INDUSTRY STUDIES ASSOCATION
WORKING PAPER SERIES

Innovation Challenges in the Lighting Industry from 1990 to 2006

By

Susan Sanderson
Judith Walls
Yin-Yi Lai
Lally School of Management and Technology
Rensselaer Polytechnic Institute
Troy, NY 12180

Kenneth Simons
Department of Economics
Rensselaer Polytechnic Institute
Troy, NY 12180

2007
Industry Studies Association
Working Papers

WP-2007-29
http://isapapers.pitt.edu/

INNOVATION CHALLENGES IN THE LIGHTING INDUSTRY FROM 1990 TO 2006

Susan Walsh Sanderson, Kenneth L. Simons, Judith L. Walls, and Yin-Yi Lai[1]

Rensselaer Polytechnic Institute

February 11, 2007

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 threat from low cost imports, but solid-state lighting, an innovative technology with much greater 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

[1] Partial funding is gratefully acknowledged from the Alfred P. Sloan Foundation and from the Center for Future Energy Systems at Rensselaer Polytechnic Institute. Insightful comments on an earlier draft were kindly provided by Kevin Dowling, Jeffery Macher, Bill McNeill, Klaus Minich, David Mowery, and David Simons.

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. While 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 paper 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 electroluminescence 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 non-traditional technology considered because they are the only alternative lighting approach that has reached sufficient maturity to be considered commercially viable in the trade, technology, and technical literatures.

This paper 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 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. 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, more cutthroat 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. Asia has led (by a slim margin) in patent invention for solid-state lighting, although firms headquartered in the U.S. and Europe also are making key contributions to these new technologies. Both new firms and incumbents are investing heavily in solid-state lighting technology, 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 research and development, and incubating startup companies as they seek to commercialize these new technologies. But retail firms like Walmart 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 $40-100 billion, about a third of which represented lamps.[2] U.S. apparent consumption of lamps, fixtures and other equipment totaled about $14.8 billion in 2004.[3] U.S. production of lamps grew steadily until the early 1970s, then fluctuated over the next twenty 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. 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 last two decades. Total imports, as a percentage of U.S. apparent consumption, increased from less than 20% in 1989 to around 50% in 2004, as shown in Figure 2. 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% of lamps were imported from China. By 2004, Chinese lamp imports represented 26% of all lamp imports, having grown more rapidly than imports from any other supplier nation, and 10% of apparent lamp consumption in the U.S. 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 out in Figure 2, these trends are more intense, with 86% of all fixtures imports in the U.S. 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

---

[2] Hadley et al. (2004) cite the figure of $40 billion, a 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.

[3] 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.

Thomas, the largest lighting fixture and control company in North America, manufactures 70% of its products in the North American region in order to keep close to its design centers and customers (Genlyte Thomas, 2005). It is introducing new energy-efficient light fixtures using compact fluorescent (CFL), high-intensity discharge (HID), and LED lamps and 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 specialty lighting applications, such as Christmas decorations, under-water lighting, and infrared and ultraviolet lamps. This sector grew steadily throughout the second half of the twentieth 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 General Electric (GE).[5] All three firms produce a wide 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 U.S., 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% market share. GE eventually gained even greater market dominance, so that by 1927 GE and its

[4] Figures 1 and 2 use 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 high-intensity discharge 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.
[6] Philips Lighting employs about 45,500 people and has 70 manufacturing facilities worldwide (Philips, 2006 p. 38).

licensees held 97% 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 twentieth 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 1990-1993 were identified using data for the US and Western Europe.[8] As noted above, we define traditional lighting to include incandescent, gas discharge, and electric arc lighting (which includes fluorescent, high intensity discharge, 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 case of multiple assignees); 232.1 applications

---

[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 U.S. (1,589 applications), Europe (976), Austria (190), 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).

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

Incandescent lamps in the U.S. account for a majority of household sales, but a smaller portion of total sales. In households, incandescent lamps represent 66.5% of sales revenues, while fluorescent and other lamps remain uncommon (Mintel, 2003). Residential sales, however, make up less than 10% of lighting demand measured in lumen-hours. Combining all economic sectors (residential, commercial, industrial, and outdoor) incandescent lamps represent 11.0% of

[9] A German patent trust, Patra Patent Treuhand, had 185.7 applications. The next three firms in number of patent applications were Toshiba with 70.2 applications, Motorola had 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 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.

lumen-hours of light output, as compared to about 57.5% for fluorescent, 31.0% for HID and 0.01% for solid-state lighting (Navigant, 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 U.K., more than three quarters of these improvements originated in countries where the big three were headquartered, the U.S., 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 the use of large-molecule gases filling incandescent lamps 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 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. General Electric (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

[10] We catalogued 134 improvements in lamp technologies between 1705 and 2005. Sources: company websites of GE, OSRAM, Siemens, Philips, and Toshiba; websites of Bellis (no dates), Williams (2005), and Arthur (no date), and Bowers (1982).

place during the first half of the last century and are documented in Bright (1958, pp. 22-30). In the latter half of the century, improvements focused largely on improved efficiency and longer lamp lives. Discovery of substances such as narrow-band phosphors led to the development of compact fluorescent lamps (CFLs), gases such as xenon yielded brighter lamps as used in automobiles, and similar improvements had medical uses including ultraviolet (UV) lamps.

While 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% of total energy used in residential and commercial sectors in the mid-1990s, as shown in Figures 3 and 4 (DOE, 1993, 1995, 1997). In 2001, 51% of the national energy consumption for lighting occurred in the commercial sector, 27% in residences, and 14% in industry; the remaining 8% was used in outdoor stationary lighting (Hong et al, 2005, p. 2). Almost half of electricity used in commercial buildings is used in lighting, as Figure 5 indicates. In the U.S., residential homes largely use incandescent lamps (90%), whereas commercial and industrial sectors use mostly fluorescents (Hong et al, 2005). If residential homes in the U.S. replaced all incandescent lamps with CFLs, they would save an estimated 35% of electricity used for all lighting applications (DOE, 1993).

Although advances in energy saving lighting technologies such as CFL lighting have been 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 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, 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 U.S. is behind the rest of the world in adoption of energy saving lighting technologies (Sandahl et al, 2006). This may soon change as 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 up-front costs and misconceptions about the efficacy of fluorescent lights (early fluorescents had poor color rendering and were noisy) led to low adoption in residences. Optimal lamp choice involves not only energy efficiency but replacement costs for burned-out lamps and labor costs to install lighting systems. In commercial and industry settings, where life cycle costs are important and companies can make upfront investments, fluorescents are usually chosen.

RADICAL INNOVATION IN LIGHTING – LEDS

Nature and Advantages of LEDs

A light-emitting diode (LED) is a semiconductor diode. It is electroluminescent, emitting color that depends on the chemical composition of the semiconductor material or compound used

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

and ranges along the spectrum from ultraviolet to infrared, as documented in Table 1. 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 longstanding 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 the predominant light sources remain incandescent and fluorescent lamps, LEDs have several potential advantages. First, they use less energy. LEDs are 3-4 times more efficient than incandescent and halogen sources. However, with the exception of laboratory devices, LEDs still fall short of fluorescent sources. Nevertheless, they are semiconductor devices and LED lighting is thought to follow an equivalent of Moore's law in computing and expected to advance rapidly and continually.

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 ten years of on-time, twice that of fluorescent lamps and twenty times that of incandescent lamps. In terms of luminous efficacy (lm/W), LEDs are already about four times as efficient as incandescent lamps, and by 2020 they are targeted to be about twelve times as efficient as current incandescent lamps and more than twice as efficient as current fluorescent lamps (Tsao, 2002, p. 4; Hadley et al, 2004, p. 5). 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 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 (Tsao, 2002, p. 8; Hadley et al, 2004, 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 (Tsao, 2002, p. 8; Hadley et al, 2004, 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 not generate ultraviolet 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]

At present, LEDs are the only viable technology competing with the various types of traditional lamps as electricity-driven sources of illumination (Hong et al, 2005). 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 technology including OLED displays (Hong et al, 2005). 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.

---

[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 since heat degrades LEDs; relevant heat sinks are improving.
[14] White OLEDs so far have achieved a power efficiency of 25-30 lm/W (Burgess, 2006; Physorg.com, 2005).

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, novel technology fills a longstanding need and the expertise and equipment of traditional lighting manufacturers does little to help them with this new approach. Second, new firms have been entering the lighting market by creating products based on LEDs, and it is 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 so manufacturing 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 much more disintegrated than in traditional lamp production.[15] This supply chain is illustrated in Figure 6. 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.

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 high-intensity discharge) are

[15] Kevin Dowling, chief Technology Officer at Color Kinetics, stated to us that "the vertically integrated giants of the semiconductor world such 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. 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.

estimated by Navigant (2003a, p. 7) to have used 41,051 trillion lumen hours of electricity in the U.S. in 2005 compared to only 5 for LEDs. Nevertheless, the LED market grew 50% between 1995 and 2000, and has been forecast as $4.7 billion by 2007 (Ashdown et al, 2004, p. 9).

LED technology has some clear advantages over traditional lighting and these have allowed LED manufacturers to displace traditional lighting markets 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. In 2001, 30% of LED sales were for backlighting, 26% for automotive uses, 26% for signs and displays, 10% for electronic equipment, 4% for signals, and 4% 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%), truck and bus lights (41%), and traffic signals (30%) (Navigant, 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 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 of response time and therefore help to prevent accidents. While 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% reduction in freezer lighting energy costs (LIGHTimes, 2006).[16]

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 respectively 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 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, the holy grail needed to complete the palette. At the time, large Japanese corporations were spending $85 million a year and Nichia did not have a research budget. Today Nichia controls 80% 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

[16] Wal-Mart installations developed in collaboration with GE and Royal Philips Electronics 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).

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. In pursuit of emerging LED technologies, government grants have been instrumental to support startup companies and university research. 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-out, 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 U.S. We will return to the role of national policies and government initiatives later in this paper.

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.[17] 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.[18] GE established a joint venture, Gelcore, with semiconductor maker Emcore in 1999, and acquired Gelcore in August 2006 for $100 million.[19] Additionally, Philips and OSRAM announced in January 2007 a cross-licensing agreement covering patents on LEDs and OLEDs (LIGHTimes, 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

---

[17] Philips' 2005 Annual Report states that Lumileds is the world's leading manufacturer of high power LEDs.
[18] Siemens gradually spun off its semiconductor division as Infineon beginning in 1999, and sold its final 18.23% stake in the company in 2006.
[19] Although Gelcore grew about 50% from 1995 through 2004, it nonetheless reported a net loss of $0.8 million in 2005. Thus when Emcore sold its 49% stake in Gelcore, it traded possible future value for immediate cash gains.

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., owned 90% by OSRAM, was formed in April 1995, with an investment of 49.7 million Euros. The company is located in Foshan, China, and has two factories in China, employing 6,000 people (OSRAM China Lighting). In February 2006, OSRAM China Lighting announced it would acquire Foshan Electrical and Lighting Co. Ltd.[20]

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%, although a portion of these revenues are shared with

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

some U.S. companies through joint ventures. Taiwan's industry holds second place at $712 million, or a market share of 25% (Taiwan Economic News, 2004a, 2004b). 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 51.3%, Taiwan's 22.7%, the U.S.'s 12%, and Europe's around 9% (Ledsmagazine.com, 2005b). Data from www.solidstatelighting.net suggest that most LED R&D is conducted in the U.S. while Asia dominates manufacturing and packaging. For example, Taiwan, China, and Korea produced the majority of blue LEDs in the world, and more than 80% 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 its youth, standards to control the quality of LED technology have not yet been developed and implemented. For instance, there is no accepted standard for how companies need to report operating lifetimes, and partly as a result, LEDs fade at different rates that vary by manufacturer. The LED industry has seen a surge of new players which has flooded the market with low quality LEDs (Toniolo, 2006). The result of such commodity production is intense price competition for lower-performance LEDs and a "huge overcapacity" (Arensman, 2005). Nevertheless, conditions remain healthy in the market for high-performance LEDs.

New Ventures

The global semiconductor market was worth $235 billion in 2005 (Gartner, 2005), 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 producing LED lamps.[21] 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.[22] Even on a national level, specialization sometimes occurs. For instance, Taiwan is strong in R&D and manufacturing of LEDs, while Korea specializes in packaging, and China, a late entrant, is setting up epitaxy, wafer and chip production (Wang & Shen, 2005). In addition, some countries specialize in production of specific LED colors: Taiwan holds a majority market share for blue GaN LEDs at 34%, closely followed by Japan at 33%, while the U.S. and Korea lag with 19% and 12% respectively (Wang & Shen, 2005).

Although LEDs are still a small subset of the semiconductor market, the rate of growth is the highest in the industry, 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 high-brightness 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 created a new niche as a "systems solutions" and lighting control technology provider. Color Kinetics has initiated several

---

[21] 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.
[22] Based on information on semiconductor companies in the LED industry gathered from solidstatelighting.net.

major projects which 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.

LED LIGHTING R&D

The big three producers are dominant in traditional lighting technology, as shown above 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 since 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 tradeoff 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. International (and U.S. and European) patent classification systems do not identify specific categories for LEDs nor for LED lighting. All patents were identified whose title contains the words "LED" and "lighting", or the phrase "light emitting diode." This criterion includes LED-type displays and, to a lesser extent, lasers, as well as LEDs whose glow is bright enough for general illumination. All patents granted are included regardless whether they originated from firms, government programs, or university research labs.

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 U.S. and Europe.[23] Our 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.[24] Patents differ widely in quality, so some of our analyses focus solely on those relatively high-value patents for which an identical patent was filed for and granted on an additional continent.[25] Patents granted in nations outside the U.S. and Europe are considered after our main analyses.

Analysis of LED Patenting

The analyses below 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.

---

[23] Data are obtained from the Espacenet worldwide patent database, maintained by the European Patent Office. 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 nations, 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 sample are the European Patent Office plus the national offices of Belgium, France, Germany, the Netherlands, and the United Kingdom. Patents from former Soviet-bloc nations are excluded.

[24] 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.

[25] Hence when we use the term "multiple continents" later, we mean at least one country in at least two continents (including the U.S. or Europe). Among the patent authorities that actually granted patents in the data, they are: North America – United States, Canada, Mexico; Europe – Germany, Great Britain, Belgium, France, Netherlands, Hungary, former Soviet Union, European Patent Office; Asia – Japan, Korea, Taiwan, Singapore, India, China, Hong Kong; South America – no relevant patents; Australia plus New Zealand; and Africa – South Africa.

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 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 four-year periods a decade apart, 1990-1993 and 2000-2003. These four-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, LED patents granted tripled from 1990-1993 to 2000-2003, as shown in Figure 7. The same trend holds when patents granted worldwide are included in the data, with LED patents granted growing from 438 in 1990-1993 to 1,114 in 2000-2003.

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. In 1990-1993, inventors located in the U.S. predominated with 41% of all of the LED patents. Inventors in Japan held second place with 33% of LED patents. Inventors in

Germany and the U.K. ranked third and fourth with 9% and 6% of LED patents respectively. Taiwan appears in fifth place with 4% of LED patents.

By 2000-2003, U.S. inventors' still-dominant share of LED patents had fallen to 35%. Likewise, Japanese inventors continued in second place, but had fallen to 21% of LED patents. The highest growth in inventions originated in Taiwan with an 18% share, moving into third place ahead of Germany (increased to 10%) and the U.K. (decreased to 4%). South Korean inventors entered the rankings at 3% of LED patents in sixth place. Other nations with at least 1% of LED patent inventions included Belgium, France, Canada, and the Netherlands.

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 was the case is to examine only those relatively high-value patents for which firms went to the expense and trouble of obtaining equivalent patents on multiple continents. The percentage of these relatively high-value patents invented in each nation appears in Figure 10 for 1990-1993 and Figure 11 for 2000-2003.

By this high-value measure Japanese and U.S. inventors dominated, producing respectively 43% and 37% of the high-value patents in 1990-1993, and 32% and 28% in 2000-2003. Taiwanese inventors account for only 2% (1 high-value patent) in 1990-1993 and 12% (11 high-value patents) in 2000-2003. The later 12% of high-value LED patents suggests that a substantial R&D competence in LEDs may have emerged in Taiwan. In terms of high-quality patents, Taiwanese inventors (and the companies in which they work) represent the highest growth of internationalization of LED patenting, while Korean inventors' share of the high-value patents grew from 4% to 6%, inventions in Germany also grew from 4% to 6%, and the U.K. share fell from 6% to 3%.

Not only did LED innovation become 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 1990-1993, the U.S. was the only country whose companies supported LED R&D abroad. LED patents were invented by inventors in Japan, the U.K., and Germany for firms headquartered in the U.S. Of the eight U.S. patents (15.6% of U.S. patents) that had R&D locations abroad, HP was assignee for four (with inventors in the U.K. and Malaysia) and Eastman Kodak was assignee for two (with inventors in Japan).

By 2000-2003, more companies were supporting R&D across the globe. Overall, companies in nine countries sponsored LED R&D abroad. U.S. companies, however, kept 92.7% of R&D within the U.S. Asian LED invention sites for U.S. firms fell from 6.7% to 2.2%, and European sites for U.S. firms fell from 8.9% to 4.0%. In 2000-2003, U.S. companies' foreign-invented patents had inventors based most frequently in France (2.2%); Canada, the U.K., Malaysia, and Taiwan (1.1% each); and the Netherlands (0.8%). European companies began to support R&D in the U.S., which now yielded 12.9% of European companies' LED patents. Asian companies also began to carry out R&D in the U.S., yielding 3.1% of Asian companies' LED patents. Furthermore Europe yielded 2.4% of Asian companies' LED patents.

To a slight degree, the U.S. became an innovation hub for companies headquartered in other countries. Of the LED patents assigned to Dutch companies, 52.8% were filed by inventors located in the U.S., as were 40.0% of patents assigned to French companies, 7.0% of patents assigned to Taiwanese companies, and 3.6% of patents assigned to German companies.

Australian companies obtained 50.0% of their patents from invention in New Zealand. Germany was an R&D source for Dutch and Korean firms, the U.K. for German and Taiwanese firms, and France for British firms. (These conclusions are based on very small numbers of patents.)

There was a corresponding shift in the number of companies using inventors overseas. In 1990-1993, four U.S. headquartered companies sponsored LED research overseas totaling seven patents. In 2000-2003, 18 companies located in all parts of the world sponsored LED research overseas totaling 27 patents. This a substantial shift, but far from complete globalization, as even in 2000-2003 only 9.5% of LED patents involved work outside companies' headquarters nations; the majority of firms patented using inventors in their home country.

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

Many LED patents came from firms not in the traditional lighting industry, including established semiconductor firms and new firms. The new firms include systems integrator Color Kinetics (founded in 1997), semiconductor firm United Epitaxy (founded in 1993), and OLED micro-displays and virtual imaging company eMagin (founded in 1996). 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). Nonetheless, the evidence shows an important role in LED technology of Asian firms, representing more than half the firms listed in Table 4, and many new entrants, representing more than 60% of the firms listed in Table 4.[26] Hence, if LED technology develops as anticipated, there could be greater participation of 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 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 2000-2003 almost four times as many patents were granted worldwide as in the U.S. and Europe, and almost five times as many individuals were granted patent rights. The majority of individual filings originated in Taiwan (35.6%) and Korea (28.6%).

Among LED patent invention worldwide, in 1990-1993 Japanese inventors led with 78.3% of LED patents, the U.S. followed with 10.7%, and all other countries each invented less than 3%. A decade later in 2000-2003, Japanese invented 41.6% of LED patents, Taiwanese

[26] 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, as apparent in the 1990-1993 patent data.

22.0%, Americans 13.9%, and Koreans 12.9% of patents. Clearly by 2000-2003 more countries, notably Taiwan and Korea, were locations for LED R&D.

When only patents granted on multiple continents (our measure of high value) are considered, during 1990-1993 Japanese invented 50.0% of LED patents, Americans 29.2%, and Koreans 6.9%. By 2000-2003, Americans invented 29.6%, Japanese 26.8%, and Taiwanese 24.8%. While Taiwan's strength in LED R&D was evident in our analysis of patents granted in the U.S. and Europe, it is more apparent when patents granted worldwide are considered.

Japanese firms dominate the rankings when patents granted worldwide are considered. In 1990-1993, nine of the top ten 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 (U.S.) was the only non-Japanese firm in the top ten during 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 eight of the top ten were Japanese. Even among the Japanese firms, however, only Hitachi, Sharp and Matsushita stayed in the top ten ranking over the decade.

The two non-Japanese firms in the top ten during 2000-2003 were Taiwanese: Epistar (founded in 1996) held 6th place with 24.5 patents, and United Epitaxy (founded in 1993) held 9th place with 18.5 patents. The big three traditional lighting firms did not make the top ten 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 twenty.

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. Ocean-spanning cross-licensing agreements, listed in Table 5, now exist between Nichia (Japanese) and Philips' (Dutch) subsidiary Lumileds, and between OSRAM (German) and Cree (American). The evidence indicates considerable global dispersion and a growing Asian contribution in LED innovation.

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 U.S., Japan, Taiwan, and South Korea, precisely those countries that dominate LED patenting. China recently announced programs targeted towards 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% 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 $385 million revenue in 2005). Universities and research institutions appear most innovative in Taiwan and Korea, which account for about a half and a fifth, respectively, of all LED patents filed by universities and research institutions.[27] The remainder is split fairly evenly between the U.S., the U.K., Japan, and Belgium. Interesting, China also features, filing 9% 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. 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 luminaire/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 (NAECA) 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% of the DOE grants were awarded to firms, with the remainder split about equally between research laboratories and universities.

---

[27] 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 2000-2003.

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 U.S, investing $90.3 billion in 1997. Of this budget, $6.8 billion was allocated toward national energy-related R&D, 64% public sector and 36% private sector (Dooley, 1999).

South Korea's lighting program is supported by a government-backed organization, Korea Photonics Technology Institute (KOPTI), which aims to produce 80lm/W white LEDs by 2008 and invests $20m per year. Funding stems mainly from the government (73.1%), but also from industry (10.4%) and the "City of Light", Gwanju (16.5%). Gwanju is the center of the LED Valley project in Korea, aimed at penetrating LEDs into TV backlighting by 2006, car lighting by 2008, and domestic lighting by 2010. Investment is significant at $100 million for the development of high brightness 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 the LCD industry, 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% equity stake. But there have also been new start-ups 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 eleven companies, Taiwan has invested $11.5 million in LED research and development during 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 towards 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, chip, packaging and applications (Steele, 2006). The country expects to be the largest market for LEDs in the world, although it acknowledges a 6-20 year lag behind Japan, Europe and the U.S. in LED device technology (Steele, 2006). The key driver behind the lighting project is energy savings. The goal is to penetrate 40% of the Chinese incandescent lighting market with 150lm/W LEDs. The project 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% 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 U.S.

One aspect that stands out among national LED programs is that Europe appears to be lagging behind the U.S. and Asian countries. The European Union’s Fifth Framework Program funds five research areas, which include nanotechnology, genomics and biotechnology, information technology, aeronautics and space, and food safety and health risk. The funding for 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 effort 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 five to eight 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 countries mentioned above are investing in white LEDs. The U.S. is investing $50 million over ten years, Korea $23.4 million over five years, Japan $10.7 million over five years, Taiwan $4.6 million over three years, China $3.3 million over three years, and Europe $1.0 million over four 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 lamps' 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% of sockets nationwide, and 4% in California, now use CFLs.

Flicker, color, up-front 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 U.S. 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 U.S. 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. In doing so, they have become substantial players in the LED market, although it remains to be seen whether they will replicate the tight oligopoly they held in the traditional lighting industry in most of the 20th century. Partly this may be because the semiconductor supply chain is fragmented and fully horizontal integration is now rare; by specializing, companies are able to keep costs down. Our analysis indicates that LED producers likewise operate at various stages of the supply chain and do not integrate horizontally. This means that the LED market has witnessed many new entrants, and also created opportunities for new ventures in areas such as system controls and integration.

While 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 whether white LEDs will successfully displace traditional general illumination, 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 should 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 U.S., 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 U.S. for semiconductors generally. In 2002, the U.S. imported $6.4 billion worth of semiconductor products from China, while exporting only $2.2 billion (Holtz-Eakin, 2005). Given its investments in R&D, China might become an important player in the global LED market.

Analysis of these trends indicate that Asian countries such as Japan and Taiwan, and possibly China and Korea, are poised to take the lead in R&D, production and diffusion of LED technology. Certainly, the evidence provided by the patent analysis seems to support this statement. Extensive public and private investment will be necessary if the U.S. 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 will be necessary if domestic markets are to grow and support the commercialization of these important energy saving technologies.

REFERENCES

Akashi, Y., L. Russell, M. Novello, and Y. Nakamura. (2003). “Comparing Lighting Energy Conservation Measures in the United States and Japan,” working paper, Lighting Research Center, Rensselaer Polytechnic Institute.

Arensman, R. (2005). “LED Market Lights Up,” *Electronic Business* 31(4), p. 24.

Arthur, A. “A Unique History of the Light Bulb,” accessed December 2006 from http://www.contentmart.com/ContentMart/content.asp?LinkID=19298&CatID=328&content=1.

Ashdown, B.J., D.J. Bjornstad, G. Boudreau, M.V. Lapsa, B. Shumpert, and F. Southworth. (2004). “Assessing Consumer Values and Supply-Chain Relationships for Solid-State Lighting Technologies,” report ORNL/TM-2004/80, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

The A to Z of Materials. (2006). “BASF Open Organic Electronics Research Laboratory,” 11 September, website http://www.azom.com/details.asp?newsID=6627 (visited 22 Sept. 2006).

Barbaro, M. (2007). “Power-Sipping Bulbs Get Backing From Wal-Mart,” *New York Times*, Jan. 2.

BASF. (2006). “Joint Innovation Lab for organic electronics research with customers and academic partners,” PRdomain.com, September 11.

Bellis, M. “The History of Fluorescent Lights,” on about.com, accessed December 2006 from http://inventors.about.com/library/inventors/bl_fluorescent.htm.

Bellis, M. “Timeline of Electrical Lighting,” on about.com, accessed December 2006 from http://inventors.about.com/od/lstartinventions/a/lighting_2.htm.

Bellis, M. “The History of the Incandescent Lightbulb,” on about.com, accessed December 2006, http://inventors.about.com/library/inventors/bllight2.htm.

Bishop, A.L, R. Worrall, L.J. Spohr, H.J. McKenzie, and I.M. Barchia. (2004). “Response of *Culicoides* spp. (Diptera: Ceratopogonidae) to Light-Emitting Diodes,” *Australian Journal of Entomology* 43(2): 184-188.

Blue. (2005). Advanced LEDs. “The 3rd International Industry Review: LED Technologies Driving the Solid State Lighting Revolution.” Market data from Strategies Unlimited presented at the conference in Hsinchu, Taiwan, May 16-18. Accessed September 2006 from http://www.compoundsemi.com/blue2005/.

Bowers, B. (1982). *A History of Electric Light & Power.* Peter Pergrinus, Ltd.

Bright, J.R. (1958). *Automation and Management*. Boston: Harvard University.

Business Wire. (2006). “Avago Technologies Introduces New High Performance Extra Bright Oval LEDs for Outdoor Electronic Sign and Signal Applications,” Sept. 19.

Burgess, D.S. (2006). “Efficient White OLED Employs Down-Conversion,” LED Focus, Photonics.com, May.

Calwell, C., C. Granda, L. Gordon, and M. Ton. (1999). “Lighting the Way to Energy Savings: How Can We Transform Residential Lighting Markets? Volume 1: Strategies and Recommendations,” Prepared by Ecos Consulting for the Natural Resources Defense Council, San Francisco, California.

Chinesewings. (2005). “Philips Celebrate the Shanghai Innovation and Technology Park Lighting Project,” 1 August.

Chiu, Y.T. (2004). “Optical Devices to Replace Toxic Lighting Mechanisms,” *Taipei Times*, April 16.

Compoundsemiconductor.net. (2004). “Japanese LED Project Targets Medical Uses,” http://compoundsemiconductor.net/articles/news/8/7/26/1.

Compound Semiconductor. (2004). “Taiwanese Suppliers Target White LED Improvements,” *Compound Semiconductor*, March.

Cox, J.B. (2003). “Semiconductor-Maker Cree Gets Boost from Taiwan Court Ruling on Patents,” *Knight Ridder Tribune Business News*, 26 September: 2.

Cree. (2006). 2006 Annual Report. Accessed from http://www.cree.com/investor/annual.htm.

Dooley, J.J. (1999). “Energy R&D in Japan,” for U.S. Department of Energy, contract DE-AC06-76RLO 1830. Pacific Northwest Laboratory, Battelle Memorial Institute. Document number PNNL-12214.

European Commission Community Research. (2002). “The Sixth Framework Programme in Brief,” brochure, December, http://ec.europa.eu/research/fp6/pdf/fp6-in-brief_en.pdf.

Gartner. (2005). “Market Share: Semiconductor Revenue, Worldwide, 2005,” commercial market study.

General Electric. “Lighting: The Last 125 Years,” accessed December 2006 from http://www.gelighting.com/na/business_lighting/education_resources/learn_about_light/history_of_light/last_years.htm.

Genlyte Thomas. (2005). Annual Report, 2005.

Griffiths, T. (2006). “Solid State Lighting Success is Niche to Niche,” LIGHTTimes Online, December 11, p. 1.

Hadley, S.W., MacDonald, J.M., Alley, M., Tomlinson, J., Simpson, M., Miller, W. (2004). “Emerging Energy-Efficient Technology in Buildings: Technology Characterizations for Energy Modelling,” prepared for the National Commission on Energy Policy. Oakridge National Laboratory, U.S. Department of Energy.

Herkelrath, M., A. Laksberg, and L. Woods. (2005). “A Brighter Future: Advances in LED Energy Efficient Lighting Technology,” manuscript, University of Washington.

Holtz-Eakin, D. (2005). “Economic Relationships Between the United States and China,” Congressional Budget Office Testimony, Statement before the Committee on Ways and Means, U.S. House of Representatives, April 14.

Hong, E., L.A. Conroy, and M.J. Scholand. (2005). “U.S. Lighting Market Characterization, Volume II: Energy Efficient Lighting Technology Options,” technical report prepared for Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy by Navigant Consulting.

Howard, W.E. (2004). “Better Displays with Organic Films,” Scientific American, 290(2): 76-81.

Japan Research and Development Center of Metals’ National Project. (2000). “Light for the 21st Century: The Development of Compound Semiconductors for High Efficiency Optoelectronic Conversion, Year 2000 Report of Results.” (English translation: 2002).

Ledsmagazine.com. (2005a). “China Promotes Benefits of Solid-State Lighting,” February, http://ledsmagazine.com/features/2/2/5/1.

Ledsmagazine.com. (2005b). “LED industry in Taiwan set to grow by 16%,” March 29, http://ledsmagazine.com/news/2/3/36/1.

Ledsmagazine.com. (2005c). “Shenzhen Starts to Build LED Manufacturing Base,” June 16, http://ledsmagazine.com/news/2/6/22/1.

Leonard, R.S. (1992). “Lighting the Path to Profit: GE's Control of the Electric Lamp Industry, 1892-1941,” *Business History Review* 66(2): 305-335.

Light for the 21st Century. (2000). The Japan Research and Development Center of Metals’ National Project on “Light for the 21st Century: The Development of Compound Semiconductors for High Efficiency Optoelectronic Conversion. Year 2000 Report.

Lightsearch Directory. www.lightsearch.com, accessed June, 2006.

Liu, Y. S. (2003). “III-V Compound Semiconductor Industry and Technology Development in Taiwan,” International Conference on Compound Semiconductor Manufacturing. GaAsMANTECH, Inc.

LIGHTimes. (2006). “Wal-Mart Sees Cold Cash in LED Holiday Lighting and LED Lighting for Refrigerator Cases,” November 21, p.1.

LIGHTimes. (2007). “Quiet Big News Announces Cross Licensing of All Osram and Philips Inorganic and Organic LEDs,” http://www.solidstatelighting.net/lightimes/?date=2007-02-02.

Maccagno, P. (2002). “Overview of the High Brightness LED Market,” in *Light Emitting Diodes 2002: The Strategic Summit for LEDs in Illumination*, conference proceedings, San Diego, CA, October.

Macher, J.T, D.C. Mowery, and D.A. Hodges. (2000). “Semiconductors,” in *U.S. Industry in 2000: Studies in Competitive Performance*, D.C. Mowery, ed., Washington: National Academy Press, pp. 245-285.

Mintel, 2003. “Lightbulbs – U.S. – May 2003”. Mintel International Group, Ltd.

Monopolies Commission. (1968). *Second Report on the Supply of Electric Lamps*, London: Her Majesty’s Stationery Office.

Navigant Consulting. (2003a). “Energy Savings Potential of Solid State Lighting in General Illumination Applications,” technical report prepared for Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

Navigant Consulting. (2003b). “Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications,” technical report prepared for Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

OLLA Project Report. (2006a). Demonstrate a white p-i-n type OLED. High brightness OLEDs for ICT & Next Generation Lighting Applications funded under the IST priority (contract nr 4607) of the European 6th Framework Programme. February 2006.

OLLA Project Report. (2006b). White pin-OLED with improved polymer injection layer and efficiency above 10 lm/W. High brightness OLEDs for ICT & Next Generation Lighting Applications funded under the IST priority (contract nr 4607) of the European 6th Framework Programme. August 2006.

OSRAM. “Highlights from 100 years of the OSRAM brand,” accessed December 2006 from http://www.osram.com/cgi-bin/press/archiv.pl?id=450.

OSRAM China Lighting Ltd. Website accessed December 2006, from http://www.osram.com.cn/aboutus/index.jsp (in Chinese).

Philips. (2006). Annual Report 2005.

Philips. "A History of Philips and Lighting. A century of innovation at Philips Lighting," accessed December 2006, on http://www.lighting.philips.com/gb_en/about/sub_feature_4.php?main=gb_en&parent=1&id=gb_en_about&lang=en.

Physorg.com. (2005). "Universal Display First to Achieve 30 Lumens Per Watt White OLED," August 5.

Rensselaer Polytechnic Institute (RPI). (2006). "Rensselaer Researchers Aim To Close 'Green Gap' in LED Technology," press release, 23 August.

Sandahl, L.J., T.L. Gilbride, M.R. Ledbetter, H.E. Steward, and C. Calwell. (2006). "Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market," Research Report Prepared for The U.S. Department of Energy Under Contract DE-AC05-76RLO 1830. Pacific Northwest National Laboratory, Richland, Washington.

Siemens. "Lighting," accessed on December 2006, http://w4.siemens.de/archiv/en/innovationen/licht.html.

Solidstatelighting.net Directors. Accessed June 2006 from http://www.sslighting.net/cts/.

Steele, B. (2006). "China Pours Millions into Solid-State Lighting Program," Ledsmagazine.com, July 25, http://ledsmagazine.com/news/3/7/21/1.

Stevenson, R. (2005). "Oil-Free Korea Prioritizes Solid-State Lighting Project," Compoundsemiconductor.net, http://compoundsemiconductor.net/articles/magazine/11/4/4/1.

Taiwan Economic News. (2004a). "Taiwan Poised to Retain No. 2 Place in World LED Production," 24 March.

Taiwan Economic News. (2004b). "Taiwanese Led Suppliers Threatened by Japanese Rivals' Bold Expansion Plans," 29 April.

Tang, Y.K. (2006). "Lighten Up: China's Resolve to Embrace Energy-Efficient Lighting Unleashes a Powerful Market Potential," *Beijing Review*, March 2, 2006 updated December 13, 2006, http://www.bjreview.com.cn/science/txt/2006-12/13/content_50654_2.htm.

The Inquirer. (2004). "Inventor of LED Honoured in his Own Day, Strike a Light," Tuesday 27 April.

Toniolo, T. (2006). "Shining a Light on Quality," Product Design & Development, November, 61 (11): 14-15.

Toshiba. "The History of Toshiba Lighting," accessed December 2006 from http://www.tlt.co.jp/tlt/english/company/company.htm and http://www.toshiba.co.jp/worldwide/about/history.html#1875.

Tsao, J.Y., ed. (2002). *Light Emitting Diodes (LEDs) for General Illumination: An OIDA Technology Roadmap Update 2002*, Optoelectronics Industry Development Association.

U.S. Department of Energy (DOE). (1993). "Housing Characteristics 1993." Energy Information Administration, Office of Energy Markets and End Use. report DOE/EIA-457.

U.S. Department of Energy (DOE). (1995). “Commercial Buildings Energy Consumption Survey.” Energy Information Administration, Office of Energy Markets and End Use, report DOE/EIA-871.

U.S. Department of Energy (DOE). (1997). “Commercial Buildings Characteristics 1995.” Energy Information Administration, Office of Energy Markets and End Use, report DOE/EIS-E-0109.

U.S. Department of Energy (DOE). (2000). “Vision 2020, The Lighting Technology Roadmap. A 20-year Industry Plan for Lighting Technology.” Office of Building Technology, State and Community Programs. Energy Efficiency and Renewable Energy.

U.S. Department of Energy (DOE). (2003). “Energy Savings Potential of Solid-State Lighting in General Lighting Applications.”

U.S. Department of Energy (DOE). (2005). “Energy Act Authorizes Next Generation Lighting Initiative,” http://www.netl.doe.gov/ssl/083105.html.

U.S. Department of Energy (DOE). (2006). “2006 Project Portfolio: Solid State Lighting,” D&R International Ltd. for Building Technologies Program, Lighting Research and Development, Office of Energy Efficiency and Renewable Energy.

Walker, R.C. (2004). “Cutting through the Buzz on Production of HB-LEDs in Taiwan, South Korea and China,” The McDonald report, March 10.

Wang, M. and J. Shen. (2005). “LEDs lighting the future: Q&A with Biing-jye Lee, president of Epistar,” Ledsmagazine.com, November.

Williams, B. (2005). “A History of Light and Lighting,” Edition: 2.3. Accessed December 2006 from http://www.mts.net/~william5/history/hol.htm.

Whitaker, T. and B. Adams. (2002). “Korea is the new compound semiconductor boom region,” Compoundsemiconductor.net, April.

Yahoo! News Australia & NZ. (2004). “China Launches 50 Semiconductor Lighting Projects,” July 22, http://au.news.yahoo.com/040722/3/q08l.html.

Zou, H. (2002). “Envoy of Brightness,” *Shanghai Star*, 24 January.

Appendix: Figures and Tables

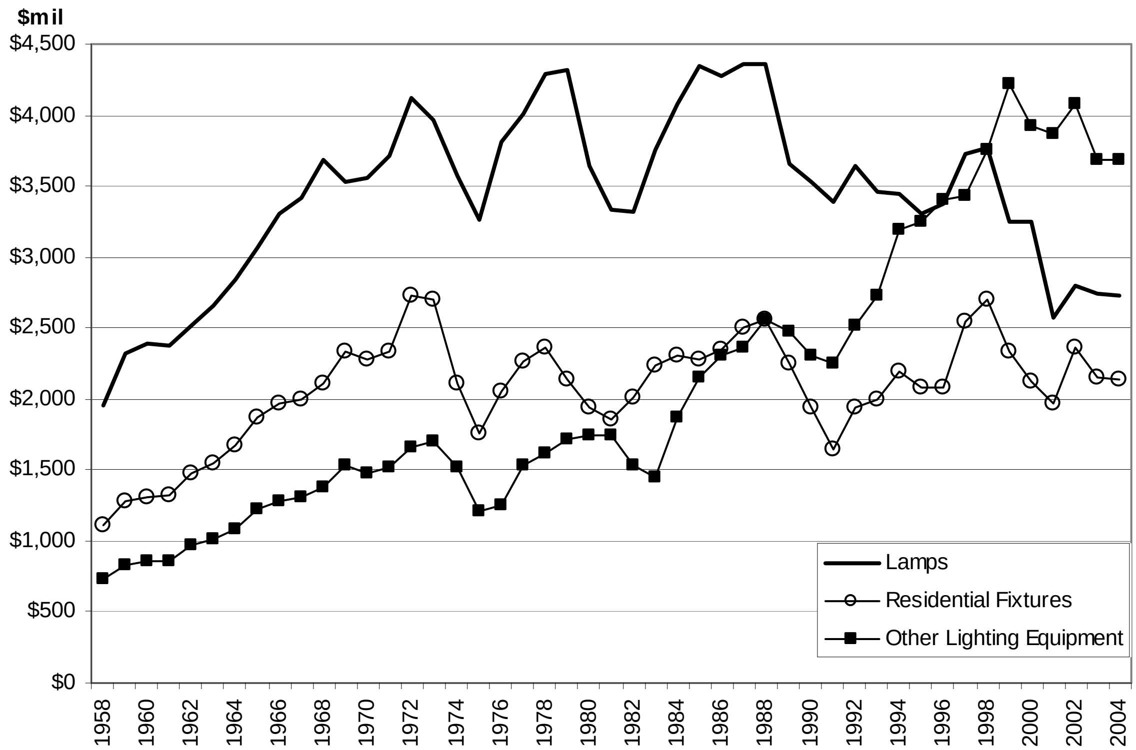

FIGURE 1 U.S. shipments of lighting products (real 2004 values)
Sources: Shipment values NBER (1958-1996), U.S. Department of Commerce, Bureau of Census (1997-2001), Bureau of Economic Analysis (2002-2004). Producer Price Index from BLS.

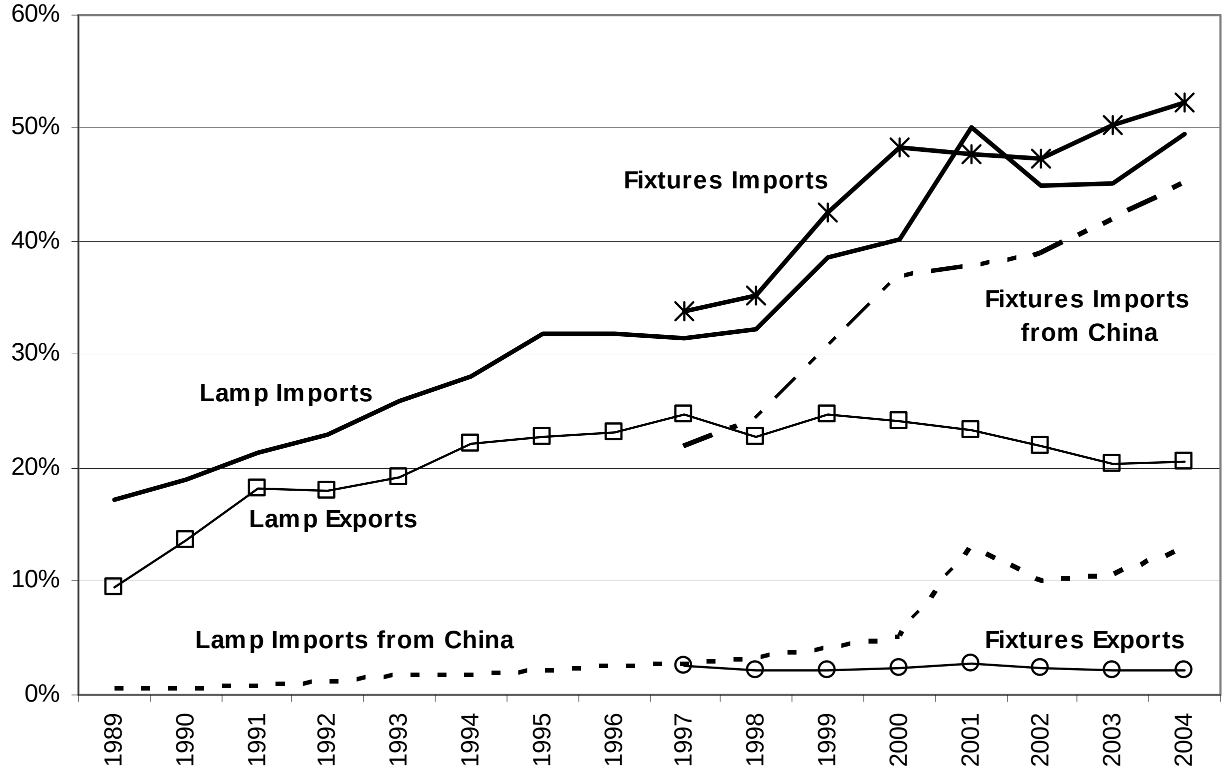

FIGURE 2 U.S. imports and exports of lamps and fixtures, total and imports from China, as percentages of U.S. consumption

Source: U.S. International Trade Commission.

Note: "Other Lighting Equipment" shows a similar pattern, with imports increasing from 38% in 1989 to 57% in 2004, and China's share of imports increased from 24% in 1996 to 32% in 2004.

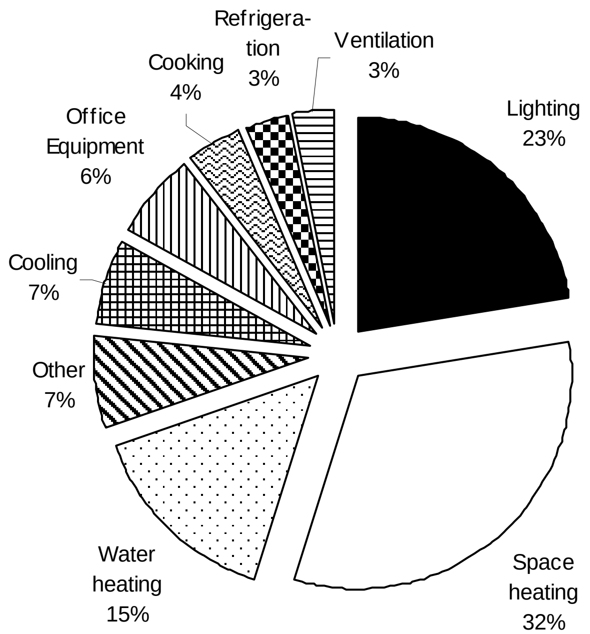

FIGURE 3 Energy consumption in U.S. commercial sector, 1995
Source: DOE (1995).

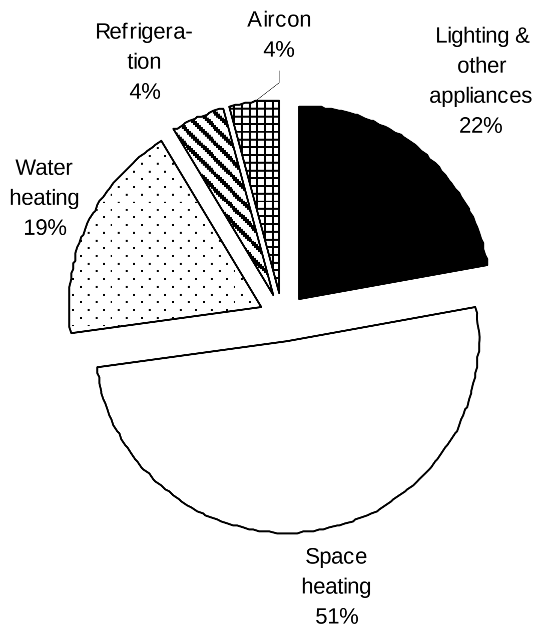

FIGURE 4 Energy consumption in U.S. residential sector, 1997
Source: DOE (1997).

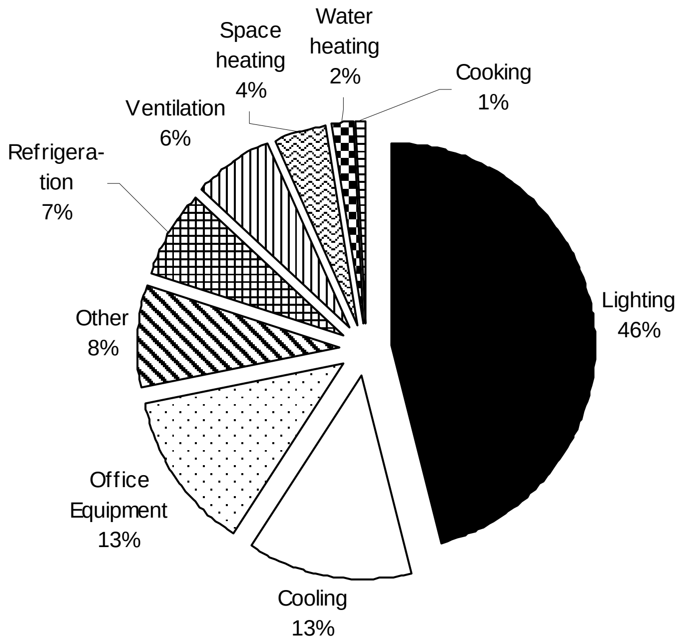

FIGURE 5 Electricity consumption in U.S. commercial sector, 1995
Source: DOE (1995).

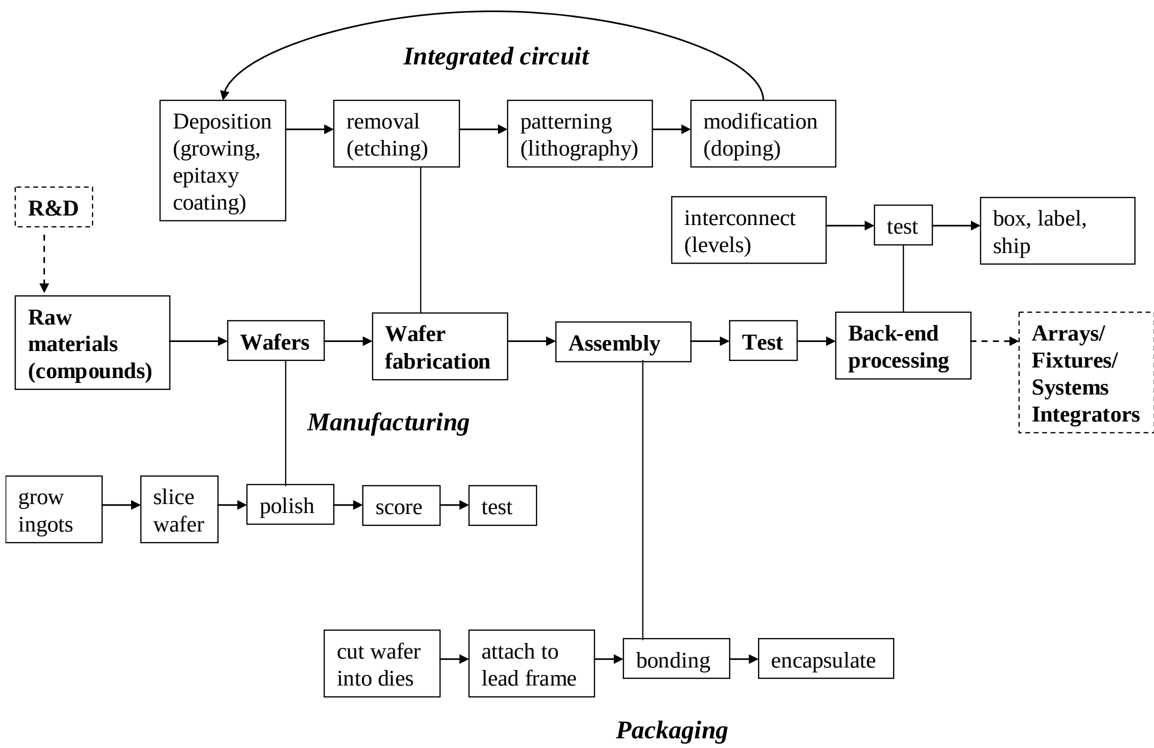

FIGURE 6 LED semiconductor supply chain

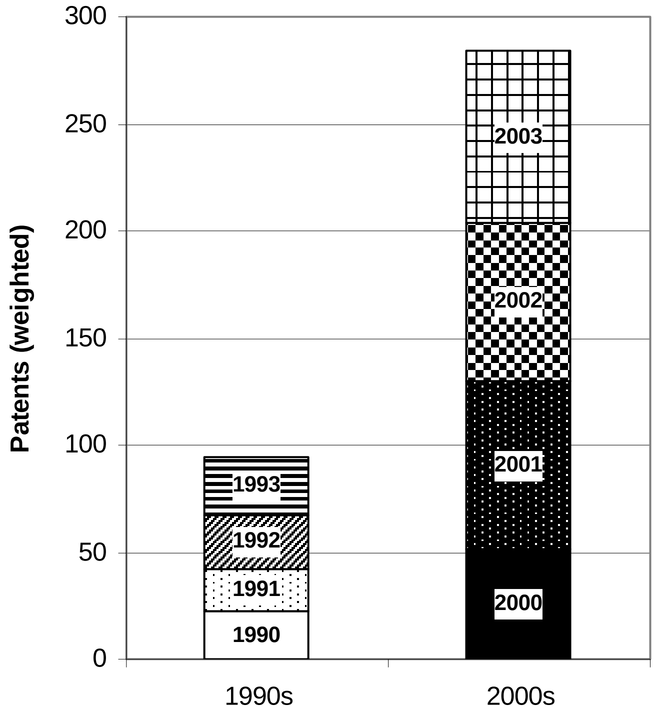

FIGURE 7 LED patents in sample granted during 1990-1993 and 2000-2003
Source: Authors' analysis of patents granted in the U.S. and Europe (see text).

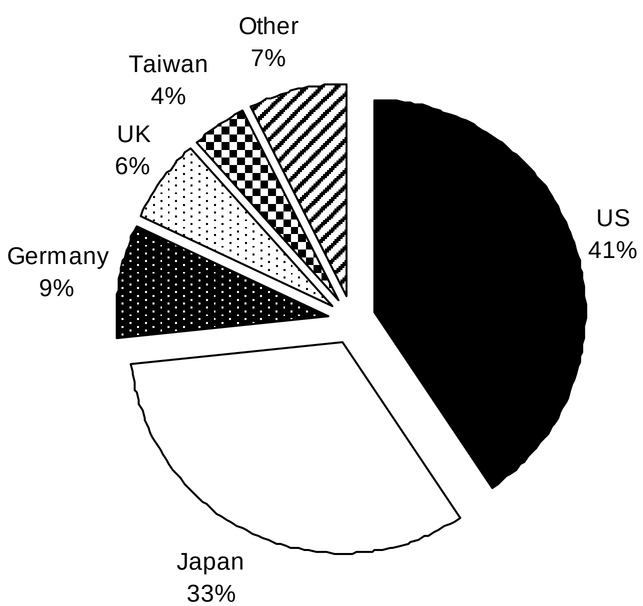

FIGURE 8 Invention locations of LED patents granted in 1990-1993
Source: Authors' analysis of patents granted in the U.S. and Europe (see text).

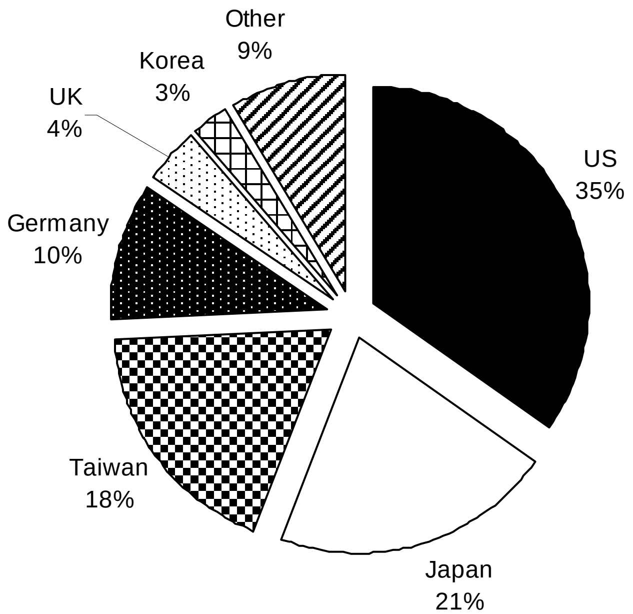

FIGURE 9 Invention locations of LED patents granted in 2000-2003
Source: Authors' analysis of patents granted in the U.S. and Europe (see text).

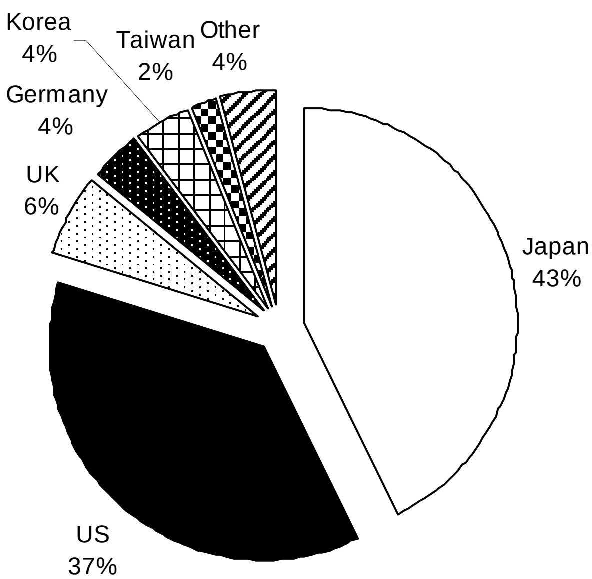

FIGURE 10 Invention locations of LED patents granted on multiple continents in 1990-1993
Source: Authors' analysis of patents granted in the U.S. and Europe (see text).

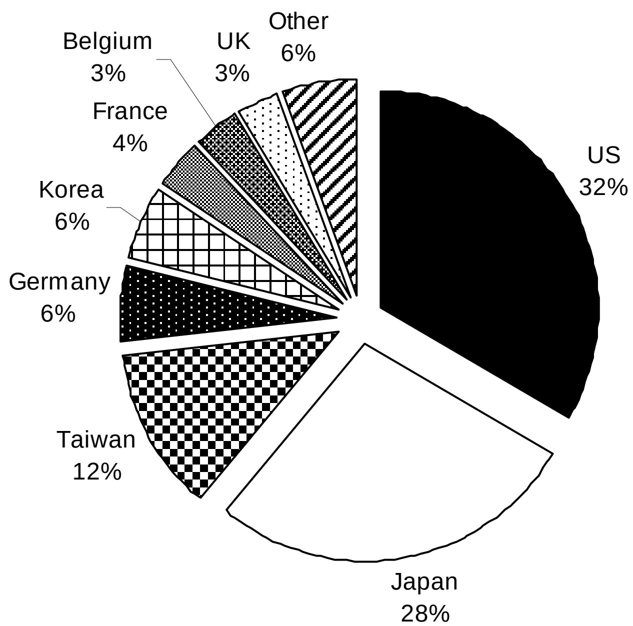

FIGURE 11 Invention locations of LED patents granted on multiple continents in 2000-2003
Source: Authors' analysis of patents granted in the U.S. and Europe (see text).

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 ultraviolet
SiC (silicon carbide) as substrate Si (silicon) as substrate, under development Al_2O_3 (sapphire) as substrate ZnSe (zinc selenide)	Blue
C (diamond)	Ultraviolet
AlN (aluminum nitride) AlGaN (aluminum gallium nitride)	Far ultraviolet

Source: Wikipedia, www.wikipedia.org/wiki/LED (accessed 30 August 2006).

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

		Location of R&D			
Location of HQ	**1990-1993**	**Asia**	**Europe**	**U.S.**	**Other**
	Asia	100.0%			
	Europe		100.0%		
	U.S.	6.7%	8.9%	84.4%	
	Other				100.0%

Source: Authors' analysis of patents granted in the U.S. and Europe (see text).

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

Location of HQ		Location of R&D			
2000-2003	**Asia**	**Europe**	**U.S.**	**Other**
Asia	94.5%	2.4%	3.1%	
Europe		87.1%	12.9%	
U.S.	2.2%	4.0%	92.7%	1.1%
Other				100.0%

Source: Authors' analysis of patents granted in the U.S. and Europe (see text).

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	-	Lumileds/Philips*	Netherlands/U.S.	13
2	6	OSRAM/Siemens**	Germany	11
3	-	Nichia	Japan	8
4	6	Sharp	Japan	7
4	-	United Epitaxy	Taiwan	7
6	-	AXT	U.S.	5
6	3	Eastman Kodak	U.S.	5
6	-	GE/Gelcore***	U.S.	5
6	6	Samsung	Korea	5
10	16	Agfa Gevaert	Belgium	4
10	-	eMagin	U.S.	4
10	-	Epistar	Taiwan	4
10	-	Lite On Electronics	Taiwan	4
10	-	Opto Tech	Taiwan	4
10	-	Sarnoff	U.S.	4
10	-	Truck Lite	U.S.	4
17	-	ColorKinetics	U.S.	3
17	6	Cree	U.S.	3
17	-	Fujitsu	Japan	3
17	1	HP	U.S.	3
17	-	Ichiko Industries	Japan	3
17	-	Leotek Electronics	Taiwan	3
17	16	Oki Electric	Japan	3
17	-	Para Light Electronics	Taiwan	3
17	-	Polaroid	U.S.	3
17	6	Stanley Electric	Japan	3
17	16	Sumitomo Electric Ind.	Japan	3
17	16	Toyoda Gosei	Japan	3

Source: Authors' analysis of patents granted in the U.S. and Europe (see text).
Note: Individuals and institutions were excluded from the table.
* includes all patents by Philips and its subsidiary Lumileds
** includes all patents by OSRAM-Sylvania and its parent company Siemens
*** includes all patents by GE and its subsidiary Gelcore

TABLE 5 Globalization of licensing, cross-licensing, agreements, deals and disputes

	White LED licenses	**Cross-licenses**	**Chip Deals**	**Disputes**
Nichia	Citizen (OEM deal)	Lumileds Toyoda Gosei Cree OSRAM	Opto Tech (OEM deal)	various
Cree	Cotco Stanley ROHM	Nichia	OSRAM (supply agreement)	
OSRAM	Harvatek Vishay Samsung SEM Lite-on Everlight ROHM Ya Hsin	Nichia Philips		Citizen Dominant
Philips		OSRAM		
Intermatix	Edison Unity Opto AOT Itswell LumiMicro			

Sources: LEDs Magazine, Cabot Media, IOPP Ltd., and LIGHTimes (2007).

TABLE 6 Major National Research Programs Pertaining to LEDs

Country	Program	Objectives	Phases	Funding	Yearly Fund Flow (est.)‡	Organizations
USA*	Energy Act of 2005: Next Generation Lighting Initiative (NGLI)	support research, development, demonstration, and commercial applications	2007-2009 2010-2013 (extension)	$50 mil a year authorized from 2007-2009 extended authorization to allocate $50mil/year from 2010-2013	$42.1 mil/year (2003-2013); includes anticipated extension of funding	partnership DOE, industry, universities & laboratories
	SSL Project Portfolio (current projects in NGLI)	six key research areas: quantum efficiency, longevity, stability and control, packaging, infrastructure, and cost reduction LED and OLED	completed projects 2003-2005 current projects through 2008	total: $70.9 mil		partnership DOE, industry, universities & laboratories
Japan	Light for the 21st Century, New Energy and Industrial Technology Development Organization (NEDO)	develop GaN-based LED technology for lighting applications Develop 13% market penetration by 2010 Produce 120lm/w and 80% efficiency by 2010	1998-2002 (first phase) over 477 new patent filings in one year	Yen 6bln ($52 mil)	$7.5 mil/year (1998-2008)	Japan R&D Center of Metals (JRCM) 13 companies and universities
	Ministry of Education, Culture, Science & Technology	develop medical equipment and therapeutic techniques based on LEDs establish the Yamaguchi-Ube Medical Innovation Centre (YUMIC) white HB-LEDs	financial year 2004 similar amounts of funding expected next 4 years (2005-2008)	Yen 500 mil ($4.6 mil) $4.6mil/year 2005-2008		several universities, more than 20 companies
South Korea**	Semiconductor Lighting National Program & KOPTI (Korea Photonics Technology Institute)	Reduce use of glass, phosphors, heavy metals Meet environmental regulations July 2006 Save $20bn on energy produce 80lm/W white LED by 2008	1993-1996: R&D by LG, Samsung, universities and Korea Research Institute 1999-2000: business phase, JVs, production runs 2001: activation phase, growth to more than 340 companies	KOPTI receives $20 mil/year in funding KOPTI equipment value: $65 mil	$59.4 mil/year (2001 - 2008); excludes equipment value, and half of LED Valley as "fiber-to-home"	KOPTI's costs covered 73.1% by government, 16.5% by Gwanju "City of Light", 10.4% by industry
	LED Valley Project	develop HB-LED second phase of a photonics industry project for HB-LEDs deploy fiber-to-the-home networks	2005-2008 2005-2008	$100 mil (first phase) $430 mil (second phase HB LED & fiber-to-home)		Gwanju "City of Light", mixture of national and local government and private-sector investment
Taiwan***	Next Generation Lighting Project	Improve performance of white LEDs 100lm/w output in labs	2004-2005: 40lm/w Second phase: 60lm/w	2004-2005: NT$383m ($11.5m)	$4.0 mil/year (2002-2005)	Consortium of 11 companies
	National Science Council	producing highly efficient LEDs led to 14 new patents and 20 new manufacturing process technologies	around 2002-2004	NT$12m ($0.4m)		NSC department of science & engineering

TABLE 6 (continued)

Country	Program	Objectives	Phases	Funding	Yearly Fund Flow (est.)‡	Organizations
China†	Semiconductor Lighting Project	Establish industrial parks with up-, mid- and down-stream products Collaboration with Taiwan and specialists from Taiwan and U.S. anticipate $19 bln LED industry by 2010	Five parks established: Shanghai, Xiamen, Dalian, Nanchang, Shenzhen First phase likely to be 2005-2010	Total investment: Yuan 10 bln ($1.2 bln), allocated as follows: Xiamen: $1.9m (with focus on optoelectronics) Dalian: $150m Shenzhen: initial investment 3 bln Yuan ($375 mil); total 20 bln Yuan ($2.5 bln) over 3-5 years (2005-2010)	$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	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 State Lighting project as part of 11th 5-Year Plan	savings from large scale conversion to LED; 100bn kW/h annually by 2015 150 lm/W LED and capture 40% of incandescent market reduce environmental pollution develop strong industrial base international cooperation if necessary	2015 goals	2006-2010: $44m		15 research institutions & 2500 companies
E.U.	Sixth Framework program	strengthen science & technology base for international competitiveness	2002-2006	$1.3 bln earmarked for nanotechnology (with IST section)	$16.3 - 32.5 mil/year (2002-2006) est. assuming 5 - 10% dedicated towards LED	

** Presidential budget for FY06 includes request of $11 mil for SSL.*

*** Korea also has a national program for LCD and displays, from 2004-2008. Key players are LG & Samsung. No funding information.*

**** Taiwan has a 6 year nanotechnology initiative launched in 2004 by NSC. Investment is NT$ 23.2 bln ($700 mil), of which 38% ($266 mil) is dedicated towards R&D, academics & HR development. The rest is for industrialization.*

† China also has an "863 Program", or the National High Technology Research & Development Program. Applied for 1557 patents in 2004 and 16.6% of spending was on advanced materials. Development of OLEDs is a focus. In 2000, achieved scale production of LED epitaxial wafers. This program and one called "National Semiconductor Lighting Engineering" all appear to be connected or the same.

‡ 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$.

Sources (in order of table): DOE (2005, 2006), Japan Research and Development Center of Metals' National Project (2000), Compoundsemiconductor.net (2004), 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).