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INTRODUCTION

Once a symbol of Edison's creative genius and the prowess of American innovation, the incandescent light bulb represents a mature technology, now mastered by new competitors and imported at pennies apiece from China. Lamp (the industry name for a light bulb) manufacturing was dominated for decades by a few firms, notably Philips, OSRAM, and General Electric (GE). Related industry segments have typically been more fragmented, with thousands of firms producing fixtures ranging from simple sconces to elaborate chandeliers. Increasingly both lamp and fixture manufacturing have been shifting to offshore locations, primarily in Asia.

Not only are North American and European lamp and fixture companies under the threat from low-cost imports, but solid-state lighting, a semiconductor- instead of bulb-based technology with greater potential energy efficiency and new capabilities, is poised to revolutionize the industry and change how we understand and use lighting—a change that will affect both traditional lamp and fixture producers. Solid-state lighting is challenging incumbents and throwing leadership in the future industry up for grabs. As innovative products composed of light emitting diodes (LEDs) are developed, new features like colors that change on command are expanding architectural possibilities. Other opportunities come from the convergence of lighting, information, and display technologies. In fiber optics light is data, and ordinary flat panel indoor lighting can serve as data transfer hubs, sending information to computers and appliances. Edison's lamp, and its successors, may soon be replaced with glowing ceiling panels or even lighting-enhanced wallpaper that changes patterns on command.

Which firms will successfully ride this new wave of innovation and what impact these changes will have on incumbents is not yet determined. Although the first wave of lighting innovation in the early 20th century spawned the development of global companies like GE, OSRAM, and Philips, these 21st-century innovations will create challenges for incumbents. New firms are emerging at all levels of the value chain to address the opportunity presented by solid-state lighting technologies.

In this chapter we contrast traditional lighting technologies with LED technologies. Traditional lighting technologies we define as incandescent, gas-discharge, and electric arc lighting (which includes fluorescent, high-intensity discharge, mercury and sodium vapor, metal halide, and neon lamps). We exclude lighting technologies such as chemiluminescence that yield insufficient light for illumination (such lights can be seen but not seen by). LED technologies (including organic and polymer LEDs) are the only nontraditional technology considered because LEDs are the only alternative lighting approach that has reached sufficient maturity to be considered commercially viable in the trade, technology, and technical literatures.

This chapter analyzes changes in lighting technology over the past two decades and its implications for U.S. industry competitiveness. We explore whether the rise of global competition is limited to low-cost manufacturing or whether strategic centers of decision making and research are moving away from the regions and firms that once dominated the industry. We examine the causes of these changes and what aspects of innovation in lighting, particularly in the arena of research and development (R&D), have changed since the 1990s. We speculate about the implications of these changes for firm strategy in the new era of intense global competition, we analyze how national policies have affected the development and diffusion of traditional and new lighting technologies, and we explore how public policy can best address the challenges and opportunities offered by solid-state lighting to aid countries in their struggles to conserve energy and reduce global warming.

We are entering an era of faster-paced competition as the lighting industry, which has been dominated by a few firms (at least in the lamp sector), faces competition from new technologies, firms, and regions. Asian firms, as well as firms headquartered in the United States and Europe, have performed strongly in patent invention for solid-state lighting and are making key contributions to these new technologies. Both new firms and incumbents are investing heavily in solid-state lighting technologies, and it remains to be seen which firms will predominate.

Public policy will likely play an important role in future developments by stimulating demand for energy-saving lighting, providing funding for R&D, and incubating startup companies as they seek to commercialize these new technologies. But retail firms like Wal-Mart are increasingly playing a role in the diffusion of energy-saving lighting technologies. We compare the policies of countries supporting development and diffusion of new lighting technologies and speculate about how these efforts may affect the location of R&D, manufacturing, and headquarters of surviving lighting producers.

EVOLUTION OF THE LIGHTING INDUSTRY

Globalization of Lighting Production

The global lighting market in 2004 was worth some $40 to $100 billion, about one-third of which represented lamps.[1] U.S. apparent consumption of lamps, fixtures, and other equipment totaled about $14.8 billion in 2004.[2] U.S. production of lamps grew steadily until the early

[1] Hadley et al. (2004) cite the figure of $40 billion, one-third of which represents lamps, but publicly available estimates of the size of the global lighting industry vary greatly, and the firm Color Kinetics in a communication with us cites the figure of $100 billion based on data from Fredonia Marketing Research.
[2] Apparent consumption equals U.S. production plus imports less exports, where U.S. production is measured as value of shipments from Bureau of Economic Analysis data, and import and export data are from the U.S. International Trade Commission.

1970s, then fluctuated over the next 20 years, stabilized during the 1990s at about 1970 levels, and finally fell somewhat at the start of the 21st century, as shown in Figure 1.

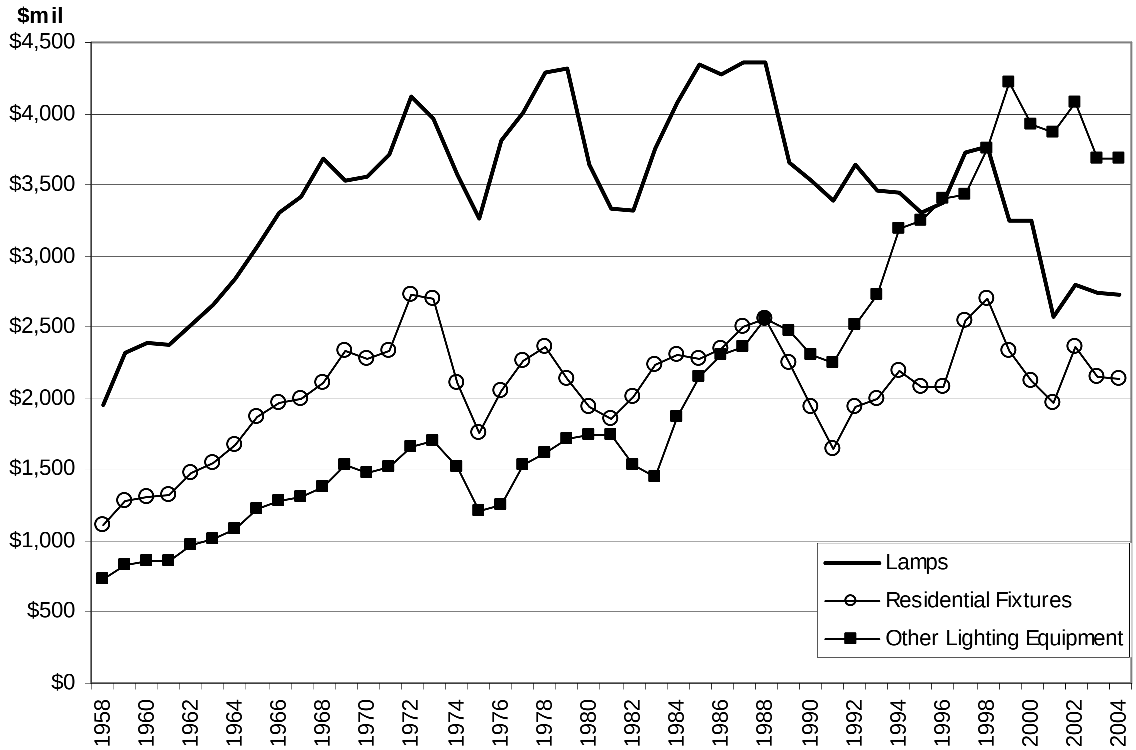

FIGURE 1**.** U.S. shipments of lighting products (real 2004 values)**.** SOURCES: Shipment values**:** National Bureau of Economic Research (1958-1996), U.S. Department of Commerce, Bureau of the Census (1997-2001), Bureau of Economic Analysis (2002-2004). Producer Price Index from the Bureau of Labor Statistics.

The eventual leveling off and downturn in U.S. lamp production in the 1990s can be explained, in part, by a steady increase in imports over the past two decades. Total imports, as a percentage of U.S. apparent consumption, increased from less than 20 percent in 1989 to around 50 percent in 2004, as shown in Figure 2.[3]

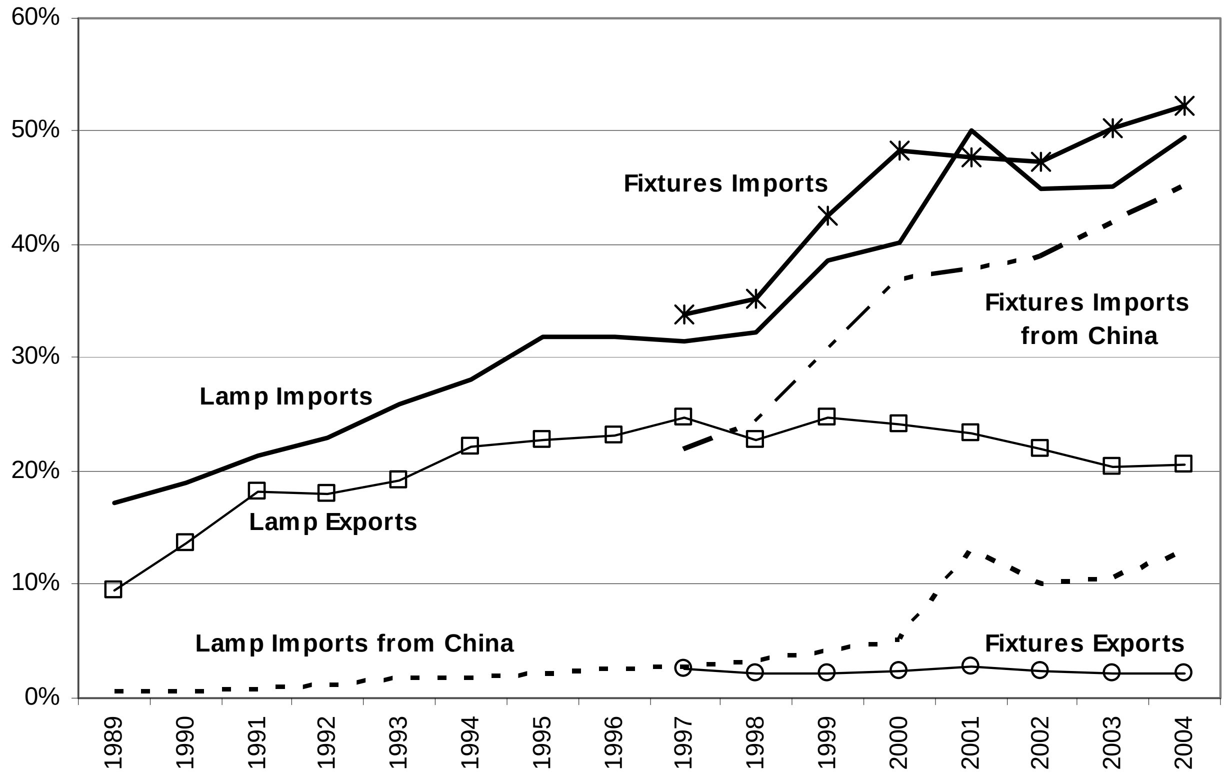

FIGURE 2. U.S. imports and exports of lamps and fixtures, total and imports from China, as percentages of U.S. consumption**.** SOURCE: U.S. International Trade Commission.

About half of the imports come from China, Mexico, and Japan, with China representing the largest share as of 2004. In 1989, less than 3 percent of lamps were imported from China. By 2004, Chinese lamp imports represented 26 percent of all lamp imports, having grown more rapidly than imports from any other supplier nation, and 10 percent of apparent lamp

[3] Not shown in Figure 2 is an additional trade category "Other Lighting Equipment," for which imports increased from 38 percent in 1989 to 57 percent in 2004, with China's share of imports growing from 24 percent in 1996 to 32 percent in 2004.

consumption in the United States. Once concentrated in the hands of three large manufacturers, the incandescent bulb industry has new competitors, primarily low-cost manufacturers in Asia.

In the fixtures industry, broken down in Figure 2, these trends are more intense, with 86 percent of all fixtures imports in the United States arriving from China by 2004. Increased fixture imports are the result of both incursion of lower-cost Chinese manufacturers and shifting production abroad by U.S. firms that seek lower-cost manufacturing sites. An exception to this trend is Genlyte Thomas, the largest lighting fixture and control company in North America, which manufactures 70 percent of its products in the North American region in order to keep close to its design centers and customers (Genlyte Thomas, 2005). Genlyte Thomas is introducing new energy-efficient light fixtures using compact fluorescent (CFL), high-intensity discharge (HID), and LED lamps and is conducting research on solid-state lighting to remain the premier fixtures company while the industry transitions to new lighting technologies.

The remaining area of growth for U.S. lighting production in the 1990s was in specialty lighting applications, such as Christmas decorations, underwater lighting, and infrared and ultraviolet (UV) lamps. This sector grew steadily throughout the second half of the 20th century and, as Figure 1 reveals, has surpassed the production value of lamps and of residential fixtures.[4]

Big Three Lamp Producers

While there are hundreds of small lamp producers, which usually specialize in one type of lamp, the global lamp market is dominated by three big players: Koninklijke Philips Electronics (Philips), OSRAM-Sylvania (OSRAM), and GE.[5] All three firms produce a wide

[4] Figures 1 and 2 use the definition of traditional lighting, as defined in the beginning of this article, for “lamps” based on SIC (3641, 3648) and NAICS (33511, 335129), which includes all traditional lamp types including (regular and compact) fluorescent and HID lamps, but excludes LED lamps.
[5] That most lamp producers specialize on a single type of lamp is apparent from industry directories such as www.lightsearch.com.

spectrum of lamps based on distinct technologies for most major commercial and residential markets. Philips has the largest global market share in lamps, and GE has the largest U.S. market share (Mintel, 2003).[6]

In the United States, GE has been a dominant player in lighting since the industry's inception (Leonard, 1992). As early as the mid-1890s, GE and Westinghouse controlled a 75 percent market share. GE eventually gained even greater market dominance, so that by 1927 GE and its licensees held 97 percent of the U.S. lamp market. Hygrade-Sylvania, whose lighting operations would much later be bought by a German producer to form OSRAM-Sylvania, was GE's largest lamp licensee. Although GE's market dominance fell in the latter half of the 20th century, it remained the largest U.S. lamp producer.

In Europe, the lamp market also became concentrated early (Leonard, 1992). The leading firm was OSRAM, formed in a 1919 merger of the three leading German lamp producers, and now wholly owned by Siemens. Second in the European market was the Dutch company Philips. In part through cooperation with a European cartel set up in the 1930s under Swiss corporation Phoebus S.A., GE made substantial inroads in Europe and became the dominant worldwide producer.[7] The big three lighting firms all maintained leading positions in traditional lighting technology.

Traditional electric lighting patent applications during the period 1990-1993 were identified using data for the United States and Western Europe.[8] As noted earlier, we define

[6] Philips Lighting employs about 45,500 people and has 70 manufacturing facilities worldwide (Philips, 2006, p. 38).
[7] GE's dominance varied substantially across nations. For example, in the United Kingdom in 1965-1967, the leading producer was British Lighting Industries, followed by Philips and OSRAM (Monopolies Commission, 1968, p. 8).
[8] Patents are included for international patent classifications H01J61-65, "Discharge lamps"; H01K, "Electric incandescent lamps"; and H5B31 and H5B35-43, which cover "Electric lighting… not otherwise provided for" excluding electroluminescent light sources (which provide sufficient light to see an object but not to see by). Patents are included for applications at patent offices of the United States (1,589 applications), Europe (976), Austria (190),

traditional lighting to include incandescent, gas-discharge, and electric arc lighting (which includes fluorescent, HID, mercury and sodium vapor, metal halide, and neon lamps). All of the big three were leaders in these traditional electric lighting technologies, with 257.8 patent applications by Philips (credit is split equally in the case of multiple assignees); 232.1 applications by GE and by Thorn, whose lighting business GE acquired in 1991; and 219.4 applications by OSRAM, Sylvania, and OSRAM's parent firm Siemens. The big three each had more patent applications than any other firm.[9]

Evolving Technology

The lighting industry has developed several types of lamps. The incandescent lamp, little changed in form since the Edison era, is an evacuated glass tube (usually refilled with a gas) in which an electric current passes through a thin filament, heating it and causing it to emit light. Mercury vapor lamps, first patented in 1901 by Peter Cooper Hewitt, are high-pressure gas arc lamps and a forerunner to fluorescent lamps. Neon lamps were invented by Georges Claude 10 years later. Fluorescent lamps, first patented by Meyer, Spanner, and Germer in 1927, use a glowing phosphor coating instead of glowing wires to increase efficiency. Special types of

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Belgium (20), Denmark (49), Spain (976), Finland (79), France (121), Germany (1,798), Ireland (3), Italy (31), Netherlands (51), Norway (22), Portugal (5), Spain (194), Sweden (20), Switzerland (22), and the United Kingdom (218). Data are drawn from the European Patent Office's Worldwide Patent Statistics Database, version April 2006 (with the coverage of the Espacenet online database). Equivalent applications in multiple nations, detected by the fact that they share an identical set of priorities (as in Espacenet), were treated as a single application by weighting each application in inverse proportion to its number of equivalents (including itself).

[9] A German patent trust, Patra Patent Treuhand (possibly associated with OSRAM or Siemens), had 185.7 applications. The next three firms in number of patent applications were Toshiba with 70.2 applications, Motorola with 36 applications, and Matsushita with 33 applications. As in most areas of patenting, there were patent applications by many other individuals and companies (the total number of relevant patent applications was 3,236 during the period 1990-1993), and meaningful analyses are based on relative numbers, not on percentages of total applications. When figures are measured in terms of the number of patents actually granted from these applications (by the time of data collection), the conclusions are similar: Philips received 213.6 patents; OSRAM, Sylvania, and Siemens, 205; GE including Thorn, 181.5; Patra Patent Treuhand, 76.9; Toshiba, 52.6; Motorola, 35; and Matsushita, 31.

incandescent lamps, such as bulbs filled with halogen gas to increase lifetime and efficiency, have also been developed.

Incandescent lamps account for a majority of household sales in the United States, but a smaller portion of total sales. In households, incandescent lamps represent 66.5 percent of sales revenues, whereas fluorescent and other lamps remain uncommon (Mintel, 2003). Residential sales, however, make up less than 10 percent of lighting demand measured in lumen-hours. Combining all economic sectors (residential, commercial, industrial, and outdoor), incandescent lamps represent 11.0 percent of lumen-hours of light output, as compared to about 57.5 percent for fluorescent, 31.0 percent for HID, and 0.01 percent for solid-state lighting (Navigant Consulting, 2003a, p. 7).

Each of these lamp types has experienced a steady march of small improvements in materials, design, light quality, energy efficiency, and manufacturing efficiency throughout the past century. While early improvements were made by independent inventors in the United Kingdom, more than three-quarters of these improvements originated in countries where the big three were headquartered—the United States, the Netherlands, and Germany.[10] In materials, for example, thorium oxide added to wires increased shock resistance, nonsag wire formulations made possible new configurations for brighter and more easily mounted incandescent filaments, and safer phosphors replaced the highly toxic beryllium coating in fluorescent lights. Examples of design changes include filling incandescent lamps with large-molecule gases to prolong filament lifetimes, new layouts of filament mounts to facilitate assembly and automated manufacture, and a proliferation of lamp varieties, shapes, and sizes. Light-quality changes were

[10] We catalogued 134 improvements in lamp technologies between 1705 and 2005. Sources: company websites of General Electric (2006), OSRAM (2006), Siemens (2006), Philips (2006), and Toshiba (2006); websites of Bellis (2006a,b,c), Williams (2005), and Arthur (2006); and Bowers (1982).

achieved by choosing appropriate filament and phosphor materials and sometimes by blocking part of the emitted light to attain, for instance, a look similar to sunlight.

Energy-saving lamps also progressed steadily but slowly. GE, for example, commercially introduced its first energy-saving incandescent lamp in 1913, but not until 1974 was the first energy-saving fluorescent lamp introduced. Manufacturing became increasingly efficient with machines and methods that allowed faster, higher-quality production with less manual labor. Automatic insertion and mounting of components, sealing, exhausting, basing, and flashing were key process technologies. Many of these and other improvements took place during the first half of the last century and are documented by Bright (1958, pp. 22-30). In the latter half of the century, improvements focused largely on improved efficiency and longer lamp lives. The discovery of substances such as narrowband phosphors led to the development of CFLs, gases such as xenon yielded brighter lamps such as those used in automobiles, and similar improvements had medical uses including UV lamps.

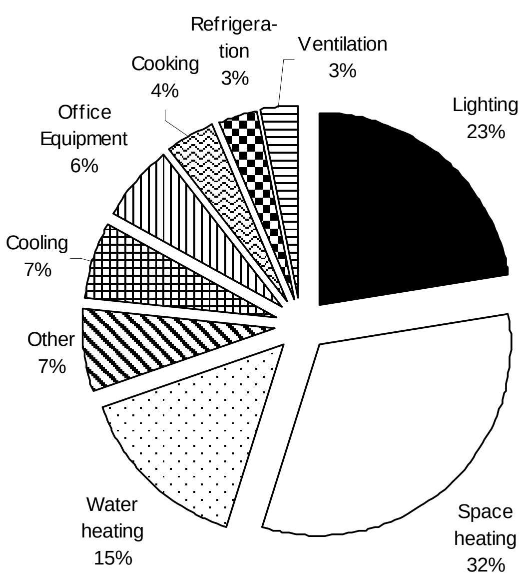

FIGURE 3. Energy consumption in U.S. commercial sector, 1995. SOURCE: DOE, 1995.

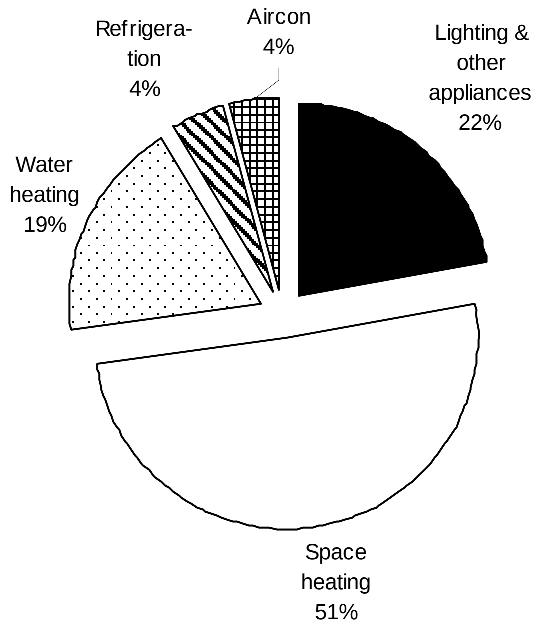

FIGURE 4. Energy consumption in U.S. residential sector, 1997. SOURCE: DOE, 1997.

Whereas lowering manufacturing costs and streamlining production were the key lighting challenges of the late 20th century, saving energy is the new driving force for 21st-century development. Lighting accounted for about 22 percent of total energy used in residential and commercial sectors in the mid-1990s, as shown in Figures 3 and 4 (DOE, 1995, 1997). In 2001, 51 percent of the national energy consumption for lighting occurred in the commercial sector, 27 percent in residences, and 14 percent in industry; the remaining 8 percent was used in outdoor stationary lighting (Hong et al., 2005, p. 2). Almost half of the electricity used in commercial buildings is used in lighting, as Figure 5 indicates.

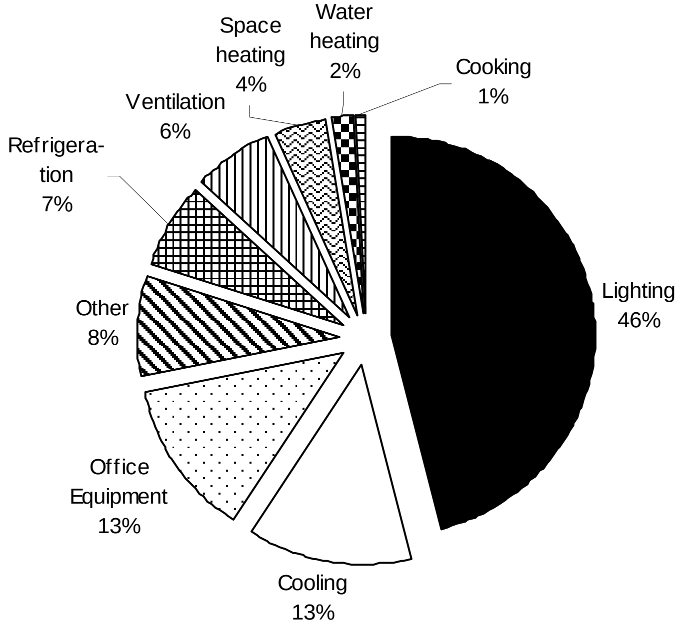

FIGURE 5. Electricity consumption in U.S. commercial sector, 1995. SOURCE: DOE, 1995.

In the United States, residential homes largely use incandescent lamps (90 percent), whereas commercial and industrial sectors use mostly fluorescents (Hong et al., 2005). If residential homes in the United States replaced all incandescent lamps with CFLs, they would save an estimated 35 percent of electricity used for all lighting applications (DOE, 1993).

Although advances in energy-saving lighting technologies such as CFL have been an important part of the strategies of the big three lamp producers, the big three have had some difficulty getting residential customers to give up incandescent bulbs and replace them with the more energy-efficient but initially more expensive bulbs. The rate of adoption of CFLs in U.S. residential households has been low, particularly compared to that of Europe and Asia. Researchers attribute those differences to a variety of factors, including national coordination of promotional efforts, different cultural attitudes about resource consumption, and higher electricity prices (Calwell et al., 1999). U.S. residential consumers lack awareness of and knowledge about CFLs. Consumer buying habits, negative perceptions, and skepticism about fluorescent lighting and relatively low electricity prices have meant that the United States is behind the rest of the world in adoption of energy-saving lighting technologies (Sandahl et al., 2006). This may soon change; for example, Wal-Mart CEO H. Lee Scott, Jr., is committed to sell 100 million CFLs a year by 2008 and the firm is making a concerted effort to change consumer behavior (Barbaro, 2007).[11]

Since lamp efficacy is central to which lamp types dominate the market, it is important to understand efficacy and its role in purchasing decisions. Efficacy in lighting can be measured in terms of lumens produced per watt of electricity (lm/W). A standard 100-watt incandescent lamp, for example, lasts about 1,000 hours and produces 15 lm/W. By comparison, a standard 30-watt fluorescent lamp lasts 20,000 hours and produces 80 lm/W. A longer-lasting and more energy-efficient bulb is less costly over the long term but higher initial upfront costs and misconceptions about the efficacy of fluorescent lights (early fluorescents had poor color rendering and were noisy) have led to low adoption in residences. Optimal lamp choice involves not only energy efficiency but also replacement costs for burned-out lamps and labor costs to install lighting systems. In commercial and industrial settings, where life-cycle costs are important and companies can make upfront investments, fluorescents are usually chosen.

[11] Wal-Mart sold about 40 million CFLs compared to 350 million incandescent light bulbs in 2005.

RADICAL INNOVATION IN LIGHTING: LEDS

Nature and Advantages of LEDs

An LED is a semiconductor diode. It is electroluminescent, emitting color that depends on the chemical composition of the semiconductor material or compound used and ranges along the spectrum from UV to infrared, as documented in Table 1.

TABLE 1. LED Color Spectrum Available from Alternative Materials

Semiconductor Material	**Color**
AlGaAs (aluminum gallium arsenide)	Red Infrared
AlGaP (aluminum gallium phosphide)	Green
AlGaInP (aluminum gallium indium phosphide)	Orange-red (bright) Orange Yellow Green
GaAsP (gallium arsenide phosphide)	Red Orange-red Orange Yellow
GaP (gallium phosphide)	Red Yellow Green
GaN (gallium nitride)	Green Pure green (emerald) Blue
InGaN (indium gallium nitride)	Bluish green Blue Near UV
SiC (silicon carbide) as substrate Si (silicon) as substrate, under development Al_2O_3 (sapphire) as substrate ZnSe (zinc selenide)	Blue
C (diamond)	UV
AlN (aluminum nitride) AlGaN (aluminum gallium nitride)	Far UV

SOURCE: Wikipedia, 2006.

The first practical visible-spectrum LED was developed in 1962 by Nick Holonyak (*The Inquirer*, 2004), and a variety of single-color LEDs followed. White LEDs have been a long-standing goal for researchers since they are most likely to replace traditional bulbs. White LEDs have been created by coating blue LEDs with a yellow phosphor, yielding a blue and yellow glow that appears white to the human eye. Another approach, taken by GE, uses UV LEDs driving phosphors, and a third approach is to use multiple colors of LEDs and combine them to create white light. Current white LEDs are cost-effective only for certain applications, such as backlighting and flashlights, and color LEDs remain more widely used.

Although incandescent and fluorescent lamps remain the predominant light sources, LEDs have several potential advantages. First, they use less energy: LEDs are three- to four-fold more efficient than incandescent and halogen sources. However, with the exception of laboratory devices, LEDs still fall short of fluorescent sources for many white light applications. Nevertheless, they are semiconductor devices and LED lighting is thought to follow an equivalent of Moore's law in computing, advancing rapidly and continually because of the pace of electronic circuit improvements.

Second, in contrast to incandescent lamps, LEDs use most of their energy in lighting (Herkelrath et al., 2005). LEDs also have a long life span, typically about 10 years of on-time—twice that of fluorescent lamps and twenty times that of incandescent lamps. In terms of luminous efficacy (lm/W), LEDs by 2004 were already about four times as efficient as incandescent lamps, and by 2020 they are targeted to be about 12 times as efficient as current incandescent lamps and more than twice as efficient as current fluorescent lamps (Hadley et al., 2004, p. 5; Tsao, 2002, p. 4). In addition, LEDs light up many orders of magnitude faster than incandescent lamps, and, rather than burning out abruptly, they do so slowly. LEDs require little maintenance and are cool to the touch, durable, and flexible. Furthermore, the technology is digitally compatible and, hence, can be integrated into digital networks, facilitating customizable electronic control.

LEDs come in many shapes and sizes and have multiple uses. Backlighting is one use, for cell phones, cars and other electronics, liquid crystal displays (LCDs), and specialized lighting applications. Specialty uses are possible since LEDs can be waterproofed, bent, shaped, multicolored, and dimmed.[12] LED applications are common in the entertainment industry, hotels, road signs, exit signs, pools, landscaping, and darkrooms.

The main drawback of LEDs is that they have not yet achieved the efficacy necessary for many white light applications. They are also still costly because they are expensive to produce. But production costs are expected to decline as volumes rise and the technology advances. For example, in 2002, the total cost of LED lamps (capital cost plus operating costs) was estimated at $16.00 per million lumen hours, compared to $7.50 for incandescent bulbs and $1.35 for fluorescent bulbs (Hadley et al., 2004, p. 8; Tsao, 2002, p. 8). However, by 2020, the total (capital plus operating) cost of LED lamps is targeted to be reduced to $0.63 per million lumen hours (Hadley et al., 2004, p. 8; Tsao, 2002, p. 8).

An additional limitation of LEDs, relative to incandescent lamps, is their imperfect color rendering, given the spectrum of light emitted. White light created by multiple color LEDs or by phosphors driven by LEDs involves a combination of wavelengths of light that differs from the color spectrum of traditional lamps and of sunshine, making objects with certain colors appear

[12] LEDs can also be designed to trap insects (through the use of insect-attracting colors) or to avoid attracting insects (since they do not generate UV light) (Bishop et al., 2004).

relatively dark. However, Ashdown et al. (2004, p. 8) indicate that color spectrum limitations are likely to be remedied as the technology progresses.[13]

Until recently, LEDs have been the only viable technology competing with the various types of traditional lamps as electricity-driven sources of illumination (Hong et al., 2005). A recently emerged technology that may become competitive with LEDs is microwave-driven light bulbs, for which claims of efficiency and low cost remain to be assessed; this technology emerged during the final stages of our work and is not assessed here (*The Economist*, 2007a,b). Our analysis (including patent data presented later) includes two newer types of LEDs: organic light-emitting diodes (OLEDs) and polymer LEDs. OLEDs, which are LEDs involving organic (carbon-based) chemicals, are promising but still in an early development stage. Ching Tang and Steven Van Slyke of Eastman Kodak invented the first OLED in 1987 (Howard, 2004). The materials in OLED devices have broad emission spectra that provide an advantage over inorganic LEDs (minor changes in the chemical composition of the emissive structure can tune the emission peak of the device). It is believed that good-quality white light is achievable from OLEDs (OLLA, 2006a, 2006b).[14] An important focus of current OLED research is on improving operational life.

In particular, OLEDs are of interest to display firms since they are capable of producing true black colors, something LCDs cannot achieve since they require a backlight to function and are never truly “off.” OLEDs can produce a greater range of colors, brightness, and viewing angles than LCDs because OLED pixels emit light directly. The display industry, with more than 70 companies including OLED pioneer Eastman Kodak, is set to commercialize OLED

[13] Other limitations of LEDs are areas of active work. For example, LEDs driven with sufficient power for automotive headlights and taillights require heat sinks because heat degrades LEDs; relevant heat sinks are improving.
[14] White OLEDs by 2006 had achieved claimed efficacy of 25-64 lm/W (Burgess, 2006; Physorg.com, 2005; Ledsmagazine.com, 2006).

technology including OLED displays (Hong et al., 2005).[15] Kodak launched the first digital camera to use a full-color OLED display in 2003. The big three traditional lighting companies have all set up joint ventures to profit from OLED technology for the display market.

LEDs as a Disruptive Technology: Diffusion Among Applications

Disruptive technology has been defined in several ways, and LEDs match at least two of the definitions. First, disruptive technology may be defined as a new technology that fills a long-standing need and for which the expertise and resources of incumbent firms does little to help them with this new approach; in this case solid-state lighting fills the need for illumination using a technology that differs totally from traditional lighting technologies. Second, disruptive technology may be defined as a technology in which new firms enter a market and threaten the market dominance of incumbent firms; in this case new firms have been entering the lighting market by creating products based on LEDs, and it has been unclear whether the leading existing lighting manufacturers can maintain strong market positions if purchases shift substantially to LEDs.

LEDs are a novel technology in lighting. LEDs are semiconductors and so manufacture of LEDs has little in common with traditional lamp production. The supply chain to produce LEDs as indicated in our discussions with industry experts is quite disaggregated, as is the case for other semiconductor technologies. Moreover, Kevin Dowling, Chief Technology Officer at Color Kinetics, stated to us that "the vertically integrated giants of the semiconductor world such

[15] In December 2007, Sony released the first commercially available OLED televisions, although they remain far from price-competitive with liquid crystal display (LCD) televisions (Eisenberg, 2007). Samsung has also been demonstrating prototype OLED displays (Gizmodo, 2008). LCDs, which are now dominant in televisions and computer monitors, are akin to (dynamically changing) stained glass windows behind which white light is projected, thus allowing some colors of light through the liquid crystals while blocking other colors. This means that light not allowed through the liquid crystals is wasted, turning electricity into heat, and that the liquid crystals require behind them a light source that adds to their thickness, weight, and cost. If OLED displays and their production methods can be improved sufficiently, therefore, they have potential advantages over LED displays: the desired color can be produced at each location on an OLED display with no wasted light and no liquid crystal layer.

as Intel and Applied Materials are becoming less numerous and rapidly becoming more the exception rather than the rule." Data on the participation of firms in each stage of the LED supply chain are available from solidstatelighting.net (2006). We catalogued the participation of each firm in each stage of the supply chain and found that most firms participate in only a single part of the supply chain, although a few large firms are involved in many parts of the supply chain. This supply chain is illustrated in Figure 6.

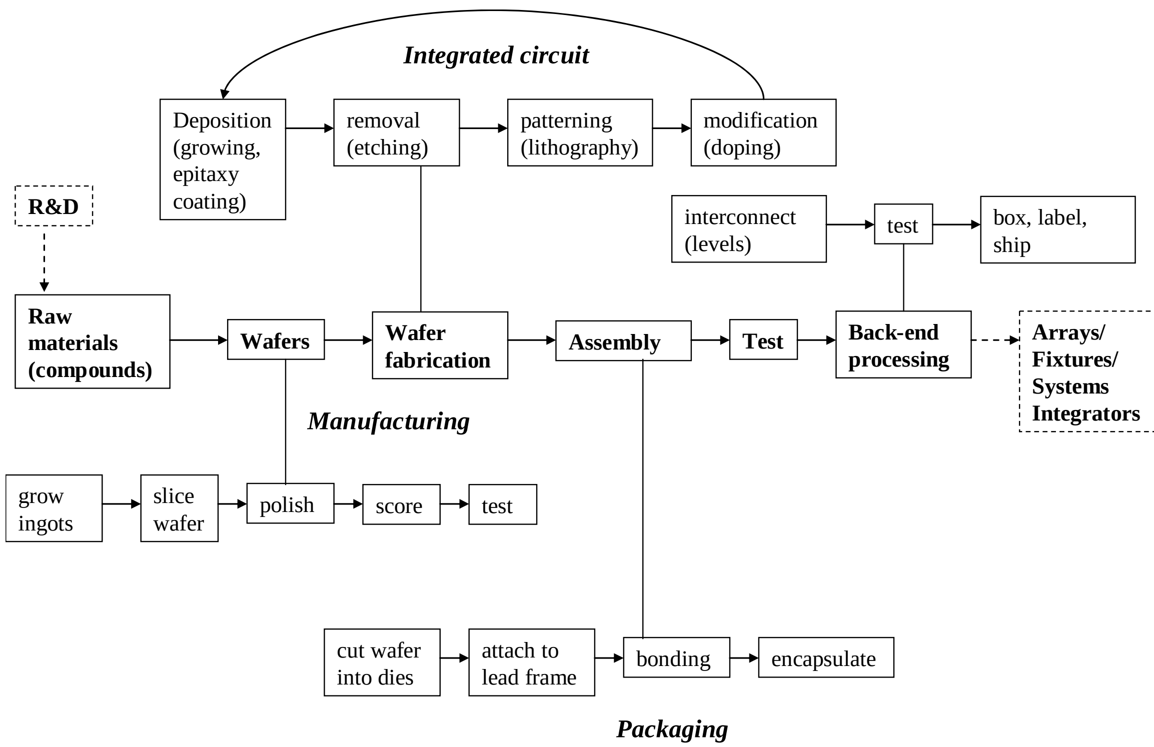

FIGURE 6. LED semiconductor supply chain.

Semiconductor firms often specialize in specific stages of the supply chain, such as R&D, epitaxy, manufacturing, packaging, testing, and back-end processing. Each stage requires unique skills and equipment and significant capital expenditure, which is one reason why firms tend to specialize rather than integrate along the supply chain. Specialization is thought to drive down prices and improve performance, and this trend is similar among LED manufacturers. The development of this new technology will likely create opportunities at all levels of the value chain.[16]

The LED market in general lighting is still small compared to traditional lamps. LED applications command a high price, but relatively few units are sold and all are for specialty purposes. Traditional lamps (incandescent, fluorescent, and HID) are estimated by Navigant Consulting (2003a, p. 7) to have used 41,051 trillion lumen hours of electricity in the United States in 2005 compared to only 5 for LEDs. Nevertheless, the LED market grew by 50 percent between 1995 and 2000 and has been forecast at $4.7 billion by 2007 (Ashdown et al., 2004, p. 9).

LED technology has some clear advantages over traditional lighting, which have allowed LED manufacturers to displace traditional lighting in niche markets (Griffiths, 2006). Indicator lights were one of the earliest uses, with color LED indicators predating the 1990s and white LED indicators used from about 2000 onward. In 2001, 30 percent of LED sales were for backlighting, 26 percent for automotive uses, 26 percent for signs and displays, 10 percent for electronic equipment, 4 percent for signals, and 4 percent for general illumination (Maccagno, 2002, cited by Ashdown et al., 2004, p. 9). By 2002, U.S. market penetration of LEDs was particularly high in exit signs (80 percent), truck and bus lights (41 percent), and traffic signals (30 percent) (Navigant Consulting, 2003b, p. xii; Hadley et al., 2004, p. 9).

Other niches that LEDs have entered include video screen backlights in the mid-1990s, decorative lighting in the late 1990s, and automobile lights including dashboard, interior, brake, and tail lights since about 2000. Other recent uses include architectural lighting, outdoor

[16] As lighting moves to LEDs, traditional bulb manufacture may also be vertically disintegrating somewhat, judging from recent comments by Jim Campbell, President and CEO of GE Consumer & Industrial (General Electric, 2007).

advertising, and long-lasting white-light flashlights. One example of the advantage of LEDs is in brake lights, where LEDs provide an extra 0.2-second response time and therefore help to prevent accidents. Although first introduced in luxury cars, LED brake lights are beginning to penetrate the more cost-conscious end of the market. Another example is Wal-Mart's adoption of LED lighting for refrigerated display cases, an application once dominated by fluorescents. As well as lowering operating costs, the LED lights are amenable to added motion sensors so that lights come on only when shoppers are nearby. As a result, Wal-Mart is investing $30 million and expects a 66 percent reduction in freezer lighting energy costs (LIGHTimes, 2006).[17]

New LED Lighting Innovators

Advances in solid-state lighting offer an opportunity and a challenge for incumbent and startup firms. Although the big three lamp manufacturers have been making substantial investments in solid-state lighting, pioneering inventors in LED lighting come from universities, research labs, and companies, and R&D plays a vital role in development of these technologies.

Advances in red, yellow, and blue LEDs have been led by different research groups and companies. Several companies have "specializations" in one industry sector, due to a combination of strategy and luck in pioneering key product or process innovations. Nichia Corp. in Japan, for example, was one of the first companies to develop blue LEDs, a key advance when only red, green, and yellow were available. It also produced the first white LEDs in 1996 (Walker, 2004). The company is an illustration of how small firms have been able to penetrate the burgeoning industry. Nichia's key researcher, Shuji Nakamura, now a professor at the University of California, Santa Barbara, was largely responsible for the development of the blue

[17] Wal-Mart installations developed in collaboration with GE and Philips represent "the biggest investment to date in LED lighting for interior application [$30 million], and it is also the single largest installation of white LED lighting replacing fluorescent lighting in a display lighting application" (Griffiths, 2006).

LED. When Nakamura was hired in 1979, Nichia was a small firm in rural Japan with only 200 employees and Nakamura was assigned a project to synthesize a commercial-grade blue LED, needed to complete the color palette. At the time, large Japanese corporations were spending $85 million a year and Nichia had a very small research budget. Today Nichia controls 80 percent of the blue LED market with Cree and Toyoda Gosei (Cox, 2003). Nakamura's successful approach departed from the standard thinking in his field and in his company. He chose gallium nitride, a material most researchers thought would not yield significant results, as the basis for his research, and continued to work on blue LEDs for 10 years. Nichia's entry into the LED market was a lucky outcome of their hiring a particular employee and of that employee's actions.

The role of individuals in innovative companies in pioneering new lighting technologies is typical of the early stages of a technology cycle in which R&D efforts are lengthy and costly. Government grants have been instrumental to support startup companies and university research in the pursuit of emerging LED technologies. Government funding has filled key technology gaps, provided funding to develop enabling knowledge and data, and advanced the solid-state lighting technology base. A team of researchers from Rensselaer Polytechnic Institute, for example, recently received $1.8 million in federal funding from the Department of Energy (DOE) to improve the energy efficiency of green LEDs, with a goal of doubling or tripling power output. The research was one of 16 projects selected for funding through the DOE's Solid-State Lighting Core Technologies Funding Opportunity Announcement, which supports enabling and fundamental solid-state lighting technology for general illumination.

"Making lighting more efficient is one of the biggest challenges we face," says Christian Wetzel, the Wellfleet Career Development Constellation Professor, Future Chips, and associate professor of physics at Rensselaer (RPI, 2006). To meet aggressive DOE performance targets that call for more energy-efficient, longer-lasting, and cost-competitive solid-state lighting by 2025, the team has partnered with startups such as Kyma Technologies and Crystal IS. Kyma, a North Carolina State University spin-off, specializes in gallium nitride substrates, while Crystal IS, founded by two Rensselaer professors, specializes in blue and UV lasers based on single-crystal aluminum nitride substrates. The DOE grant has funded these startups and researchers.

Government support has also been important for building demand and aiding firms to improve quality and reduce prices—keys to further diffusion. Such programs promote early diffusion of energy-saving technologies and are not unique to the United States. We will return to the role of national policies and government initiatives later in the chapter.

CORPORATE STRATEGIES TOWARD INNOVATION

The "Big Three"

The big three traditional lighting manufacturers, Philips, OSRAM, and GE, have responded to the opportunities in LED lighting by creating joint ventures with semiconductor firms that had preexisting expertise in these technologies. They later acquired these joint ventures outright. Philips established a joint venture in optoelectronics with Hewlett-Packard (HP) in 1999 (when HP split in two in 1999, the optoelectronics group was assigned to a new firm, Agilent Technologies) and acquired the venture Lumileds in 2005 for $950 million.[18] OSRAM established a joint venture with Infineon Technologies AG (formerly Siemens Semiconductors) in 1999, and acquired the venture in 2001, naming it OSRAM Opto Semiconductors GmbH.[19] GE established a joint venture, Gelcore, with semiconductor maker

[18] Philips' 2005 Annual Report states that Lumileds is the world's leading manufacturer of high-power LEDs.
[19] Siemens gradually spun off its semiconductor division as Infineon beginning in 1999, and sold its final 18.23 percent stake in the company in 2006.

Emcore in 1999, and acquired Gelcore in August 2006 for $100 million.[20] Additionally, Philips and OSRAM announced in January 2007 a cross-licensing agreement covering patents on LEDs and OLEDs (LIGHTimes, 2007), and Philips acquired the LED lighting controls firm Color Kinetics in August 2007.

Historically, the locus of innovation for traditional (i.e., non-LED) lamps originated in the primary R&D centers of the big three lighting firms in Germany, the Netherlands, and the United States. While these labs are still very important, in recognition of Asia's increasingly important role in the traditional lighting industry, the three firms have set up manufacturing, engineering, and R&D activity in other parts of the world, principally in Japan and Taiwan. Efforts are also being made to penetrate the Chinese market. GE, for example, began investing in China through joint ventures. The company combined a finished product purchasing center and an R&D center to form the GE Asia Lighting Center in Shanghai. By 2002, GE had four major plants in Shanghai and one in Xiamen, and had invested over $100 million in China for lighting, according to Matthew Espe, former president and CEO of GE Lighting (Zou, 2002).

Philips established an R&D campus with the Shanghai Science and Technology Commission with annual expenditures of $50 million, the majority of which is in lighting. Between 1988 and 2005, Philips Lighting established nine solely owned and joint ventures and five R&D centers, of which one conducts global level research while the other four mainly focus on the Asia-Pacific region (Chinesewings, 2005).

OSRAM China Lighting, Inc., 90 percent of which is owned by OSRAM, was formed in April 1995 with an investment of 49.7 million Euros. The company is located in Foshan, China,

[20] Although Gelcore grew about 50 percent from 1995 through 2004, it nonetheless reported a net loss of $0.8 million in 2005. Thus, when Emcore sold its 49 percent stake in Gelcore, it traded possible future value for immediate cash gains.

and has two factories in China, employing 6,000. In February 2006, OSRAM China Lighting announced it would acquire Foshan Electrical and Lighting Co. Ltd.[21]

Asian LED Producers

Beyond their expanding importance in the traditional lighting industry, Asian firms also play a significant role in the global LED market. Japan's LED industry leads with $918 million in sales, or a world market share of 47 percent, although a portion of these revenues are shared with some U.S. companies through joint ventures. Taiwan's industry holds second place at $712 million, or a market share of 25 percent (Taiwan Economic News, 2004a,b). LEDs are the largest type of compound semiconductor production in Taiwan (Liu, 2003). Another source estimates the global LED market at $5.4 billion in 2004, with Japan's share at 51.3 percent, Taiwan's 22.7 percent, the United States 12 percent, and Europe around 9 percent (Ledsmagazine.com, 2005b). Data from www.solidstatelighting.net (2006) suggest that most LED R&D is conducted in the United States whereas Asia dominates manufacturing and packaging. For example, Taiwan, China, and Korea produced the majority of blue LEDs in the world, and more than 80 percent of the production of InGaAlP high-brightness (HB) LEDs in 2004. China boasts about 600 enterprises directly related to the LED industry in China, employing about 40,000 people (Ledsmagazine.com, 2005a).

Because of the youth of the industry, quality remains variable across firms and is sometimes difficult to assess. Quality for an LED includes a long operating lifetime before substantial fading occurs, controls to ensure against defective chips, and consistency of operating characteristics including a claimed color emission spectrum, light intensity, voltage drop, and

[21]Source: "OSRAM China Lighting's Announcement to Acquire Foshan Electrical and Lighting Co. Ltd.," http://business.sohu.com/20060614/n243727208.shtml (in Chinese).

viewing angle (Toniolo, 2006b). The LED industry has seen a surge of new players which has flooded the market with low-quality LEDs (Toniolo, 2006a). The result of such commodity production is intense price competition and a “huge overcapacity” for lower-performance LEDs (Arensman, 2005). For high-performance LEDs, competition remains less intense. Among consumers, low-quality LEDs may give a bad reputation to all LEDs.

New Ventures

The global semiconductor market was worth $262.7 billion in 2006 (Gartner, 2007), considerably outstripping LED industry revenues of $3.7 billion in 2004 (www.gelcore.com). A large number of materials, substrates, epitaxy, packaging, and manufacturing companies have entered the LED market. In February 2006, lighting industry directory Lightsearch.com listed 71 companies that produced LED lamps.[22] Most companies operate at a single stage of the supply chain, illustrated in Figure 6. For example, companies that perform epitaxy do not usually do manufacturing or packaging. Likewise, most companies that focus on packaging do not produce raw materials or substrates. Moreover, companies that focus on basic R&D do not operate in the rest of semiconductor production.[23] Even on a national level, specialization sometimes occurs. For instance, Taiwan is strong in R&D and manufacturing of LEDs, whereas Korea specializes in packaging, and China, a late entrant, is setting up epitaxy, and wafer and chip production (Wang and Shen, 2005). In addition, some countries specialize in the production of specific LED colors: Taiwan holds a majority market share for blue GaN LEDs at 34 percent, closely followed by Japan at 33 percent, whereas the United States and Korea lag with 19 and 12 percent, respectively (Wang and Shen, 2005).

[22] Recall that “lamp” as used in the traditional lighting industry means “bulb,” and note that the former term is most appropriate for LED lighting as no glass bulb is involved. Lamp here means a light-producing device, not a fixture.
[23] Based on information on semiconductor companies in the LED industry gathered from solidstatelighting.net (2006).

Although LEDs are still a small subset of the semiconductor market, they have rapid growth in demand, making this an attractive market for new and existing semiconductor firms. LEDs offer opportunities for semiconductor firms to diversify into a new market that promises long-term growth potential. For example, Avago Technologies, the world's largest privately held semiconductor company, recently announced three new series of HB full-color LEDs for the outdoor electronic signs and signals market (*Business Wire*, 2006).

At the other end of the supply chain, LED "integrators" like Color Kinetics play an important role in LED lighting. Since its establishment in 1997, Color Kinetics has built an impressive patented portfolio of these technologies, which it uses in LED lighting systems. Color Kinetics has pioneered intelligent LED systems that are networked and has created a new niche as a "systems solutions" and lighting control technology provider. Color Kinetics has initiated several major projects that integrate LED lights with sound, movement, and rhythm through digital controls, and is working on white light systems. A subway tunnel in Chicago, for example, is bathed in several colors of LED light that periodically change (giving the impression of a sunset). The company leverages its strengths in innovation and engineering and works with selected Chinese manufacturers to assemble systems. In August 2007, Philips acquired Color Kinetics, which became Philips Solid-State Lighting Solutions, a business unit of Philips Lighting's Luminaires group.

LED LIGHTING R&D

The big three producers are dominant in traditional lighting technology, as shown earlier using data on patents for these technologies. In this section we analyze the R&D positions of these and other firms for LED lighting.

Methodology: Analysis of Patent Data

To assess trends in the global location of LED lighting R&D we use patent data. Patent data yield information on successful R&D outputs. Although the information is partial because many inventions and innovations are not patented, within an industry patents are highly correlated with R&D spending and are indicative of R&D success. Moreover, patents yield relatively defensible property rights and hence represent an important component of the value of firms' R&D outputs.

To analyze LED-related patents that pertain to lighting, a search criterion is needed to identify relevant patents. Choice of a criterion involves a trade-off between finding a subset of mainly relevant patents versus finding all relevant patents mixed with many more non-LED and non-lighting patents. We therefore chose a criterion to identify mainly relevant patents at the cost of excluding some LED lighting-related patents.[24] All patents were identified whose title contains the key word or phrase "LED(s)", "OLED(s)", "L.E.D.(s)", or "light emitting diode(s)", or the equivalents of the latter phrase in German, French, Spanish, Italian, or Portuguese.[25] Other languages, including Asia-specific languages, effectively are almost always included in our search because for almost all other languages the database we used has English translations of titles. The search criterion includes LED applications, including LED-type displays and (rarely) lasers, as well as LEDs whose glow is bright enough for general illumination. All patents granted are included regardless of whether they originated from firms, government programs, or university research labs.

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[24] International patent classification systems do not identify specific categories for LEDs or for LED lighting, and we draw on international data for which this limitation applies.

[25] The non-English terms used are "lichtemittierende Diode(n)", "Leuchtdiode(n)", "diode(s) luminescente(s)", "diodo(s) electroluminoso(s)", "diodo luminescente", "diodi luminescenti", "diodo(s) emissores de luz", and "diodo(s) emitindo-se claro(s)". The verb "led" sometimes appears in titles for reasons unrelated to light emitting diodes, so we read all patent titles and eliminated patents for which "led" was used as a verb.

Since both the traditional and LED lighting industries are global in terms of the firms involved and startup efforts, we obtained data for patents issued in most nations worldwide, although we focus initially on patents granted in the United States and Europe.[26] For logistical reasons (we had to look up information by hand from actual copies of thousands of patents), we restricted the sample in the latter analysis to patents whose title included either "LED(s)" and "lighting", or the phrase "light emitting diode(s)". Our primary focus on U.S. and European patents addresses concerns that patents from other nations may face quite different approval requirements.

Patents are counted only once if the identical patent is filed multiple times in different nations.[27] Patents granted in nations outside the United States and Europe are considered after our main analyses.

Analysis of LED Patenting

The analyses that follow compare the headquarters nationality of patenting firms and also the national R&D locations where invention was carried out. The headquarters location of a firm was identified as the international headquarters nation of the firm to which a patent was assigned. If a firm was owned by a "parent" firm, we use the headquarters nation of the parent firm. Rarely, patents were applied for by multiple firms or individuals, and assignee credit was divided

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[26] Data are obtained from the Espacenet worldwide patent database, maintained by the European Patent Office (EPO). The data include patents granted by the relevant patent authorities in almost all nations worldwide (a detailed listing is available from the Espacenet website), including not only the most developed world but also Eastern European and developing Asian, Middle Eastern, and African nations (or cooperating regions) with significant innovative activity. The European patent authorities for which LED patents appear in the primary sample are the European Patent Office plus the national offices of Austria, Finland, France, Germany, Italy, Sweden, and the United Kingdom. Patents from former Soviet-bloc nations are excluded. In our secondary sample of patents from patent authorities worldwide, patent authorities that actually granted patents in the data are (ordered by continent) the United States, Canada, Mexico; Germany, Great Britain, Belgium, France, Netherlands, Hungary, former Soviet Union, European Patent Office; Japan, Korea, Taiwan, Singapore, India, China, Hong Kong; Australia, New Zealand; and South Africa.

[27] Equivalent patents filed in multiple nations are identified as catalogued on the EPO's Espacenet patent web server, which defines equivalents based on identical priority claims.

equally among these applicants. The R&D location where invention was carried out was determined by the nation listed in the address of each inventor named on the patents. Since inventors' addresses are not generally available in electronic bibliographic data, we looked up the nation for each inventor using the original patent documents. Rarely, different inventors of a single patent had addresses in different nations, in which case credit for each R&D nation was divided in proportion to the number of inventors in each nation.

LED patent data are compared in two 4-year periods a decade apart, 1990-1993 and 2000-2003. These 4-year periods ensure an adequate-sized, representative sample of patent activity. Comparing between periods facilitates analysis of trends in R&D activity in LED lighting.

Number of LED Patents in 1990-1993 and 2000-2003

As LEDs have developed growing markets in new applications, so has LED R&D grown. Based on U.S. and European patents, the number of LED patents granted quintupled from 1990-1993 to 2000-2003, as shown in Figure 7.[28]

[28] Substantial growth also holds using our worldwide data for a narrower range of patent titles, with LED patents granted growing from 438 in 1990-1993 to 1114 in 2000-2003.

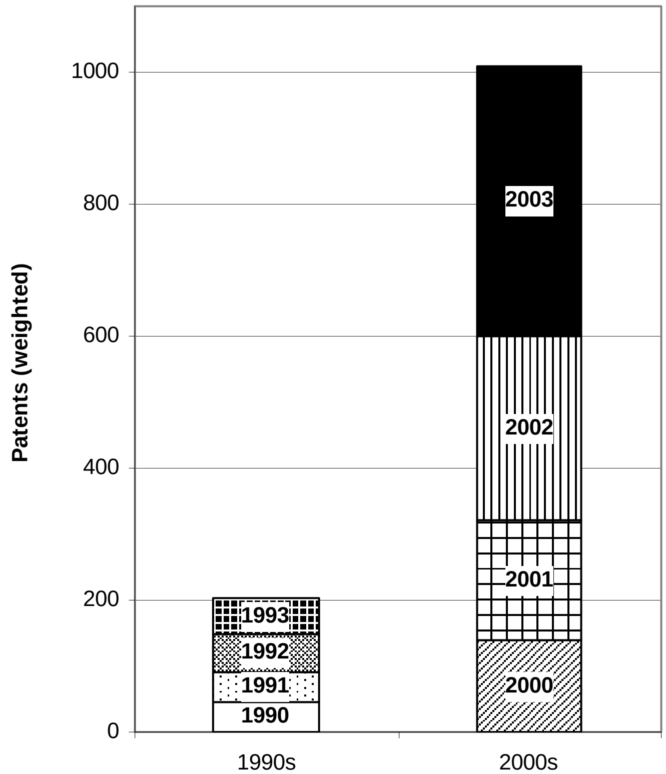

FIGURE 7. LED patents in sample granted during 1990-1993 and 2000-2003. SOURCE: Authors' analysis of patents granted in the United States and Europe (see text).

Globalization of LED R&D: U.S. and European Patents

The locations of inventors as reported on patent applications reflect where R&D occurred. We therefore assessed relative inventive activity in each nation, for 1990-1993 in Figure 8 and 2000-2003 in Figure 9, by determining the percentages of patents with inventors in each nation.[29] In the period 1990-1993, inventors located in the United States predominated with

[29] When computing the percentages of LED invention done in different nations, one concern is whether some nations' inventions might be of systematically poor quality, so that while those nations' inventors *appear* to accomplish a lot of R&D, in reality the value of their R&D output is much lower. One means to check whether this is the case is to examine only those relatively high-value patents for which firms went to the expense and trouble of obtaining equivalent patents in multiple countries or on multiple continents. Hence, we also examined patents using these criteria. These analyses yielded conclusions similar to the results reported in the text.

47 percent of all of the LED patents. Inventors in Japan held second place with 27 percent of LED patents. Inventors in Germany ranked third with 8 percent of LED patents, followed by inventors in Sweden, Korea, Taiwan, France, and the United Kingdom, each with 2-3 percent of LED patents.[30]

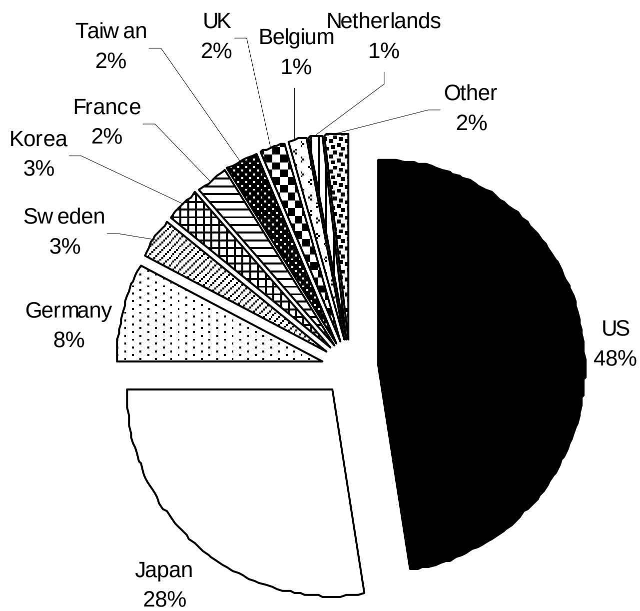

FIGURE 8. Invention locations of LED patents granted in 1990-1993. SOURCE: Authors' analysis of patents granted in the United States and Europe (see text).

[30] Percentages in this section often represent small numbers of patents, so readers are cautioned that small variations in patenting activity can sometimes lead to substantial changes in the precise percentages reported. Our primarily conclusions, however, are robust to typical random variations, with statistical significance tests reported in footnotes. Differences in arrival rates of patents in 1990-1993 were statistically significant between the United States and Japan (p=.0014), between Japan and Germany (p<.001), and (marginally) between Germany and Sweden (p=.0525), using exact p-values from exact Poisson regressions. (Here and below, exact Poisson tests are actually close approximations because they use rounded-to-integer values of weighted patent counts, rather than making assumptions about statistical (in)dependence between locations of inventors of some patents.)

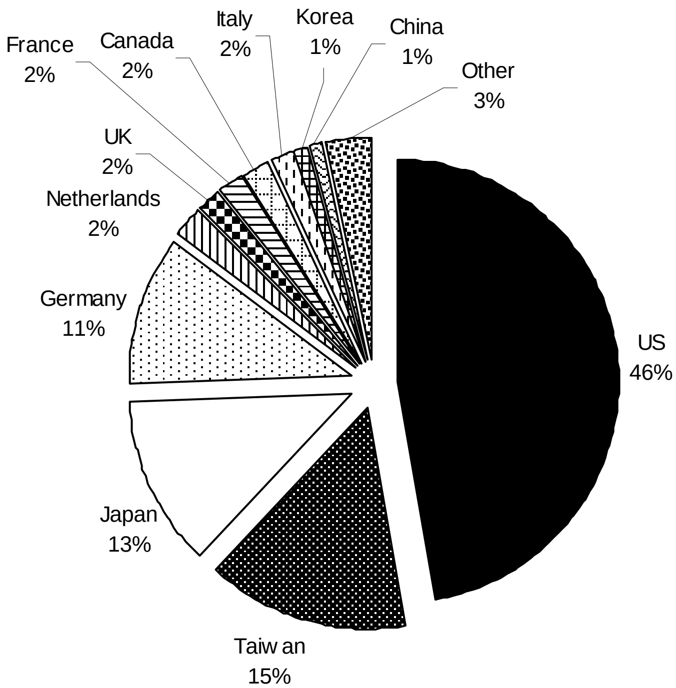

FIGURE 9. Invention locations of LED patents granted in 2000-2003. SOURCE: Authors' analysis of patents granted in the United States and Europe (see text).

In the period 2000-2003, U.S. inventors' share of LED patents remained dominant at 47 percent. Rapid growth in inventions occurred in Taiwan, whose inventors achieved a 15 percent share of LED patents, ahead of Japanese inventors whose share had fallen to third place with 13 percent of LED patents. German inventors' share grew slightly to 11 percent of LED patents.[31] Other nations' share of LED patent invention remained at 2 percent or less.

[31] The differences between Taiwanese versus Japanese, and Japanese versus German, patent invention in 2000-2003 each involve 16-17 patents, and it is difficult to tell whether these reflect statistically meaningful differences in nations' propensities to generate LED inventions; these nations' rankings reported here should not be construed to indicate practically or statistically significant differences. (Exact significance tests are not feasible to compute in these cases, because the numbers of patents involved make exact Poisson calculations highly computationally intensive.) German inventors' arrival rate of patents was statistically significantly (p<.001) greater than the highest-ranked of nations with less invention, using an exact p-value from exact Poisson regression.

TABLE 2. Location of Inventor vs. Firm Headquarters, 1990-1993

	Location of R&D			
Location of HQ	**Asia**	**Europe**	**U.S.**	**Other**
Asia	98.4%		1.6%	
Europe		100.0%		
U.S.	5.8%	2.9%	91.3%	
Other				100.0%

SOURCE: Authors' analysis of patents granted in the United States and Europe (see text).

TABLE 3. Location of Inventor vs. Firm Headquarters, 2000-2003

	Location of R&D			
Location of HQ	**Asia**	**Europe**	**U.S.**	**Other**
Asia	95.2%	0.9%	3.6%	0.3%
Europe	0.7%	76.0%	22.9%	0.4%
U.S.	1.4%	1.9%	95.1%	1.6%
Other				100.0%

SOURCE: Authors' analysis of patents granted in the United States and Europe (see text).

Not only did LED innovation become somewhat more international, but non-U.S. companies became more international in the locations where they carried out research. Location of R&D (i.e., of inventors) is compared to locations of corporate headquarters in Table 2 for 1990-1993 and Table 3 for 2000-2003. During the period 1990-1993, the United States was the only country whose companies supported substantial LED R&D abroad.[32] LED patents were filed by inventors in Japan, the United Kingdom, and Germany for firms headquartered in the United States. Of the nine U.S. patents that had R&D locations abroad, Eastman Kodak was assignee for four, with inventors in Japan, and the remaining five had inventors in the United Kingdom (twice), France, Japan, and Malaysia.

By 2000-2003, more companies were supporting R&D across the globe. Overall, companies in 13 countries sponsored LED R&D abroad. U.S. companies, however, kept 95.1 percent of R&D within the United States. Asian LED invention sites for U.S. firms fell from 5.8 to 1.4 percent, and European sites for U.S. firms fell from 2.9 to 1.9 percent. In the period 2000-2003, U.S. companies' foreign-invented patents had inventors in Canada (1.6 percent) and nine other nations (each less than 1 percent). European companies began to support R&D in the United States, which now yielded 22.9 percent of European companies' LED patents. Asian companies also began to carry out R&D in the United States, yielding 3.6 percent of Asian companies' LED patents. Furthermore, Europe yielded 0.9 percent of Asian companies' LED patents.[33]

To a slight degree, the United States became an innovation hub for companies headquartered in other countries, mainly for Philips. Of the LED patents assigned to Dutch companies, 67.3 percent were filed by inventors located in the United States, as were only 1.8 percent of patents assigned to German companies. Germany also was an R&D source for 7.4

[32]This difference between the United States and other nations is marginally statistically significant, p=.059, using Fisher's exact test (two-tailed). (The test is approximate because it uses rounded-to-integer values of weighted patent counts, rather than making assumptions about statistical (in)dependence between locations of inventors of some patents.)

[33] Use of inventors outside the home country in 2000-2003 was statistically significantly less for United States patent applicants than for non-United States firms (p<.001 using Fisher's exact test as in the preceding footnote), with no significant difference between United States and Asian patent applicants.

percent of Dutch firms' patents. These shifts largely reflect the internationalization of Philips as it acquired other firms and joint ventures.

There was a corresponding shift in the number of companies using inventors in other countries. In the period 1990-1993, six U.S.-headquartered companies sponsored LED research abroad, totaling nine patents, while only one European and one Japanese company sponsored LED research abroad with only one such patent each. In the period 2000-2003, 25 companies located in all parts of the world sponsored LED research abroad, totaling 95 patents. This a substantial shift, but far from complete globalization, as even in 2000-2003 only 5.2 percent of LED patents involved work outside companies' headquarters nations; the vast majority of patents still used inventors in firms' home countries.

As Table 4 shows, there was a shift from 1990-1993 to 2000-2003 in the dominant firms in LED patenting.[34] Dominant firms are ranked here in LED applications generally, including LED-type displays and LED backlights, not just LEDs for general illumination. The listed firms are unlikely to include materials makers because of the search criteria used. Only four of the top 10 firms that filed LED patents in 1990-1993 remained in the top 10 a decade later (OSRAM plus its parent firm Siemens, Xerox, Eastman Kodak, and HP) and four entirely new LED patent assignees had appeared in the new top 10. All of the big three traditional lighting firms featured at the top of LED patenting in 2000-2003 (Philips ranked first, OSRAM second, and GE third). Of these big three, Philips and (through Siemens) OSRAM had LED patents in 1990-1993. The emergence of the big three as the dominant LED firms in 2000-2003 can clearly be attributed to their joint ventures that allowed them to enter fully into the semiconductor-based LED market.

[34] The shift in firms' rank ordering from 1990-1993 to 2000-2003 is statistically significant ($p < .001$) using Wilcoxon's signed-rank test.

TABLE 4. Leading Firms in LED Patenting, 2000-2003 versus 1990-1993

Rank 2000-2003	Rank 1990-1993	Company	Headquarters Country	Patents 2000-2003
1	32	Philips/Lumileds[a]	Netherlands/U.S.	69.0
2	9	OSRAM/Siemens[b]	Germany	41.0
3	-	GE/Gelcore[c]	U.S.	26.5
4	-	United Epitaxy/Epistar[d]	Taiwan	17.2
5	3	Xerox	U.S.	14.5
5	13	Oki	Japan	14.5
7	1	Eastman Kodak	U.S.	14.0
8	2	HP[e]	U.S.	9.0
8	-	Para Light Electronics	Taiwan	9.0
10	-	Hon Hai Precision	Taiwan	8.0
11	-	IBM	U.S.	7.0
11	-	Lite On Electronics	Taiwan	7.0
13	8	Samsung	Korea	6.8
14	-	Nichia	Japan	6.0
15	10	Cree	U.S.	5.3

[a] Includes all patents by Philips and its subsidiary Lumileds, Agilent as former joint venture partner of Lumileds, and Color Kinetics acquired in 2007.
[b] Includes all patents by OSRAM-Sylvania and its parent company Siemens, as well as 6.5 patents held by Patra Patent Treuhand.
[c] Includes all patents by GE and its subsidiary Gelcore.
[d] Includes all patents by United Epitaxy, Epistar with which it merged in 2005, and Epitech with which it merged in 2007.
[e] HP patents in the 1990s pertain to technology such as LED print heads that may not have been owned by HP's spin-off Agilent, which became part of Philips.

NOTE: Individuals and institutions were excluded from the table. SOURCE: Authors' analysis of patents granted in the United States and Europe (see text).

Many LED patents came from firms not in the traditional lighting industry, including established semiconductor firms. Semiconductor firm United Epitaxy, founded in 1993, is one of several such Taiwanese firms. Firms' ranks are measured somewhat noisily here, because the sample of patents used does not cover every LED patent (as noted in our earlier description of patent methods).[35] Nonetheless, the evidence shows an important role in LED technology of Asian firms, representing half the firms listed in Table 4.[36]

Hence, the big three lighting firms have managed to established dominant positions in LED lighting technology. Nonetheless, if LED technology develops as anticipated there may be greater participation by firms in Japan, Taiwan, and perhaps Korea and other Asian nations in the global lighting industry.

Globalization of LED R&D: Worldwide Patents

The results differ somewhat when patents from Japan, Taiwan, and other nations are included. These patents were initially excluded because of concerns over whether patents are of comparable quality and value in different nations and because the U.S. and European markets have been two of the world's largest. However, focusing only on U.S. and European patents may introduce a bias because some applicants develop R&D competence but apply for patents only in their home countries. Also there may be international differences in propensities to patent in different markets. Filings by individuals (instead of companies) showcase the differences; in the period 2000-2003 almost four times as many patents were granted worldwide as in the United States and Europe, and almost five times as many individuals were granted patent rights, using our worldwide sample of data with a restricted definition of LED patents. The majority of individual filings originated in Taiwan (35.6 percent) and Korea (28.6 percent).

[35] Errors in ranking could result if certain companies are less likely than others to include our search terms in their patent titles, and our purpose is not to compute exact rankings. However, the rankings computed confirm industry impressions and are approximately valid absent any odd variations in firms' choice of terminology in patent titles: the difference between Philips and OSRAM in their arrival rate of patents was statistically significant (p=.010), the difference between OSRAM and GE was not statistically significant at conventional levels (p=.114), the difference between OSRAM and United Epitaxy / Epistar was statistically significant (p=.002), and the difference between GE and United Epitaxy / Epistar was not statistically significant (p=.174), using exact p-values from exact Poisson regressions.

[36] If cumulative measures of LED patenting were considered, Asia would likewise emerge as playing an important role. Asian countries, particularly Japan, had strong early LED R&D, which is apparent in the 1990-1993 patent data.

Among our sample of LED patent invention worldwide, in 1990-1993 Japanese inventors led with 78.3 percent of LED patents, the United States followed with 10.7 percent, and all other countries each invented less than 3 percent. A decade later in 2000-2003, Japanese invented 41.6 percent of LED patents, Taiwanese 22.0 percent, Americans 13.9 percent, and Koreans 12.9 percent of patents. Clearly by 2000-2003 more countries, notably Taiwan and Korea, were locations for LED R&D.[37] Hence, these results indicate a possibly greater role of Asian inventors, when patents applied for in Asian nations are considered along with those in U.S. and European nations.

Other Indicators of R&D

Other indicators of globalization and Asian strength in LED innovation are international joint ventures and licensing agreements. Joint ventures in LEDs occurred between each of the big three traditional lighting firms and other international firms, as discussed earlier, all in 1999, with all three subsequently acquiring the joint ventures. International cross-licensing agreements, listed in Table 5, now exist between Philips (Dutch) and OSRAM (German), Philips and Nichia (Japanese), Philips and Toyoda Gosei (Japanese), OSRAM and Nichia, OSRAM and Seoul Semiconductor (Korean), OSRAM and Avago (American), Cree (American) and Nichia, and

[37] Japanese firms dominate the rankings when patents granted worldwide are considered. In the period 1990-1993, 9 of the top 10 ranked firms were Japanese. The five highest ranking firms by LED patents were Hitachi (35 patents), NEC (31), Toshiba (30), Mitsubishi (27), and Sanyo (23). Eastman Kodak (United States) was the only non-Japanese firm in the top 10 during the period 1990-1993. By 2000-2003, the top five ranking firms for LED patents were also Japanese: Nichia (38), Hitachi (30), Sharp (29), Showa Denko (26), and Citizen (25), and 8 of the top 10 were Japanese. Even among the Japanese firms, however, only Hitachi, Sharp, and Matsushita stayed in the top 10 ranking over the decade. The dominance of Japanese firms could, however, reflect differences in patent systems such as how often multiple claims are combined in one patent, coupled with the fact that firms are typically most likely to apply for patents in their home countries as well as possible international locations. The two non-Japanese firms in the top 10 during the period 2000-2003 were Taiwanese: Epistar (founded in 1996) held sixth place with 24.5 patents, and United Epitaxy (founded in 1993) held ninth place with 18.5 patents. The big three traditional lighting firms did not make the top 10 by this measure: Philips/Lumileds is ranked in 12th place, Osram plus Siemens in 15th place, and GE plus Gelcore in 36th place. Two Korean firms, LG and Samsung, were in the top 20. When only patents granted on multiple continents (a measure of high value) are considered, U.S. inventors are responsible for a slightly larger percentage of the sample than indicated here.

Cree and Seoul Semiconductor. The table also indicates other international licensing, disputes, and strategic research partnerships. The evidence indicates considerable global dispersion and a growing Asian contribution in LED innovation.

TABLE 5. Globalization of LED Patents: Licenses, Alliances, and Disputes

	Philips (Lumileds)	**OSRAM**	**GE Lumination**	**Cree**	**Nichia**	**Seoul Semi-conductor**
Philips (Lumileds)						
OSRAM	Cross-license					
GE Lumination						
Cree		Chip supply from Cree				
Nichia	Cross-license	Cross-license	Strategic alliance	Cross-license		
Seoul Semi-conductor		Cross-license		Cross-license	Lawsuits	
Epistar	Dispute				Dispute (resolved)	
Toyoda Gosei	Cross-license				Settlement	Strategic partnership
Citizen		Dispute (resolved)			White LED license	
ROHM		White LED license		License		
Lite-On		White LED license		License		
Kingbright		Lawsuit		License		
Others		White LED licenses; Cross-license; Dispute[a]		Licenses; lawsuit[b]	Investment[c]	

SOURCE: Ledsmagazine.com, 2007.

NOTES: Cross-licenses are agreements to share rights to large numbers of LED patents. A "license" indicates that a firm acquired the right to use a patent owned by a firm at the top of the table. White LED licenses pertain specifically to patents for white-light-producing LEDs. A "dispute" indicates a patent lawsuit brought by a firm at the top of the table against another firm. The "settlement" between Nichia and Toyoda Gosei involves patent infringement lawsuits that

had been brought by each firm against the other. Strategic alliances and strategic partnerships are joint LED technology development efforts involving the two companies indicated.
[a] OSRAM has white LED patents licensed to Harvatek, Vishay, Samsung SEM, Everlight, Ya Hsin, Lednium (Optek); a cross-license with Avago; and a resolved dispute against Dominant.
[b] Cree has LED patents licensed to Cotco and to Stanley and a lawsuit against BridgeLux.
[c] Nichia has an investment in and chip-license agreement with Opto Tech.

NATIONAL PROGRAMS AS INNOVATION DRIVERS

Promoting R&D

The development and market penetration of LEDs is closely linked with government policies and national programs. This is not uncommon in the semiconductor industry. For example, Japan saw extensive growth in semiconductor R&D, which displaced U.S. leadership in the DRAM market, following a mid-1970s research program (Macher et al., 2000). There appears to be a correlation between countries' national research programs for LEDs and innovative activity in those countries. Key LED programs exist in the United States, Japan, Taiwan, and South Korea, precisely those countries that dominate LED patenting. China recently announced programs targeted toward LED innovation and high-technology industries in general. Judging by the impact of similar research programs in other nations and import of U.S. and Taiwanese talent, China may become an additional key player in the LED industry.

While national programs collaborate extensively with universities and research labs, such institutions account for only about 4 percent of all LED patents, reflecting the limited funding available for commercializing their basic research. Nonetheless, university spin-offs have often created major companies such as Cree (with a market capitalization of $1.69 billion and revenue of $385 million in 2005). Universities and research institutions appear most innovative in Taiwan and Korea, accounting for about one-half and one-fifth, respectively, of all LED patents filed by universities and research institutions.[38] The remainder is split fairly evenly among the United States, the United Kingdom, Japan, and Belgium. Interestingly, China also features, filing 9 percent of all LED patents by universities and research institutions. With the exception of Belgium, each of these countries has a national program dedicated to development of LED lighting, with goals to improve energy efficiency and gain market share in general illumination, as outlined in Table 6.

TABLE 6. Major National Research Programs Pertaining to LEDs

Country, Funds[a]	**Program**	**Phase & Objectives**	**Funding**	**Organizations**
USA[b] estimated $42.1 mil/year (2003-2013); includes anticipated extension of funding	Energy Act of 2005: Next Generation Lighting Initiative (NGLI)	• 2007-2009: support research, development, demonstration, and commercial applications	$50 mil a year authorized from 2007 to 2009	Partnership DOE, industry, universities & laboratories
		• 2010-2013 extension	Extended authorization to allocate $50mil/year from 2010-2013	
	SSL Project Portfolio (current projects in NGLI)	• Completed projects 2003-2005: six key research areas: quantum efficiency, longevity, stability and control, packaging, infrastructure, and cost reduction	Total: $70.9 mil	Partnership DOE, industry, universities & laboratories
		• Current projects through 2008: LED and OLED		

[38] Research output at universities has often been measured by journal publication rather than patents, but it would be difficult to use a publication-based measure here without possible language-related biases (non-English speakers frequently publish in non-English journals not catalogued in available publications databases). Our measure of patents rather than publications may be more pertinent to applied than to basic research. The numbers are based on all patents (including national patents) during the period 2000-2003.

Country, Funds[a]	Program	Phase & Objectives	Funding	Organizations
Japan estimated $7.5 mil/year (1998-2008)	Light for the 21st century, New Energy and Industrial Technology Development Organization (NEDO)	• 1998-2002 (first phase): develop GaN-based LED technology for lighting applications	Yen 6bln ($52 mil)	Japan R&D Center of Metals (JRCM)
		• Develop 13% market penetration by 2010 (over 477 new patents already filed in one year)		13 companies and universities
		• Produce 120 lm/w and 80% efficiency by 2010		
	Ministry of Education, Culture, Science & Technology	• Financial year 2004: develop medical equipment and therapeutic techniques based on LEDs	Yen 500 mil ($4.6 mil)	Several universities, more than 20 companies
		• Similar amounts of funding expected next 4 years (2005-2008): establish the Yamaguchi-Ube Medical Innovation Centre (YUMIC)	$4.6 mil/year 2005-2008	
		• White HB-LEDs		
South Korea[c] estimated $59.4 mil/year (2001 - 2008); excludes equipment value, and half of LED Valley as "fiber-to-home"	Semiconductor Lighting National Program & KOPTI (Korea Photonics Technology Institute)	• 1993-1996 (R&D by LG, Samsung, universities, and Korea Research Institute): reduce use of glass, phosphors, heavy metals	KOPTI receives $20 mil/year in funding	KOPTI's costs covered 73.1% by government, 16.5% by Gwanju "City of Light," 10.4% by industry
		• 1999-2000 (business phase, JVs, production runs): meet environmental regulations July 2006	KOPTI equipment value: $65 mil	
		• Save $20 bil on energy		
		• 2001 (activation phase, growth to more than 340 companies): produce 80 lm/W white LED by 2008		

Country, Funds[a]	Program	Phase & Objectives	Funding	Organizations
	LED Valley Project	• 2005-2008: develop HB-LED	$100 mil (first phase)	Gwanju "City of Light," mix of national and local government and private-sector investment
		• 2005-2008: second phase of a photonics industry project for HB-LEDs	$430 mil (second phase HB LED & fiber-to-home)	
		• Deploy fiber-to-the-home networks		
Taiwan estimated $4.0 mil/year (2002-2005)	Next Generation Lighting Project	• 2004-2005 (40 lm/w): improve performance of white LEDs	2004-2005: NT$383 mil ($11.5 mil)	Consortium of 11 companies
		• Second phase (60lm/w): 100lm/w output in labs		
	National Science Council	• Circa 2002-2004: producing highly efficient LEDs	NT$12 mil ($0.4 mil)	NSC department of science & engineering
		• Led to 14 new patents and 20 new manufacturing process technologies		
China[d] estimated $248.8 mil/year (2005-2010); only includes initial investment for five parks and the 5-year plan; not directly comparable to other nations' figures as this includes manufacturing site investments	Semiconductor Lighting Project	• Five parks established in Shanghai, Xiamen, Dalian, Nanchang, Shenzhen: establish industrial parks with up-, mid-, and down-stream products; first phase likely to be 2005-2010: collaboration with Taiwan and specialists from Taiwan and U.S.; anticipate $19 bil LED industry by 2010	Total investment: Yuan 10 bil ($1.2 bil), allocated as follows: Xiamen: $1.9 mil (with focus on opto-electronics), Dalian: $150 mil, Shenzhen: initial investment 3 bil Yuan ($375 mil); total 20 bil Yuan ($2.5 bil) over 3-5 years (2005-2010)	Xiamen: three companies and government & cooperation with Taiwan; Dalian: JV between companies and science & technology group; Shenzen: university, local city government support & 200 companies
	National Solid	• 2015 goals: savings	2006-2010:	15 research

Country, Funds[a]	Program	Phase & Objectives	Funding	Organizations
	State Lighting project as part of 11th 5-Year Plan	from large-scale conversion to LED; 100 bil kW/h annually by 2015	$44 mil	institutions & 2,500 companies
		• 150 lm/W LED and capture 40% of incandescent market		
		• Reduce environmental pollution		
		• Develop strong industrial base		
		• International cooperation if necessary		
E.U. estimated $16.3-32.5 mil/year (2002-2006) est. assuming 5-10% dedicated toward LED	Sixth Framework program	• Strengthen science & technology base for international competitiveness	$1.3 bil earmarked for nano-technology (with IST section)	

[a] The yearly fund flow was estimated as an annual mean of all funding programs over the entire time range of the programs. All figures in US$.
[b] Presidential budget for fiscal year 2006 includes request of $11 mil for SSL.
[c] Korea also has a national program for LCD and displays, from 2004-2008. Key players are LG and Samsung. No funding information.
[d] China's "863 Program," or National High Technology Research & Development Program, includes development of OLEDs as a focus.

SOURCES (in order of table): DOE (2005, 2006), Japan Research and Development Center of Metals' National Project (2000), Stevenson (2005), Compound Semiconductor (2004), Chiu (2004), Yahoo! News Australia & NZ (2004), Tang (2006), Ledsmagazine.com (2005c, 2005a), Steele (2006), European Commission Community Research (2002).

Often the dedicated lighting program benefits from other supporting legislation or programs. For example, the U.S. initiative to develop LEDs may be partly driven by programs such as Vision 2020, an industry-led program to develop a technology roadmap for lighting, initiated by the U.S. Department of Energy. The program's goals are to develop standards for lighting quality; increase demand for high-quality lighting solutions; strengthen education and credentials of lighting professionals; provide R&D incentives to accelerate market penetration of advanced lighting sources and ballast technologies for superior quality, efficiency, and cost-effectiveness; and develop intelligent lighting controls and flexible luminaries/system delivery platforms (DOE, 2000). Apart from aims to establish integrated energy-efficient lighting systems, the program has also launched the Energy Star voluntary labeling program designed by the EPA and the National Appliance Energy Conservation Act that bans low-efficiency magnetic ballasts. Grants awarded by the DOE in 2006 totaled nearly $60 million, with a further $12 million provided by contractors (DOE, 2006). Some 65 percent of the DOE grants were awarded to firms, with the remainder split about equally between research laboratories and universities.

Similarly, Japan has an LED association that promotes R&D and standardization in the LED industry. As well as aiming for energy-efficient lamps, the association has established a medical innovation center that conducts R&D on LED use in medical equipment and therapeutics. A 1979 Energy Conservation Law in Japan, updated in 1999, has been a key driver of energy conservation in factories, buildings, machinery, and equipment. Japan is the second-largest government supporter of R&D in general, after the United States, investing $90.3 billion in 1997. Of this budget, $6.8 billion was allocated toward national energy-related R&D—64 percent public sector and 36 percent private sector (Dooley, 1999).

South Korea's lighting program is supported by a government-backed organization, Korea Photonics Technology Institute, which aims to produce 80 lm/W white LEDs by 2008 and invests $20 million per year. Funding stems mainly from the government (73.1 percent), but also from industry (10.4 percent) and the "City of Light", Gwanju (16.5 percent). Gwanju is the center of the LED Valley project in Korea, aimed at penetrating LEDs into television backlighting by 2006, car lighting by 2008, and domestic lighting by 2010. Investment is significant at $100 million for the development of HB LEDs (plus $430 million partly for fiber-to-the-home) from 2005 through 2008. In addition, the Korean private sector, namely Samsung and LG, are investing in LCDs and OLEDs, using Korea's LED infrastructure as a platform. *Chaebols* such as Samsung and LG are doing so through their business units and research labs, as well as a partial spin-off in the case of LG, in which it still has a 60 percent equity stake. But there have also been new startups for epiwafer foundries, substrates/GaAs ICs, and fiber optic components—many set up by researchers from Samsung and LG or by university professors (Whitaker and Adams, 2002).

Taiwan has had support from the National Science Council for LED research. Together with a consortium of 11 companies, Taiwan has invested $11.5 million in LED research and development during the period 2003-2005. The second phase, to produce high-efficiency LEDs, is expected to receive $0.4 million in funding. The goal is to produce 100 lm/W output efficiency of LED bulbs in laboratories. In addition, Taiwan has a 6-year national initiative on nanotechnology worth $700 million, some of which is dedicated toward LEDs (Liu, 2003).

China has budgeted $44 million to address solid-state lighting R&D needs as part of its 11th Five Year plan. The program will include 15 research institutions and university labs, and more than 2,500 companies involved in LED wafers, chips, packaging, and applications (Steele, 2006). The country expects to be the largest market for LEDs in the world, although it acknowledges a 6- to 20-year lag behind Japan, Europe, and the United States in LED device technology (Steele, 2006). The key driver behind the lighting project is energy savings. The goal is to penetrate 40 percent of the Chinese incandescent lighting market with 150 lm/W LEDs. The program has been responsible for the establishment of five industrial parks in China during 2004 and 2005, backed by government, company, and university investment. The objective of the program is to save 30 percent of energy spent on lighting, the same as generated by the Three Gorges Project, in the next 15-20 years. An underlying national solid-state lighting project by the Ministry of Science and Technology aims to reduce environmental pollution and improve technology to develop a strong industrial base. Apart from its dedicated semiconductor lighting project, China is investing heavily in the semiconductor and advanced material industries in general. China is also focused on collaborating internationally to develop its semiconductor industry, recruiting talent particularly from Taiwan and the United States.

One aspect that stands out among national LED programs is that Europe appears to be lagging behind the United States and Asian countries. The European Union's Fifth Framework Program funds five research areas: nanotechnology, genomics and biotechnology, information technology, aeronautics and space, and food safety and health risk. The funding for the period 2002-2006 is $17.5 billion. Of this, $3.4 billion is assigned to the Information Society Technologies program which includes research into semiconductor technologies and LEDs. The program funds research institutions, universities, and other organizations. The lack of specific initiatives for LED innovation may explain European countries' minor share of LED patents.

Some European countries have more specific programs dedicated toward LEDs. In September 2006, for example, the German Ministry of Education and BASF inaugurated a new research lab, the Joint Innovation Lab (JIL) (BASF, 2006). The JIL is a cooperative effort between 20 BASF experts and industrial and academic partners researching new materials in organic electronics, concentrated particularly on OLEDs for organic photovoltaics and appliances in the lighting market (OPAL). The German Ministry of Education and Research intends to invest around $800 million in the OPAL project. In addition, BASF spends over $1 billion on R&D each year. It is hoped that the projects will strengthen Germany's position in the emerging market of organic electronics and create the scientific and technological basis for initiating the production of OLED-based lighting (*A to Z of Materials*, 2006).

In the newer technology of OLEDs, much of the work is concentrated in research institutions and academia, both domestically and abroad. To be commercially viable, OLED research requires substantial infusion of capital. Foreign industry, heavily funded by their governments, could develop an insurmountable lead in the technology, making it very difficult for U.S. manufacturers to compete, if the U.S. government does not provide comparable support. With appropriate support from government and industry, commercialization could occur in as little as 5 to 8 years (Tsao, 2002).

A push is also being made to pursue good white LEDs, the "holy grail" of LED lighting. Analysis of PIDA data compiled by DigiTimes shows that each of the aforementioned countries are investing in white LEDs. The United States is investing $50 million over 10 years, Korea $23.4 million over 5 years, Japan $10.7 million over 5 years, Taiwan $4.6 million over 3 years, China $3.3 million over 3 years, and Europe $1.0 million over 4 years (Wang and Shen, 2005).

Demand Drivers

To spur innovation indirectly, regulations and incentives for energy-saving technologies can enhance demand for new lighting technologies. In a study comparing U.S. and Japanese lighting industry conservation measures, Akashi et al. (2003) found that conservation can be encouraged by regulation, incentives, and awareness campaigns. The U.S. Energy Policy Act of 1992 prohibited manufacturing and import of lamps that do not meet efficiency standards and mandated that lamp lumen output, efficiency, and life be printed on packaging, making it easier for consumers to compare and select more energy-efficient products. Nevertheless, consumers still experience considerable confusion in choosing lighting, particularly for residential settings. In new construction, builders have generally installed basic lighting packages that lack energy efficiency and other quality improvements in favor of lower capital costs (rather than lower operating costs). Bridging the gap between available lighting technology and consumer knowledge is a significant challenge and one that in Japan is met jointly by government and industry initiatives.

Future diffusion of LED lighting may reflect patterns now apparent for CFLs, which, although more efficient than incandescent and halogen lamps, have achieved low penetration in the U.S. market. Only about 2 percent of sockets nationwide, and 4 percent in California, now use CFLs. Flicker, color, upfront cost, and other drawbacks have contributed to their slow adoption, so that greater energy efficiency alone seems insufficient to penetrate much of the market, although the efforts of Wal-Mart to promote CFLs may result in a significant change in consumer behavior.

IMPLICATIONS AND POLICY RECOMMENDATIONS

This chapter has documented a shift taking place in the lighting industry. Traditional lamps are being replaced with CFLs. While the early traditional lighting industry was dominated by three big companies—GE, Philips, and OSRAM—as production of lamps became commoditized competitive pressures in lighting increased. Lower prices and margins shifted production of traditional lamps to Asia, especially China, the largest source of lamp imports in the United States. Improvements in lamp efficiency led to the development of fluorescents and other types of lamps, which successfully penetrated commercial and industrial markets and are poised to enter U.S. residential markets after years of delay among consumers who lacked awareness and were unwilling to spend money up front for savings later on.

A new lighting technology, LEDs, is leading to a shift in how we view lighting. LEDs have already penetrated end-use markets for automobile brake lights, signs and displays, backlighting, and traffic signals. Investments in the development of white LEDs are setting the stage for the use of LEDs as general illumination and threaten the traditional lighting industry and its three big players. LEDs are a disruptive technology that has allowed many new players to enter the lighting market. While Japan and the United States dominate the LED market in terms of R&D and revenue, their market share is being eroded by fast-growing entrants, especially from Taiwan. Taiwan leads global production of blue (GaN) LEDs (Wang and Shen, 2005), has the second- or third-largest amount of LED patents by our counts in 2000-2003, and has two firms high on our LED patent ranking tables.

Philips, OSRAM, and GE were not involved in the early stages of LED technology development. It was only in 1999 that the big three decided to enter the LED market through a series of joint ventures that the companies later acquired. These firms may further build their strengths in this technology through acquisition. In mid-June 2007, Philips acquired Color Kinetics for approximately $791 million.[39] These big three firms appear to have established dominant positions in LED technology, judging from our patent analyses. However, it remains to be seen whether the big three will replicate the tight oligopoly they held in the traditional lighting industry in most of the 20th century. Partly this is because the semiconductor supply chain is fragmented as firms in this sector are typically not vertically integrated; by specializing, companies are able to keep costs down. Our analysis indicates that LED producers likewise

[39] At the time of the announcement Color Kinetics had 71 patents granted and over 15,000 installations. The merged entity will operate under the name Philips Solid-State Lighting Solutions, with intelligent and premium LED product lines ultimately co-branded Philips/Color Kinetics (Color Kinetics, 2007).

operate at various stages of the supply chain and do not integrate vertically. This means that the LED market has witnessed many new entrants and has also created opportunities for new ventures in areas such as system controls and integration.

Although LEDs have some clear advantages over traditional lamps, such as added flexibility, integration with digital systems, and higher energy savings, they are also still costly to produce. The question remains when (indeed whether) white LEDs will successfully displace traditional general illumination technologies, especially among residential buyers. Evidence from CFL, HID, and other efficient traditional technologies shows low penetration rates among consumers. To aid success of LED lighting, therefore, governments might not only fund basic R&D but also promote awareness among consumers so that LED lighting products diffuse in the residential market. Governments worldwide are making significant investments into LED R&D and promotion of the technology. Government programs, such as the one in the United States, have allowed small startups and university research labs to make progress on LED R&D and gain a foothold in this new market.

U.S. and Asian government programs, in particular, have made the largest investments. China, which is still at the early stages of ramping up capacity and technology to produce LEDs and therefore lagging behind other countries, is addressing R&D in solid-state lighting as part of its 11th Five Year Plan and is setting up five business parks dedicated to these new lighting technologies. China has a strong interest to meet its own energy-efficiency needs. Already, there is a trade imbalance between China and the United States for semiconductors generally. In 2002, the United States imported $6.4 billion worth of semiconductor products from China, while exporting only $2.2 billion worth (Holtz-Eakin, 2005). Given its investments in R&D, China might become an important player in the global LED market.

Analysis of these trends indicates that Asian countries such as Japan and Taiwan, and possibly China and Korea, are poised to take an increased role in R&D, production, and diffusion of LED technology. Evidence provided by the patent analysis suggests a potential shift toward these Asian nations. Extensive public and private investment will help if the United States is to keep up with the opportunities presented by these new technologies. Moreover, efforts to encourage consumers to use solid-state lighting as it becomes efficacious in new applications may help domestic markets to grow and support the commercialization of these important energy-saving technologies.

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