs contained in electronic devices and televisions could be recycled along with other electronic waste if the costs of recovering metals contained in LEDs were justified by metal prices.

Byproduct Material Requirements for Selected Light-Emitting Diode Markets

Table 2 provides rough estimates of the amounts of nine byproduct metals found in LEDs for selected market applications. Estimates for 2010 and 2014 were developed based primarily on LED compositions reported by a study conducted by the University of California, Davis (Lim and others, 2010; Julie Schoenung, University of California, Davis, oral commun., October 7, 2011). LED demand estimates were developed by McKinsey & Company, Inc. (2011) and DisplaySearch, and numerous other sources of published information (PC Electronic Components, 2009; LEDs Magazine, 2010) and personal contacts. Composition data derived from the University of California, Davis study were assumed to report minimum content levels because the T1 three-quarter-size chips analyzed in the University of California, Davis study, while widely used, are of a smaller chip size than the LEDs that are used in some applications. Values reported in table 2 should be considered as minimum approximations of the amount of the selected materials contained in LEDs because not all LED applications or phosphor combinations were considered. Compositions may differ significantly if different phosphors from those selected are used. Because a growing number of LEDs are being custom manufactured to meet customer specifications, reliable data on the exact composition of LEDs and their phosphors, such as REE variety and weight percentages, are difficult to acquire, can differ by manufacturer, and are considered proprietary information (U.S. Department of Energy, 2010c). Because an examination of the great variety of LEDs commercially available was beyond the scope of this study, estimates were developed for a limited number of LED applications using a limited set of LED and phosphor types to provide a perspective of the industry for the most common applications. Table 2 is not intended to cover the material requirements for all LED applications. Estimates should be considered to be a snapshot because LED technol-

Table 1. Selected sources of lighting for light bulbs producing a similar light intensity measured in lumens.

Light source	Light bulb lifetime, in hours	Cost of ownership[1]		Efficiency, in percent	Efficacy, in lumens per watt
		1 year	5 years		
60-watt incandescent light bulb	1,000	$18	$90	5	15
Warm compact fluorescent lamp (CFL)	13,600	$6	$28	20	60
60 lumens per watt warm white light-emitting diode (LED)	50,000	$18	$36	30	100

[1]Calculated based on the cost of purchasing specified light bulbs over the specified timeframe, costs for operating said light bulbs for 8 hours per day, and maintenance costs associated with the device. An electricity cost of $0.10 per kilowatthour was assumed. The assumed cost of an incandescent bulb is $0.50, of a CFL bulb is $2.00, and of an LED bulb is $14.00. Data are from Humphreys (2008).

Table 2. Material requirements of selected metals for selected light-emitting diode markets for 2010 and 2014.

[Does not cover the material requirements for all light-emitting diode (LED) applications, so should be considered as minimum approximations of selected material requirements. Many other small applications not included could increase LED material estimates. Estimates should be considered a series of two snapshots because LED technology is constantly changing, as are the amounts and types of constituent materials. Actual material requirements could differ significantly from these estimates because LEDs are not generic and do not have the standardized composition used in these estimates. Values are included for the LED chip and the phosphor, where appropriate, but do not include materials external to the chip such as the light assembly or LED drivers. Market data are from McKinsey & Company, Inc. (2011), and LED composition data are from Lim and others (2010). Data may not add to totals shown because of rounding. As, arsenic; Ce, cerium; Eu, europium; Ga, gallium; Gd, gadolinium; In, indium; La, lanthanum; Tb, terbium; Y, yttrium; e, estimated; —, negligible]

Application	LEDs produced[e]		Materials used in LEDs, in kilograms								
	Units, in millions	Percentage of total	As	Ce	Eu	Ga	Gd	In	La	Tb	Y
2010											
Signage	13,000	22	480	—	—	360	—	7	—	—	—
Traffic signals	2,900	5	28	43	9	25	33	1	34	12	100
General lighting	7,700	13	—	390	6	9	500	6	—	—	160
Automotive	770	1	12	32	11	19	17	1	18	7	230
Televisions	6,000	10	1	32	28	9	—	—	—	—	650
Computer monitors	1,400	3	1	8	7	4	—	1	—	—	160
Laptop computers	4,900	8	1	26	22	13	—	1	—	—	530
Handheld electronic devices	22,000	37	120	170	42	130	—	4	180	63	2,100
Total	59,000	100	640	700	130	570	550	21	230	82	3,900
2014											
Signage	18,000	12	660	—	—	500	—	9	—	—	—
Traffic signals	6,000	4	110	170	36	100	130	1	140	49	410
General lighting	65,000	42	—	3,300	50	78	4,200	52	—	—	1,300
Automotive	2,300	2	52	130	72	62	43	15	45	16	1,600
Televisions	28,000	18	1	150	130	44	—	—	—	—	3,000
Computer monitors	16,000	10	1	77	67	30	—	2	—	—	1,600
Laptop computers	14,000	8	1	75	65	30	—	2	—	—	1,500
Handheld electronic devices	22,000	5	120	170	41	130	—	4	170	62	2,100
Total	170,000	100	940	4,100	460	980	4,400	85	350	130	12,000

ogy is constantly changing, as are the amounts and types of constituent materials. Actual material requirements could differ significantly from the estimates because LED types in use are not generic and do not have the standardized composition used in these estimates. In addition, table 2 does not show the material requirements for LEDs beyond 2014 when LED consumption is expected to increase in most existing applications and to be used in new applications in the automotive and general lighting sectors.

Although the data listed in table 2 are not all inclusive, some inferences may be drawn from these estimates. First, the consumption of the nine materials selected for analysis in LED applications is very small given the billions of LEDs that are manufactured. The estimated 59 billion LEDs consumed in 2010 would require only about 3.9 t of yttrium, 0.7 t of cerium, 0.6 t each of arsenic, gallium, and gadolinium, and smaller amounts of the rare earths europium, indium, lanthanum, and terbium. Based on estimates of the projected growth of the industry, the 170 billion LED consumption in 2014 would require approximately 12 t of yttrium, 4.4 t of gadolinium, 4.1 t of cerium, 1 t of gallium, and less than 1 t of all the other materials listed in table 2. Applications that use white LEDs require very little arsenic, while applications that use red LEDs tend to require more arsenic. Most of the gallium used in LEDs is for signage and handheld electronic devices. The greatest amount of cerium used in LEDs is for general lighting applications. Yttrium used in LEDs is primarily intended for backlit televisions and handheld devices. As demand of LEDs for these sectors changes and newer LEDs and phosphors with different compositions are developed, it is likely that the distribution and quantity of these materials will change as well.

Even though billions of LEDs are produced each year, study data indicate that the total material requirement in 2010 for eight of the nine materials assessed in this study was less than 1 t for each commodity. The study showed that about 3.9 t of yttrium was consumed in the LED markets assessed in this evaluation. The amount of total REEs required for LED phosphors is small when compared with the amounts of REEs required for phosphors that are used in CFLs and other lighting types, and the distribution of rare earths in LEDs is different than the distribution of rare earths in CFLs and fluorescent lighting. These results are consistent with the estimates of Byron Capital Markets, which suggest that growth of the LED industry would have little effect on demand for rare earths (Hykawy and others, 2010). Consequently, data suggest that the available supply of these byproduct materials, including rare earths, should be able to meet the growing demand of the LED industry, at least for the next 5 years.

The latest (December 2011) survey of critical materials conducted by the U.S. Department of Energy forecasts that LED technology used in general lighting will not begin to significantly affect global REE demand until about 2017 (U.S. Department of Energy, 2011c). The consumption of materials used in LEDs consumed by the lighting sector (particularly cerium, europium, gadolinium, lanthanum, terbium, and yttrium) will likely increase after 2017.

Any LED supply shortages over the next 5 years would most likely be the result of a short-term lack of manufacturing and processing capacity or changes in supply of Chinese raw materials or manufactured products as a result of export restrictions. For 2010, China's export quota for rare earths was 22,512 t of REO-equivalent from domestic producers and traders and 7,746 t from Sino-foreign joint ventures (Tse, 2011). This represents about half the level of exports of rare earths allowed in 2000. End-use applications such as LED wafers that are produced outside of China and rely heavily on Chinese raw materials of rare earths are affected most by these quotas. However, end-use markets that use Chinese REEs but manufacture the finished product in China (such as many phosphor powders) are not affected by the Chinese restrictions, although they may be affected by tariffs imposed by some importing countries.

Summary

The light-emitting diode (LED) industry is expanding because various governments have been phasing out the use of traditional incandescent lighting in favor of more efficient lighting systems, increased monitoring of fluorescent lighting, technological improvements, and decreased cost. The longer life and reduced power consumption of some LEDs have led to annual energy savings, reduced maintenance costs, and lower emissions of carbon dioxide, sulfur dioxide, and nitrogen oxides from powerplants because of the resulting decrease in energy consumption required for lighting applications when LEDs are used to replace less-energy-efficient sources. Metals such as arsenic, gallium, indium, and the rare-earth elements (REEs) cerium, europium, gadolinium, lanthanum, terbium, and yttrium are important mineral materials used in LED semiconductor technology. Most of the world's supply of these materials is produced as byproducts from the production of aluminum, copper, lead, and zinc. The rare earths required for LED production come from China, and most LED production facilities are in Asia.

The LED manufacturing process is complex and is undergoing much change with the growth of the industry and the changes in demand patterns of associated commodities. In many respects, the continued growth of the LED industry, particularly in the general lighting sector, is tied to its ability to increase LED efficiency and color uniformity while decreasing the costs of producing, purchasing, and operating LEDs. Research is supported by governments of China, the European Union, Japan, the Republic of Korea, and the United States. Because of the volume of ongoing research in this sector, it is likely that the material requirements of future LEDs may be quite different than those of LEDs currently (2011) in use with attempts by the industry to reduce costs by reducing material requirements of expensive heavy rare-earth phosphors and increasing the sizes of wafers for economies of scale. Improved LED performance will allow customers to reduce the number of LEDs in automotive, electronic, and lighting applications, which could reduce the overall demand for material components.

Other than perhaps short-term interruptions resulting from market forces and (or) geopolitical events, significant long-term material constraints that would impede consumption of LEDs as a replacement for traditional incandescent lighting are not anticipated. Because arsenic concentration in LEDs is reportedly lower than what is required by Federal and State guidelines, arsenic in LEDs does not pose a safety hazard, and the small amount of arsenic required for LED production is not anticipated to lead to supply disruption unless regulations governing arsenic production and processing facilities in China and other producing countries are tightened, delaying production or increasing the cost of arsenic enough to impair the production of LEDs. An increase in gallium demand beyond current (2011) capacity can be satisfied by expansion of recovery circuits at existing alumina facilities or increased recycling of gallium arsenide wafers. The supply of indium is anticipated to be able to meet growing industrial demand because exploration of deposits containing high amounts of indium has become more attractive and supply is being increased by adding or expanding additional recovery circuits. Recovery of indium from tailings and slags and research on the recycling of indium from flat-panel liquid crystal display or LED-backlit televisions are showing promise. Non-Chinese sources for rare earths are being developed and are likely to be in operation in time to meet increasing demand for rare earths from the LED sector. Because most LED component production and manufacturing occurs in Asia and many LED producers have established supply contracts with Chinese producers of rare earths, a significant amount of the metallic gallium, indium, and the rare earths used for LED production will likely continue to come from Chinese sources at least for the next 5 years; however, a greater amount of these materials are now being processed in Japan, the Republic of Korea, and Taiwan. As non-Chinese sources of rare earths come into production, these new mines are likely to be sources of light REEs, but China will likely remain the leading source of supply for the heavy REEs suitable for use as LED dopants and phosphors for the next few years. Increased research in the development of phosphors that use smaller amounts of or different REEs is intended to reduce dependence on rare earths from China. Supply disruption or rare earths and other specialty metals could take place if China's specialty metal exports are redirected to domestic markets.

Because the cost of recovery is high, the lifespan for LEDs is comparatively long; thus, the LED waste volume was low in 2010, and few LEDs were recycled. The minute metal content of LEDs leads to a high cost for recovery, so recycling of LEDs outside of electronic waste is unlikely in the near term, although some LED producers are evaluating recycling options. Recycling of metals from LEDs in electronic waste is possible if the costs of recovering metals are justified by demand and metal prices.

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