CHAPTER 1

LED Lighting

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Summary

Light-emitting diodes (LEDs) are a semiconductor technology whose application to general-purpose lighting is rapidly growing, with significant potential for energy savings. LED devices perform exceptionally well in lab conditions, proving up to 10 times more efficient than incandescent lights. These impressive laboratory results can be diminished in actual use in a lighting fixture because of remaining technical and design challenges. However, LED lighting products are now available that are three to four times more energy efficient than incandescent bulbs and last up to five times longer than compact fluorescents, so far the longest-lasting lighting alternative. Several large, well established firms in the traditional lighting industry have been working to resolve performance issues related to lamp and fixture design. Yet to be resolved is the cost issue; while LED or "solid state" lighting is rapidly dropping in price, it remains several times more expensive than traditional lights.

The market for general-purpose LED lighting is currently very small, but it is growing rapidly as the technology improves and costs go down. In 2007 the global LED market was $4.6 billion, and the general lighting portion represented only an estimated 7% of these sales, behind LEDs for mobile appliances (44%), signs and displays (17%), and automotive uses (15%). Within the global lighting market, estimated at an annual $40-$100 billion—roughly one-third of which consists of light bulbs—LED-based lighting represents an even smaller portion: an estimated .01%. Still, sales of LED-based lighting products have grown 40–60% annually in recent years, and they are expected to reach $1.6 billion by 2012.

Each of the three largest players in the traditional lighting market, Philips (the Netherlands), OSRAM (Germany), and General Electric (United States), has developed a strong presence in LED lighting through joint ventures and acquisitions of specialty firms. While these traditional lighting giants have so far played a leading role, they face competition from new LED firms, especially in Japan, Taiwan, South Korea, and other Asian countries.

A key technology leader in LED lighting is Durham, North Carolina-based Cree, Inc. During the 2008 Beijing Olympics, the Bird's Nest stadium and Water Cube aquatic center were lit by 750,000 red, blue, and green LED chips manufactured in Durham by Cree. The company has experienced tremendous growth in recent years, quadrupling its work force to nearly 3,200 workers since 2002. The company holds patents on a large number of LED technology improvements. Cree continues to manufacture these innovations domestically even though other semiconductor manufacturing has largely moved overseas; this way it can protect both its intellectual property and its high quality standards, two major factors in its success. Cree's experience highlights the importance of innovation, research and development in an environment of steady job loss in U.S. manufacturing.

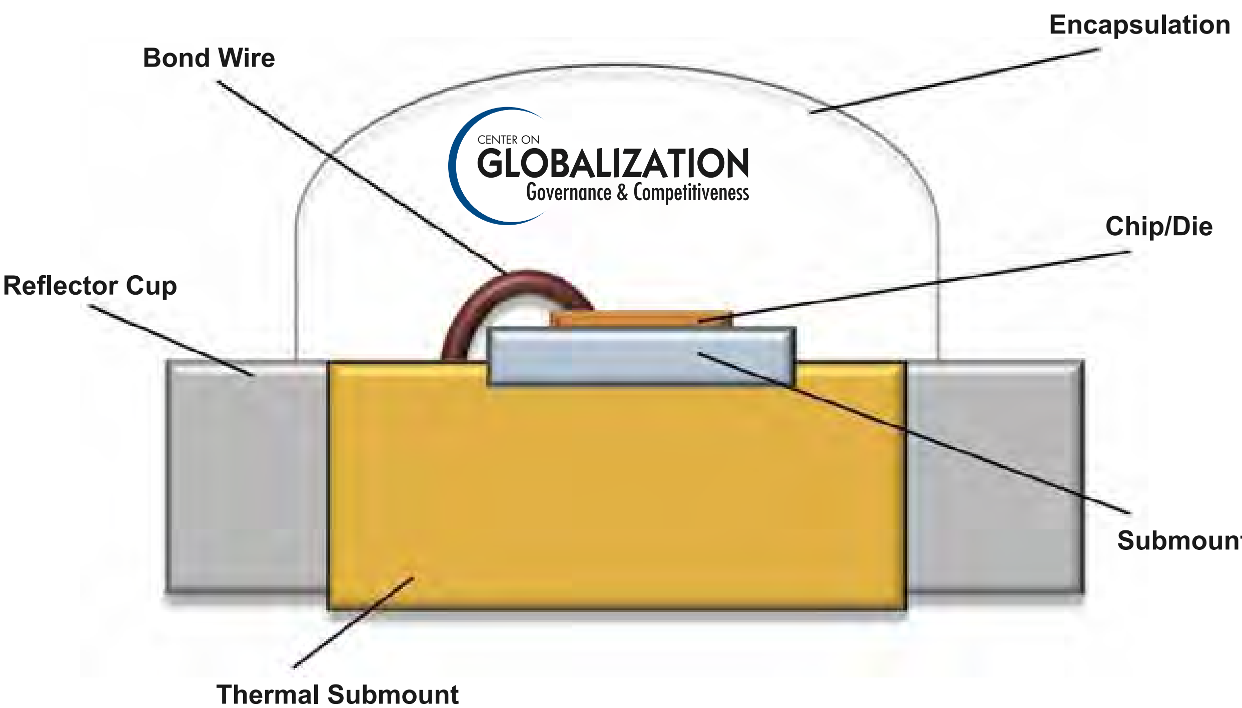
Introduction

Light-emitting diodes (LEDs) are semiconductor devices that convert electricity to light. LED lighting is also called "solid state lighting" because the light is emitted from a solid object—a block of semiconductor material—rather than from a vacuum or gas tube, as in traditional incandescent or fluorescent lights. LED technology has existed in specialized applications since the 1960s. Unlike incandescent or fluorescent lights, LEDs are not inherently white. "White" light is actually a mix of wavelengths in the visible spectrum, whereas LEDs emit light in a very narrow range of wavelengths, and so are ideal for producing colored light (U.S. DOE, 2008).

To date LEDs have been used widely to create the highly efficient red, green, and blue lights in devices including digital clocks, watches, televisions, dashboards, and traffic lights. In 1993 Japan's Nichia Corporation devised a way to create white light from a single diode. This discovery initiated the ongoing quest to develop an LED-based technology that can produce a high-quality, "warm" white light suitable for general illumination (ToolBase Services, 2008).

LED lighting technology has its own terminology distinct from traditional lighting. The light-emitting part of an LED lighting product, the chip, is a very small square of semiconductor material, (also called a die). This chip is "packaged" with several components within an epoxy dome. Unlike traditional lighting products, LED lighting does not involve a bulb. Instead, a number of LED packages are clustered in a housing to form an LED lamp. An LED lamp cannot simply be screwed into a traditional lighting fixture like an incandescent or fluorescent bulb; instead, it must be integrated into a specially designed lighting fixture, or luminaire—although the installation skills needed to install an LED luminaire are the same as for traditional lighting fixtures. A simple diagram of an LED package—the basis for an LED lamp—is shown in Figure 1-1.

Figure 1-1. Example of LED Package With Major Components



Source: CGGC, based on industry sources.

The number of solid state lighting products is growing rapidly, including recessed "downlights" (under-cabinet and ceiling fixtures from which light is directed straight downward), portable lights, lights for retail displays, and outdoor lighting for streets and parking lots (U.S. DOE, 2008a). LED lighting products have considerable potential to reduce electricity consumption and the associated greenhouse gas emissions. In lab conditions, current LED devices are up to 10 times more efficient than incandescent lights. However, while incandescent and compact fluorescent lights are measured "bare bulb," LED-based lights are measured in the fixture, or luminaire—where their efficiency is diminished because of several technical issues. Even given this difference, the best LED lighting products can be three to four times more energy efficient than incandescent bulbs, producing 45-50 lumens per watt (lm/W), compared to typical incandescents (12–15 lumens per watt) and compact fluorescent bulbs (at least 50 lumens per watt). The best solid state downlights now available produce 60 lumens per watt (Pattison, 2008).

Figure 1-2. LED Street Light and LED Indoor Lighting

Source: U.S. DOE, 2008d

Source: U.S. DOE, 2008c

Another area in which LEDs have major potential is in the product's lifespan. The devices themselves have exceptionally long life, but this can be considerably diminished in an inadequately designed fixture. Traditional fixtures are designed to take the heat generated by an incandescent bulb and radiate it outward. The heat generated by an LED must be conducted away from the device, or it will fail prematurely—but this is a significant engineering challenge, because the heat must be conducted in the opposite direction from the light output (Pattison, 2008). Nonetheless, a high-quality LED lighting product in a well-designed fixture can have a dramatically longer life span than traditional lighting, with a useful life of 30,000 to 50,000 hours under normal use, compared to 10,000 hours for comparable compact fluorescents and 1,000 hours for typical incandescent lamps (U.S. DOE, 2008a).

McKinsey & Company estimates that LED lighting in commercial applications expected to be available in 2015—along with advanced fluorescents (super T8 systems)—have the potential to reduce greenhouse gas emissions 110 million tons by the year 2030 (McKinsey & Company and Conference Board, 2007). However, the quality of currently available LED lighting products varies widely, with the poorest-performing white LEDs yielding only slightly better efficiency than incandescent lamps. Makers of LED devices are focusing on creating a high-quality, diffuse beam of white light similar to that cast by traditional incandescent, halogen, and fluorescent light bulbs, while traditional lighting manufacturers are facing a steep learning curve to accommodate LED lamps adequately in light fixture design. Still, the principal remaining issue is the cost of solid state lighting products. While dropping rapidly, the cost of LEDs is several times higher than incandescent and fluorescent lamps. Although much of this cost can be recouped in energy savings and avoided lamp replacements over the product's lifetime, the upfront cost puts off many consumers and businesses.

Meanwhile, efforts are being made to develop new standards, test procedures, and rating systems to keep up with the quickly changing market (U.S. DOE, 2008b). The U.S. Department of Energy's much-anticipated ENERGY STAR Solid-State Lighting program, a new labeling system similar to the more general set of standards for energy efficient consumer products, went into effect on September 30, 2008 (LEDs Magazine, 2008b).

The Department of Energy (DOE) has also recognized the need to support the development of solid-state lighting with a strong research and development (R&D) program. By January 2008, DOE-funded research projects had resulted in 18 solid-state lighting patents (U.S. DOE, 2008e). In FY2007 the program received $30 million in congressional appropriations, and the current value of investment contracts is $74.8 million (Wright, 2008). According to a comparison of DOE forecasts versus actual progress, the performance of LED solid-state lighting is improving much more rapidly than anticipated, and this trend is expected to continue through 2015. Analysts attribute the rapid progress in part to strong support provided by the DOE program along with intensive efforts of innovative U.S. firms, including Philips Lumileds and Cree (Wright, 2008).

LED Lighting Value Chain

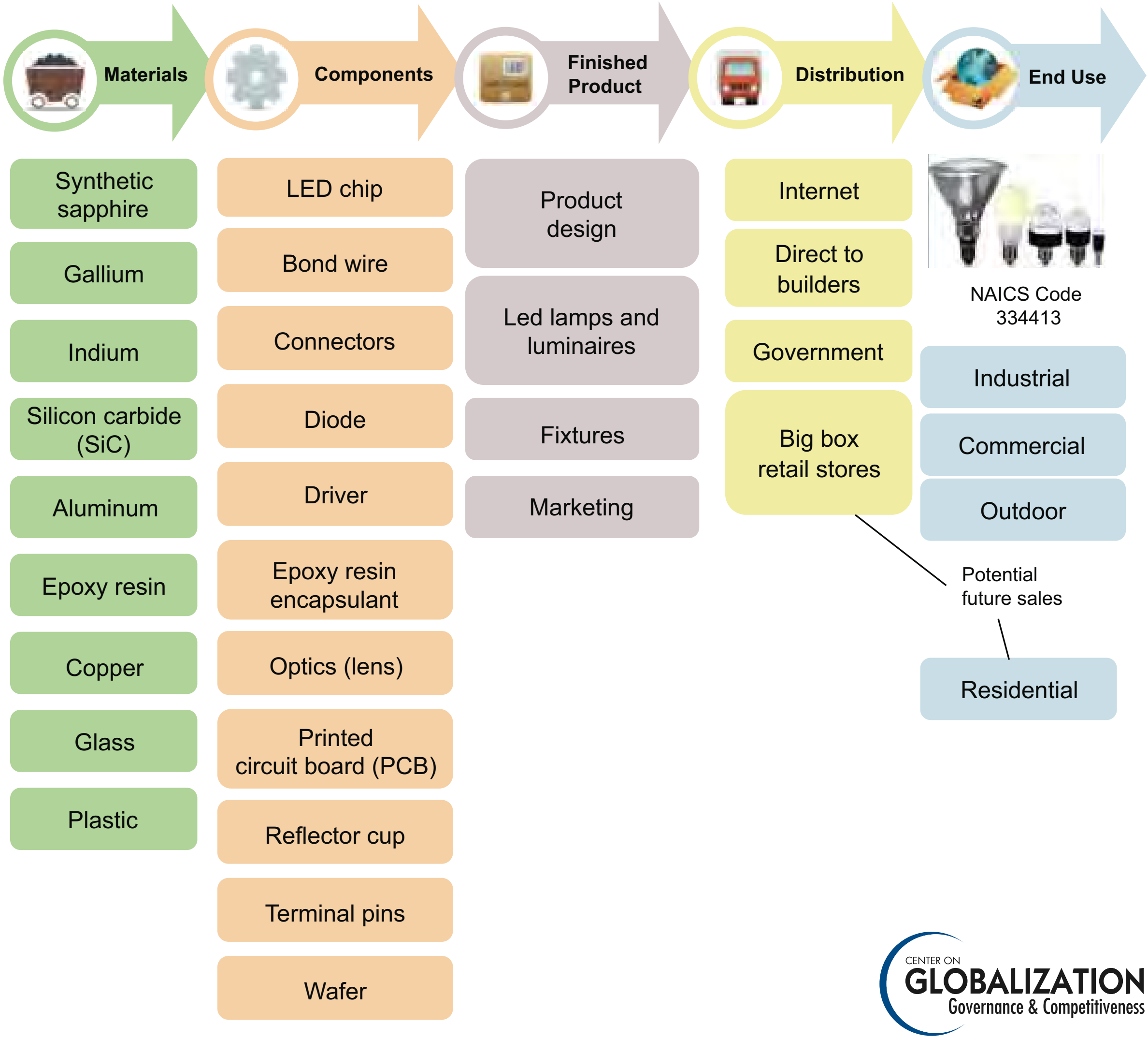
For this report we have divided the LED lighting value chain into five segments: materials, components, finished product, distribution, and final sales (see Figure 1-3). A more complete value chain with illustrative company information appears at the end of this chapter.

The major U.S. and non-U.S. firms involved in the LED lighting industry span, to varying degrees, the manufacture of LED chips, LED "lamps," and "luminaires," (fixtures), which typically integrate a number of LED lamps. Solid state lighting manufacture encompasses product design, product manufacture, and marketing and selling. Many Asian firms do the product design and manufacture for original equipment manufacturer (OEM) companies that market and sell the product under their own brand. Companies in North America and Europe, in contrast, tend to do product design, marketing and selling, but—with the notable exceptions of Cree, Philips Lumileds, and a number of smaller firms—many outsource the manufacturing to Asian subcontractors (Scheidt, 2008a).

To date, LED general-purpose lighting products have not been sold in retail stores. Instead, LED distribution has occurred primarily through Internet sales and direct sales to businesses and builders. For example, Cree has made volume shipments to significant building projects including corporate campuses, hotels, and restaurants. These large businesses find the economics of LED-based lighting increasingly compelling, especially since much of their lighting is on most or all of the time, and frequent replacement of traditional bulbs is expensive. Texas-based United Supermarkets has retrofitted refrigerated display cases in all of its 47 stores with a GE Lumination LED lighting product (GE Lumination, 2008). Recently Wal-Mart Stores Inc. decided to use LED lighting products in the refrigerators and freezers of all 4,200 of its U.S. stores, and it is now testing LED lights for store parking lots (Krieger, 2008).

Cree is also partnering with five universities, including the University of California at Santa Barbara and Tianjin Polytechnic University in China, to use LED lighting in offices, dormitories, parking garages, and other campus facilities (Cree Inc., 2008d). In another Cree-initiated program, "LED City," governments partner with industry to put LED lighting in U.S. municipal infrastructures. In the case of one participant city, Ann Arbor, Michigan, "Maintenance savings far outstrip the costs, at a 4.4-year payback" (U.S. DOE, 2008f).

Figure 1-3. Simplified LED Lighting Products Value Chain



Source: CGGC, based on company websites and interviews.

Materials and Components

LEDs are made from a variety of semiconductor materials, including different combinations of gallium, indium, arsenic, nitrogen, and phosphors. A partial list of the common compounds used appears in Figure 1-4, along with resins, plastics, and metals associated with the other major components in an LED package. LEDs do not contain mercury, a toxic substance that is found in small amounts in compact fluorescent bulbs.[1] Among the major LED materials, gallium (a mainstay of the electronics industry) is the most heavily used, especially for blue LEDs (Moskalyk, 2003). Aluminum is the most cost-effective material to recycle, suitable to be used again and again without loss of quality.

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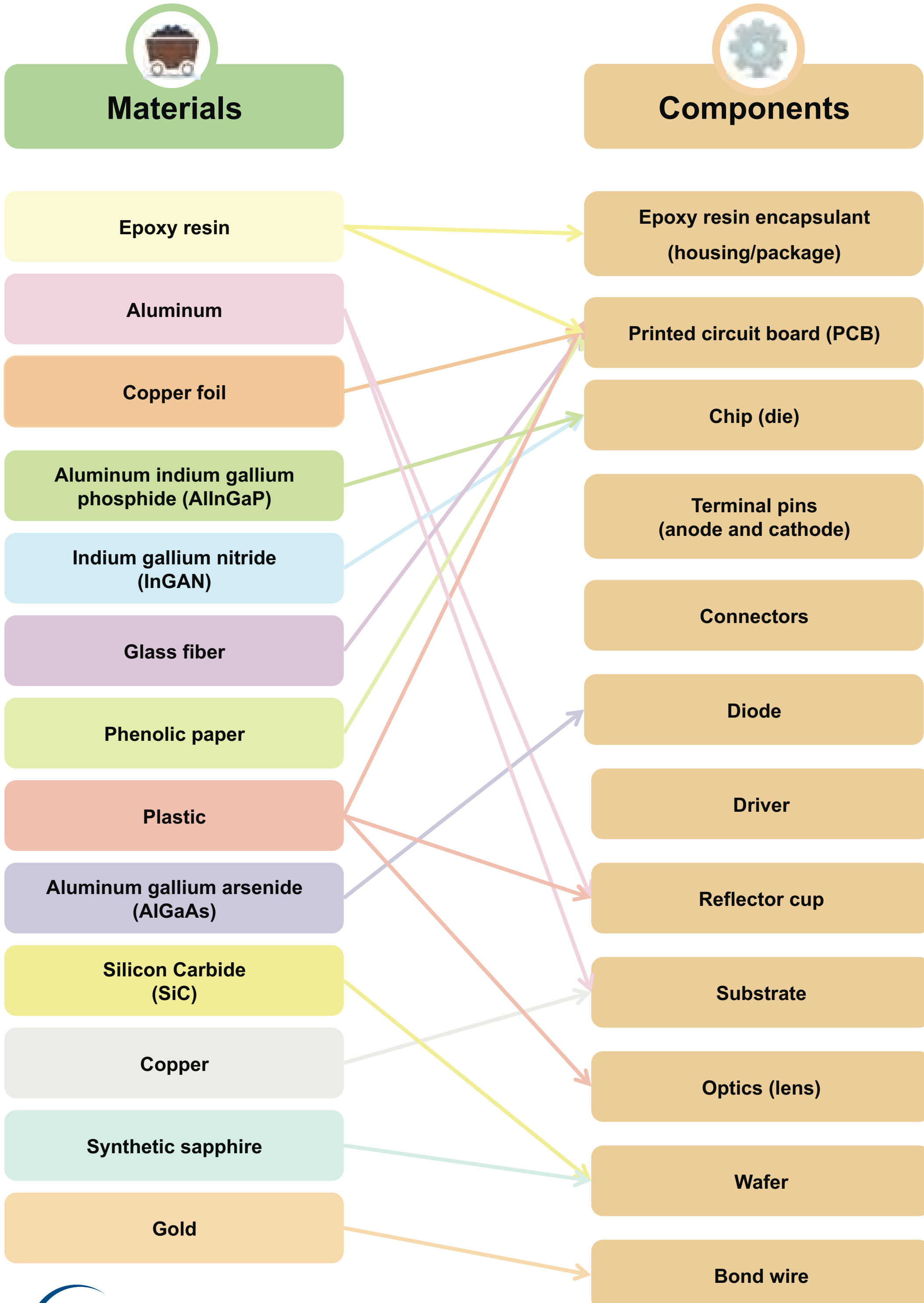
[1] Compact fluorescent bulbs contain a small amount of mercury, which can be released if the bulb is broken. However, it is important to note that efficient compact fluorescents, by saving electricity, reduce mercury emissions from coal-burning power plants. According to the Environmental Protection Agency (EPA), “if all 290 million CFLs sold in 2007 were sent to a landfill (versus recycled, as a worst case), they would add 0.13 metric tons, or 0.1%, to U.S. mercury emissions caused by humans” (U.S. DOE ENERGY STAR, 2008).

Figure 1-4. LED Package Components and Corresponding Materials*



*Not an exhaustive list.

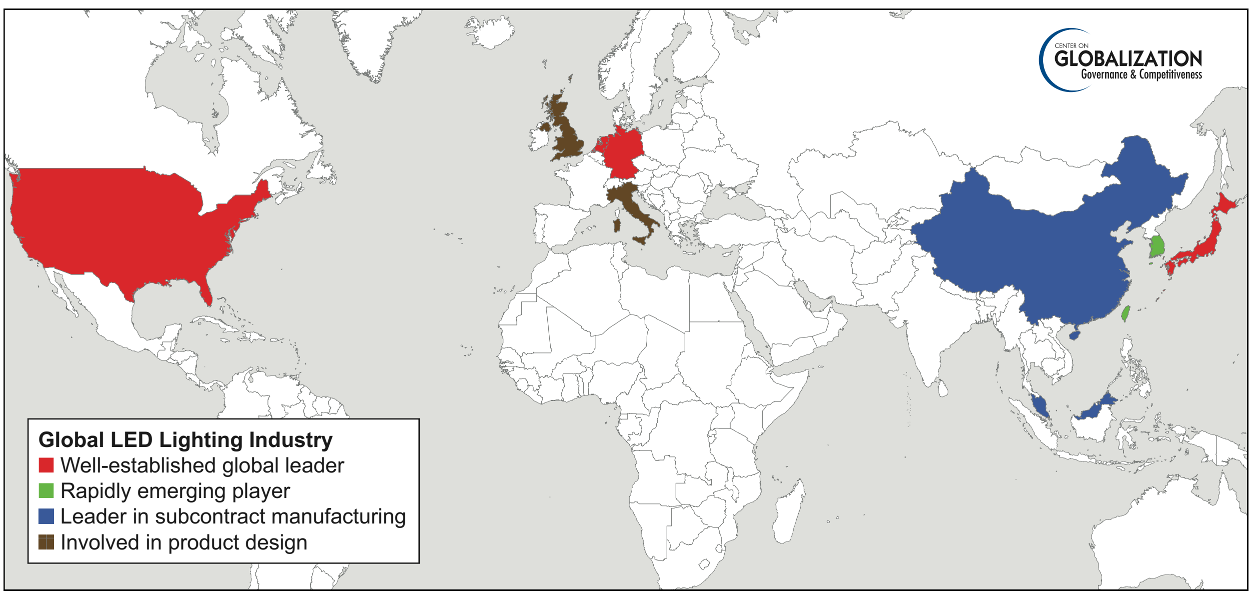
Sources: CGGC, based on company websites, interviews, LEDs Magazine, 2008a.

LED Lighting Market

The market for LEDs for general lighting purposes is currently very small, but it is growing rapidly as the technology improves and costs go down. In 2007 the global LED market was $4.6 billion, and the general lighting portion represented only an estimated 7% of these sales, behind mobile appliances (44%), signs and displays (17%), and automotive (15%) (LEDs Magazine, 2008c). Within the global lighting market, estimated at $40–$100 billion—roughly one-third of which consists of light bulbs—LED lighting represents an even smaller portion: an estimated .01% of sales (Sanderson et al., 2008). To date, commercial and outdoor applications have figured most prominently in LED lighting, ranging from retail store illumination to street lights. Residential applications are still largely under development. Still, sales of LED-based general-purpose lighting products have grown 40-60% annually in recent years, and they are expected to reach $1.6 billion by 2012 (Krieger, 2008).

Three large players have traditionally dominated the general lighting market: Philips (the Netherlands), OSRAM (Germany), and General Electric (United States). Each of these has developed a strong presence in LED lighting through joint ventures with, and acquisitions of, specialty firms. Philips, for instance, has a large facility, Lumileds, in California and is a major manufacturer of LED chips for use in the company's own packaged LED lighting products; it also sells packaged chips to other firms. OSRAM is a top manufacturer of LED components, as is General Electric, under its Ohio-based subsidiary Lumination (formerly Gelcore). While these traditional lighting giants have so far played a leading role in the LED general lighting industry, they face competition from new LED lighting firms, especially in Japan, Taiwan, Korea, and other Asian countries.[2]

Figure 1-5. Global LED Lighting Industry



Source: CGGC, based on industry sources and interviews.

An overview of the distribution of activity in the global LED lighting industry is found in Figure 1-5. Leading firms are found in Japan, the United States, and Europe (especially Germany

[2] For a thorough analysis of the development of the LED lighting industry, see Sanderson et al., 2008.

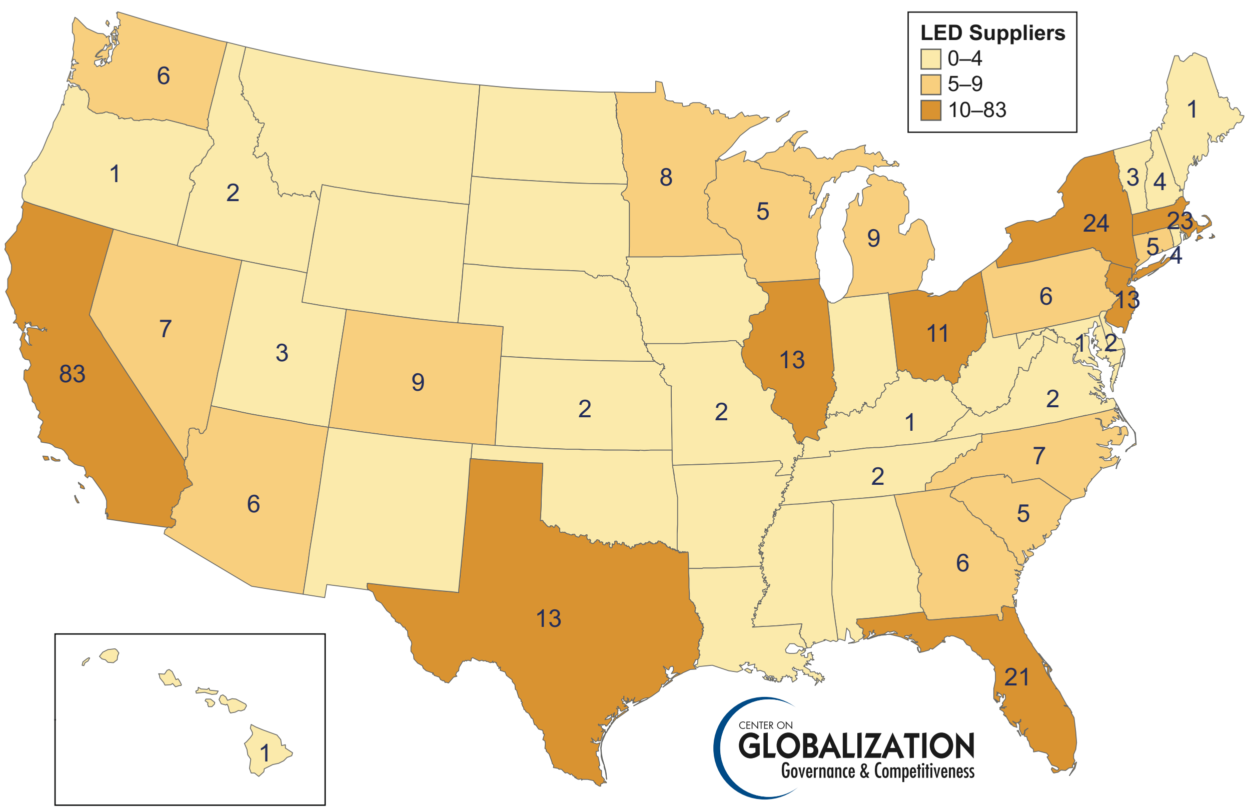
and the Netherlands). Rapidly emerging leaders are found in Taiwan and South Korea, and important players in LED product design are found in the United Kingdom and Italy (Sanderson et al., 2008). The leading country for subcontract manufacturing of LEDs is China, followed by Malaysia (Scheidt, 2008a).

Illustrative Companies

A list of important global and U.S. firms in LED lighting is found in Table 1-1. The world's leading LED firms include large suppliers that make a number of diverse semiconductor products, including LEDs. These firms include Vishay (U.S.), Toyoda Gosei (Japan), and Avago (U.S.). Other lead firms include those that focus solely on LEDs, such as the world leader, Nichia (Japan), and the top U.S. manufacturer of LEDs, Cree, Inc. in Durham, North Carolina. The LED market encompasses a large number of new entrants, especially from Taiwan, many of which are specialty firms that keep costs down by specializing in one part of the value chain (Sanderson et al., 2008).

The geographic distribution of U.S. LED supplier firms is found in Figure 1-6. These firms are spread throughout the United States, with the highest concentration of components and fixture involvement in California. Additional leading chip and component supplier firms are concentrated in North Carolina, Illinois, and Michigan. Small firms with roles in LED lighting, especially fixtures, are geographically dispersed.

Figure 1-6. 311 U.S. LED Supplier Firms, 2008



Source: CGGC, based on LEDs Magazine, LED Suppliers Directory 2008.

Table 1-1. LED Lighting: Illustrative Global and U.S. Firms[3]

Company	State/Country	Total Employees	Sales (USD mil)	Manufacturer Type
Toyoda Gosei	*Japan*	*27,036*	*$6,612.0*	LED Chips
Nichia Corporation	*Japan*	*4,600*	*n/a*	
OSRAM Opto Semiconductors	CA, *Germany*	*3,500*	*$621.2*	
Veeco	NY	1,216	$403.0	
Epistar Corporation	*Taiwan*	*3,207*	*$310.7*	
Cree	NC	3,168	$394.1	
Seoul Semiconductor	*S Korea*	*984*	*$284.2*	
Philips Lumileds	CA, *Netherlands*	300	$75.0	
Seikoh Giken	*Japan*	*853*	*$62.5*	
BridgeLux	CA	13	$3.0	
KLA-Tencor	CA	6,000	$2.7	
SemiLEDs	*Taiwan,* ID	*n/a*	*n/a*	
Toyoda Gosei	*Japan*	*25,360*	*$5,796.0*	LED Components
Everlight Electronics	*Taiwan*	*2,768*	*$309.0*	
Nichia Corporation	*Japan*	*4,600*	*n/a*	
OSRAM Opto Semiconductors	CA, *Germany*	*3,500*	*$621.2*	
Cree	NC	3,168	$394.1	
Dow Corning Corporation	MI	1,281	$2,205.0	
Supertex	CA	410	$83.0	
Power Integrations	CA	385	$191.0	
Edison Opto Corporation	*Taiwan*	*304*	*$16.8*	
Philips Lumileds	CA, *Netherlands*	300	$75.0	
Rubicon Technology	IL	144	$34.1	
GE Lumination (Formerly Gelcore)	OH	84	$15.0	
CAO Group	UT	50	$38.0	
Luminus Devices	MA	4	$1.5	
Gentex	MI	2,718	$653.0	LED Lighting Products and Fixtures
Cree	NC	3,168	$394.1	
American Opto Plus LED	CA	1,000	$450.0	
Teledyne Technologies Inc.	CA	8,130	$1,622.3	
Philips Lumileds	CA, *Netherlands*	300	$75.0	
LEDtronics	CA	300	$40.0	

[3] Please note that this is not an exhaustive or definitive list, nor is it a ranking of companies.

Company	State/Country	Total Employees	Sales (USD mil)	Manufacturer Type
GE Lumination (Formerly Gelcore)	OH	230	$6.0	
CAO Group	OH	84	$15.0	
Opto Technology	IL	50	$38.0	
Agilight	IL	29	$6.0	
Philips Color Kinetics**	MA	168	$65.0	
American Bright (subsidiary of Bright LED, Taiwan)	CA	15	$65.0	
Lighting Science Group	TX	70	$2.8	
LSI Industries	OH	1,400	$305.3	
Lynk Labs	IL	3	$2.0	

Source: CGGC, based on OneSource, ReferenceUSA, company annual reports, industry sources and interviews.

**Philips acquired Color Kinetics in 2007, changed the name to Solid State Lighting Solutions, and subsequently renamed the company Philips Color Kinetics (Hamilton, 2008).

Italicized firms are non-U.S. firms. Note: This table includes firms for which LED-related production may or may not be the main activity.

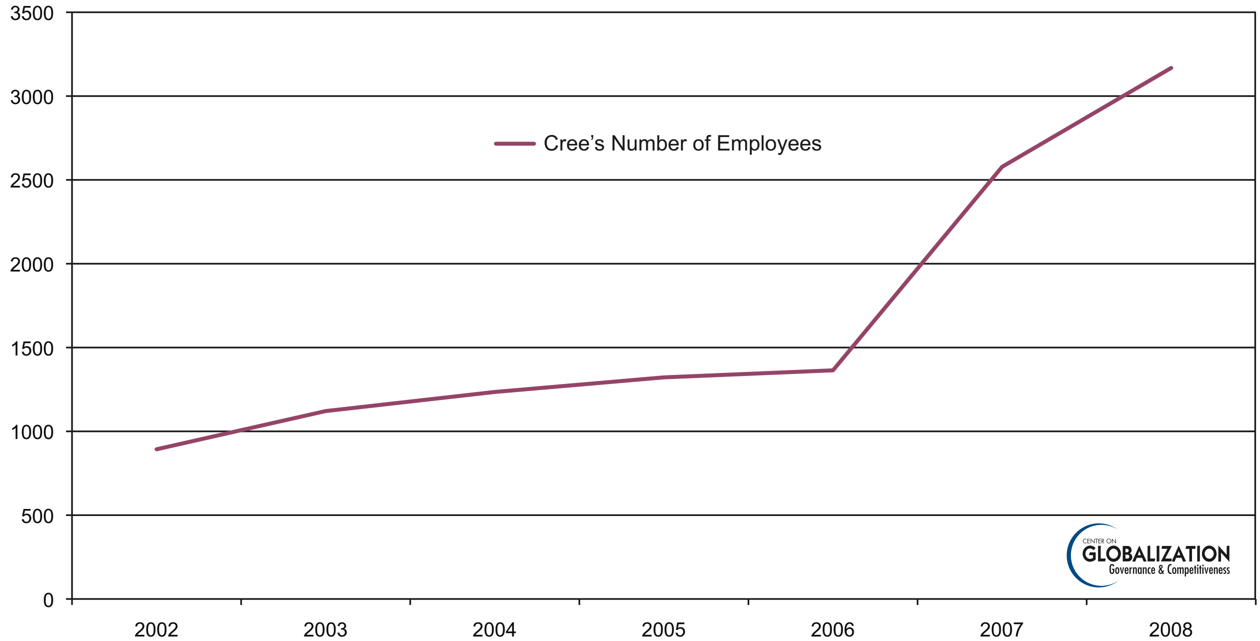
Case Study: A North Carolina LED Company Lights the Beijing Olympics

The U.S. leader in LED lighting is the Durham, North Carolina-based semiconductor company Cree, Inc. The company was founded in 1987 and introduced the first blue LED in 1989. Cree's major product families include a broad range of efficient blue and green LED chips; semiconductor materials for advanced electronic and opto-electronic devices; packaged LED lamps for many applications including general illumination; LED luminaires, or fixtures for commercial applications such as downlights used in corporate campuses, hotels, and restaurants; high brightness LEDs; power-switching devices; and radio-frequency/wireless devices (Cree Inc., 2008c).

Cree has experienced tremendous growth in recent years, improving LED technology and working with other companies to apply LED chips and lighting in new ways. The company's revenue grew from $228 million in 2003 to $493 million in FY2008 (Scheidt, 2008b). Cree has collaborative relationships with Asian LED manufacturers such as Kingbright Electronic Company in Taiwan and Seoul Semiconductor Company in Korea. Many of the company's LED products are distributed in Japan by the Sumitomo Corporation. Cree recently acquired LED Light Fixtures, Inc., and Intrinsic Semiconductor Corporation, increasing its overall share of the U.S. market (Cree Inc., 2002-2008). In October 2008 Cree announced a long-term strategic agreement with the Austrian Zumtobel Group, a global market leader in professional lighting, to sell LED downlights to the European market (Cree Inc., 2008a).

The experience of Cree highlights the importance of innovation and research and development in an environment of slow but steady job loss in the U.S. semiconductor manufacturing industry. Cree holds patents on a large number of LED technology improvements, and as demand for its innovative products has increased, the company's work force has nearly quadrupled, from 893 people in 2002, to 3,168 regular full and part-time employees in 2008 (see Figure 1-7). In the 2008 Beijing Olympics, the Bird's Nest stadium and Water Cube aquatic center were lit by 750,000 red, blue, and green LED chips manufactured in Durham by Cree (Wolf, 2008).

Figure 1-7. Cree, Inc. Employees, 2002–2008



Source: CGGC, based on Cree, Inc. 2002, 2003, 2004, 2005, 2006, 2007, and 2008 Annual Reports.

Table 1-2. Cree, Inc., Selected Milestones

1980s	
July 1987	Cree founded
August 1989	Introduced first blue LED
1991	
October	Released world's first commercial SiC wafers
2001	
November	Announced blue laser lifetimes in excess of 1,000 hours
2005	
February	Achieved standard LED efficiency of 100 lumens/watt in R&D
June	Introduced MegaBright 290 Gen 2 LED Product
2006	
June	Demonstrated a 131-lumens/watt white LED
August	Introduced EZBright1000 LED power chip for general lighting applications
October	Delivered the XLamp XR-E Series LED, the first 160-lumen white power LED

2007	
March	Expanded the XLamp XR-E and XR-C series of LEDs with warm white color temperatures
April	Acquired COTCO Luminant Device Ltd. of Hong Kong
September	Achieved 1,000 lumens from a single LED
2008	
March	Acquired LED Lighting Fixtures, Inc., expanding Cree's opportunities in the general-purpose lighting market
April	International House of Pancakes (IHOP) franchise in Northern Virginia adopts Cree LED lighting products as the preferred lighting for all existing and future restaurants
May	Volume shipments of recessed LED down lights for significant projects, including corporate campuses, full-service hotels, and global restaurant chains

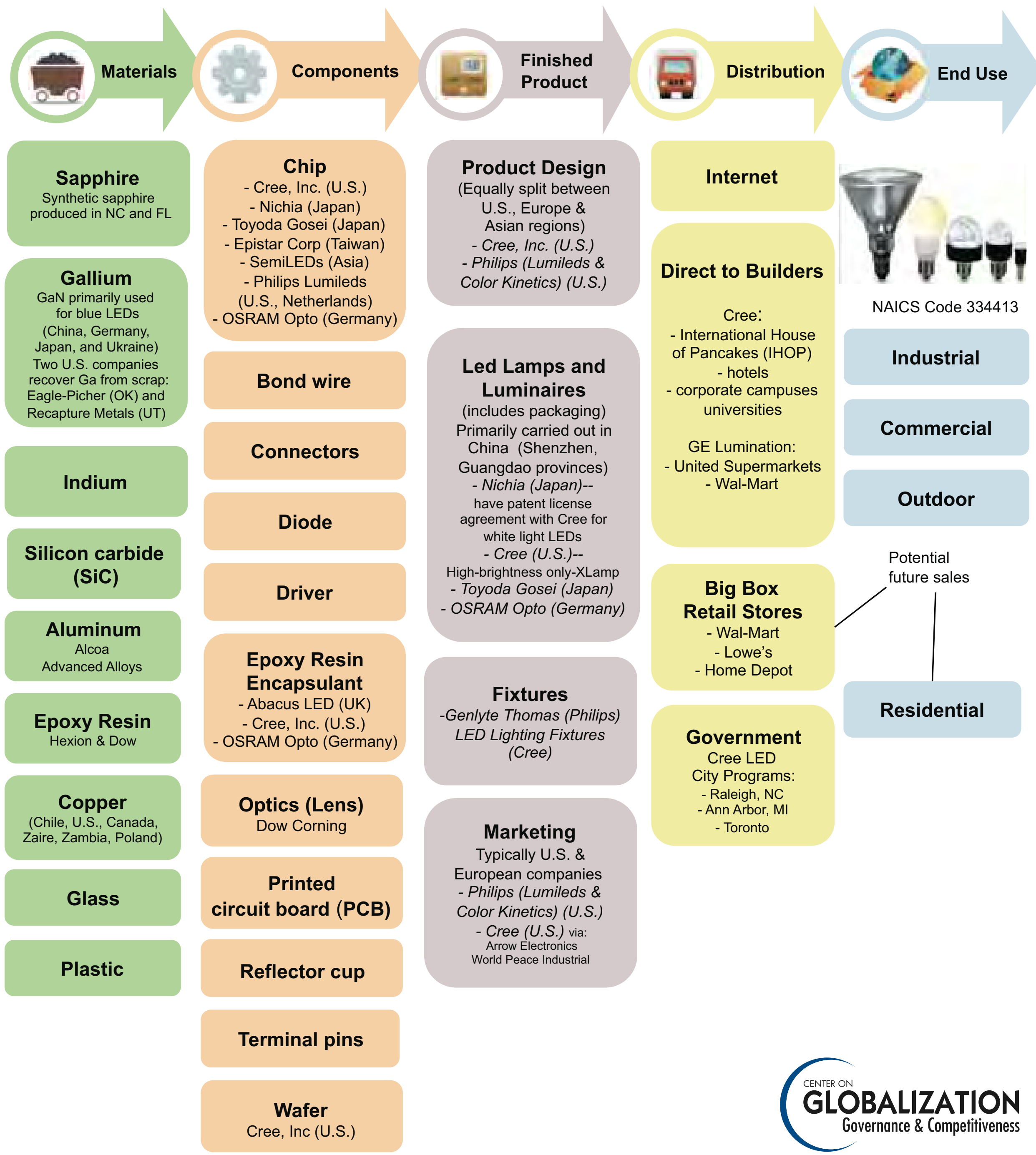
Source: Partial list of company milestones adapted from Cree Inc., 2008b

Conclusion

LED lighting products occupy a small but fast-growing segment of the global lighting industry. LED technology belongs to the semiconductor industry, in which much of the manufacturing occurs in Asia. However, U.S. firms can play a crucial role in developing and manufacturing the next generation of LED lighting products. Many LED products, especially the vital LED chips, rely on breakthrough technologies and require particularly high quality standards, indicating a preference for manufacturing close to home. This is important in today's global economy, where, as each new technology eventually stabilizes and the scale of production expands, the manufacturing base often moves to less expensive, mass operations overseas. The U.S. DOE has served a vital function by supporting U.S. research and development and by establishing labeling and standards. According to Morgan Pattison, a technology consultant to the DOE Solid State Lighting Research program, the vital question is, "Will the quality domestic and Japanese manufacturers of high-brightness LEDs be able to bring costs down before the lower-end manufacturers in Taiwan and China can bring performance up?" (Pattison, 2008).

Perhaps a piece of the answer lies in the experience of North Carolina-based Cree, Inc., which has become a global leader in high-quality, high-brightness LEDs, rolling out frequent innovations and continuing to manufacture domestically. Cree's success in this environment highlights an important link between innovation and the continued viability of U.S. manufacturing jobs.

Figure 1-8. LED Lighting Value Chain, with Illustrative Companies



Source: CGGC, based on company websites, interviews, industry sources, and Sanderson et al., 2008.

References

Cree Inc. (2002-2008). *Annual Reports*.

---. (2008a). Cree and Zumtobel Announce Strategic Agreement for LED Downlights in Europe. Retrieved October 10, 2008, from http://www.cree.com/press/press_detail.asp?i=1223469799504

---. (2008b). Major Business and Product Milestones. Retrieved October 10, 2008, from http://www.cree.com/press/pressreleases.asp?y=2008

---. (2008c). Cree Products. Retrieved June 3, 2008, from http://www.cree.com/products/index.asp

---. (2008d). Universities Switch to LED Lighting to Help Save Energy, Reduce Costs and Protect the Environment. *Press Room*. Retrieved April 8, 2008, from http://www.cree.com/press/press_detail.asp?i=1208871738420

GE Lumination. (2008). Texas-Sized Savings: United Supermarkets uses GE Lumination LED Refrigerated Display Lighting to slash energy costs. Retrieved September 26, 2008 from http://www.geconsumerproducts.com/pressroom/press_releases/lighting/led_lighting/unitedsupermkt.htm

Hamilton, Thomas. (2008). Product Marketing Manager, Philips Color Kinetics. Personal communication with CGGC research staff. October 9.

Krieger, Sari. (2008, September 15). Bright Future: Thanks to improved technology, LEDs may be ready to take off. *Wall Street Journal*. Retrieved October 8, 2008, from http://online.wsj.com/article/SB122123942429828649.html?mod=googlenews_wsj

LEDs Magazine. (2008a). 2008 LED Suppliers Directory. *LEDs Magazine*.

---. (2008b). ENERGY STAR Solid-State Lighting program is now effective, *September*.

---. (2008c). LED Market Growth Predicted to Exceed 20% Over Next Five Years. *LEDs Magazine, April*.

McKinsey & Company and Conference Board. (2007). *Reducing US Greenhouse Gas Emissions: How Much at What Cost?*

Moskalyk, R.R. (2003). Gallium: the backbone of the electronics industry. *Minerals Engineering, 16*(10).

Norton, Frank. (2008, April 23). Cree Revenue Jumps, but Expenses Hit Profits. *Raleigh News & Observer*. Retrieved June 18, 2008, from http://www.newsobserver.com/business/story/1046861.html

Pattison, Morgan. (2008). President, Solid State Lighting Services, Inc. Personal communication with CGGC research staff. October 13-14, 2008.

Sanderson, Susan Walsh, Simons, Kenneth L.; Walls, Judith L.; and Lai, Yin-Yi. (2008). *Lighting Industry: Structure and Technology in the Transition to Solid State*. Paper presented at the Alfred P. Sloan Foundation Industry Studies Annual Conference 2008.

Scheidt, Paul. (2008a). Product Marketing Manager, Cree Inc. Personal communication with CGGC research staff. May 29, 2008.

---. (2008b). Product Marketing Manager, Cree Inc. Personal communication with CGGC research staff. September 16, 2008.

ToolBase Services. (2008). LED Lighting. *NAHB Research Center*. Retrieved April 8, 2008, from http://www.toolbase.org/Technology-Inventory/Electrical-Electronics/white-LED-lighting

US DOE. (2008). Color Quality of White LEDs. Retrieved October 3, 2008, from http://www.netl.doe.gov/ssl/PDFs/ColorQualityofWhiteLEDs.pdf

---. (2008a). LED Basics. *Building Technologies Program*. Retrieved October 9, 2008, from http://www.netl.doe.gov/ssl/PDFs/LEDBasics.pdf

---. (2008b). LED Luminaire Reliability. *Building Technologies Program*. Retrieved October 2, 2008, from http://www.netl.doe.gov/ssl/PDFs/LuminaireReliability.pdf

---. (2008c) Karney, Richard. Review of the ENERGY STAR Solid State Lighting Luminaire Criteria. Retrieved October 15, 2008 from http://www.netl.doe.gov/ssl/PDFs/energy_star/KarneyENERGYSTAR08.pdf

---. (2008d). Solid State Lighting. *Building Technologies Program*. Retrieved October 2, 2008, from http://www.netl.doe.gov/ssl/technetwork.htm

---. (2008e). Solid-State Lighting Patents Submitted as a Result of DOE-Funded Projects. *DOE Solid-State Lighting Portfolio*. Retrieved October 10, 2008, from http://www.netl.doe.gov/ssl/PDFs/Materials_2008/Patents_08FS.pdf

---. (2008f, January 29-31, 2008). *Transformations in Lighting: 2008.* Paper presented at the SSL R&D Workshop, Atlanta, GA.

US DOE ENERGY STAR. (2008). Frequently Asked Questions: Information on Compact Fluorescent Light Bulbs (CFLs) and Mercury. Retrieved October 9, 2008, from http://www.energystar.gov/ia/partners/promotions/change_light/downloads/Fact_Sheet_Mercury.pdf

Wolf, Alan M. (2008, August 8). Cree LEDs are Stars of Show. *News & Observer*. Retrieved October 10, 2008, from http://www.newsobserver.com/business/story/1169019.html

Wright, Phillip. (2008). DOE Brightens Trend on Solid State Lighting. Retrieved February 25, 2008, from http://wrtassoc.com/category/green-technology/