Light Emitting Diodes and the Lighting Revolution: The Emergence of a Solid-State Lighting Industry

Susan Walsh Sanderson
Lally School of Management
Rensselaer Polytechnic Institute
110 8th Street
Troy, NY 12180-3590
USA
Tel: (518) 276-2933
Fax: (518) 276-8661
Email: sandes@rpi.edu

Kenneth L. Simons*
Department of Economics
Rensselaer Polytechnic Institute
110 8th Street
Troy, NY 12180-3590
USA
Tel: (518) 276-3296
Fax: (518) 276-2235
Email: simonk@rpi.edu

Forthcoming in *Research Policy*

Second (Final) Revision, October 2013

First version May 2012

* Corresponding author.

Light Emitting Diodes and the Lighting Revolution: The Emergence of a Solid-State Lighting Industry

Abstract

Emergence of new industries from evolving technologies is critical to the global economy, yet has been relatively understudied due to the paucity of available data. This study draws lessons on industry emergence, by analyzing how a solid-state lighting (SSL) industry grew out of light emitting diode (LED) technologies that evolved for half a century, with participation by tens of thousands of researchers in universities, national laboratories, and firms. Using data on publications, patents, and firms combined with business history we trace the evolution of SSL through a succession of market niches. At times a few researchers with unorthodox research approaches made breakthroughs that greatly advanced particular technology trajectories and pushed LED research in unexpected directions. A succession of LED market niches advanced the technology and provided profits to incentivize continuing research. Innovating firms developed a thicket of patents and captured substantial profit, but were embroiled in extensive litigation that was ultimately resolved through cross-licensing. A major new generation of lighting products is now disrupting the traditional lighting industry. Although the leading incumbent lighting firms all invested early and heavily in SSL, the industry's future leadership is uncertain.

Keywords: industry emergence, technology evolution, technological trajectories, market niches, patent litigation, disruptive technology

Light Emitting Diodes and the Lighting Revolution: The Emergence of a Solid-State Lighting Industry

1. Introduction

The light emitting diode (LED), first commercialized in the 1960s, is now poised to replace most light bulbs with a high-tech alternative known as solid-state lighting (SSL). If SSL achieves even a little of its expected potential, it will save energy and money compared to existing light bulbs (incandescent and fluorescent), spur radical approaches to lighting design and products, and integrate with electronic circuitry to facilitate surprising applications. By 2013, SSL replacement bulbs are common in stores and have reached a cost low enough to be attractive to many consumers. Firms with SSL products have been flooding the lighting industry: light emitting diode producers like Cree making solid-state replacement lights; entrepreneurial startups like Soraa and BridgeLux creating new solid-state lighting devices; and firms like Samsung and Sharp with experience in related technologies, now competing directly with incumbent light bulb makers Philips, Osram-Sylvania, and GE in the newly emerged solid-state lighting industry.

This study draws lessons from the co-evolution of basic science, industrial technology, and niche applications that are stepping-stones to a mass market application. Development of today's SSL products required a maze of technology evolution, with false starts and unexpected turns. The many thousands of researchers and organizations who developed these technologies experimented with poorly understood materials, pioneered manufacturing methods, and redesigned complementary technologies such as encapsulants, phosphors, driver electronics, heat sinks, and fixtures to create light-emitting properties they needed. As these players interacted and competed, they created new uses and markets for their technologies, from the initial red indicator lights to calculator and watch displays, signs, flashlights, brake lights, traffic lights, architectural lights, and backlights for mobile devices and televisions. Myriad characteristics and colors that were developed along the way combine to make today's efficient white light.

Solid-state lighting development was by no means a discrete event, but grew out of multiple generations of technology, innovation, and niche applications. Once mere indicator lights, LEDs made steady inroads into niche markets that provided stepping-stone profit opportunities to help propel LED science and technology, not only affecting efficiency and cost but also creating white-light emission techniques crucial for general illumination. Costs are plummeting through ongoing improvement of upstream component manufacturing technology, including for the semiconductor devices inside LEDs. Today's solid-state lighting products are opening an era of product experimentation and competition that promises new features and architectures that are difficult to predict. Not only may solid-state lighting lead to different wiring and fixture systems, but solid-state lights of the future may incorporate capabilities of LEDs that seem totally foreign to existing light fixtures – for example, data communication devices that extend (and exceed) the bandwidth of wireless routers; disease-causing organism detection and eradication; automatic adjustment of color, intensity, and direction for users' needs; and circadian rhythm regulation.

This case is doubly interesting because, like most emergent industries, the new SSL industry is developing in competition with incumbent lighting technologies. By the early 2000s, the dominant light bulb manufacturers in North America and Europe were Philips, Osram-Sylvania, and GE, with other companies such as Toshiba predominant elsewhere. All suffered low profitability given demand for cheap commodity lamps increasingly supplied from Chinese and other less-developed country manufactories. Despite efforts at improvement, conventional light bulb efficiency appears to be reaching fundamental physical limits. In contrast, research from 1970 to 2000 was driving LEDs' light output upward about 30% per year, with costs falling about 20% per year, suggesting convergence with traditional lighting by about 2010 to 2015. The leading lighting firms all foresaw the move toward solid-state lighting. The three Western firms combined with semiconductor firms to create joint ventures that they would eventually acquire, while Toshiba developed internal LED capabilities for displays and backlights, with all firms apparently attempting to retain leadership in lighting products.

The findings provide an overview of key processes involved in the evolution of technology and products as a new industry is created. This yields a stylized portrait that coincides with findings reported by previous researchers for other industries. LED technology (including a still nascent organic LED technology) went through a series of developmental stages, each leading to development of products suitable for particular market niches. In many cases firms entering LED-related niche markets developed technology and niche products in ways that drew on their expertise in related industries, and profits from these stepping-stone products spurred further technology development. Driving the drawn-out and punctuated technology evolution were large numbers of scientists, including key individuals who developed major technological breakthroughs. Successful commercial development and national research expenditures enhanced the base of technology in ways that spurred succeeding technology generations and, despite considerable patent litigation, led to the recent emergence of the general illumination solid-state lighting industry.

2. The Process of Technology Development

Although under-researched compared to periods after industry creation, technology development preceding a new industry has been studied particularly by economists of industry evolution and technological change and by historians of business and technology. These researchers' findings, and related work throughout economics, sociology, and management, provide context to understand what is learned from solid-state lighting relative to previously studied technologies.

2.1. Unpredictable Paths of Technology Evolution

Research on technology evolution suggests, in contrast to simplistic models of technology, that there are many paths to discovery and it is hard to predict which path will succeed (Nelson and Winter, 1982). Many researchers work on similar topics simultaneously, to the point that two or more scientists usually arrive at the same (broadly-defined) major scientific invention (Merton, 1963). Although most studies of innovation and technology focus on successful innovations, technology development includes many more unsuccessful attempts (Pinch and Bijker, 1984, p.405; Basalla, 1988). Chance helps shape technology development and may yield outcomes different from, and potentially inferior to, what could have been (David, 1985; Arthur 1988a, 1988b). For the safety bicycle, for example, many participants working from 1879 to 1898 drove the gradual emergence of characteristics and features of the final artifact (Pinch and Bijker, 1984, p.416).

Firms, and institutions such as universities, play a critical role in the development and evolution of technology. New products and services, Nelson and Winter (1982) suggest, are the basis on which firms compete, and the market is a 'selection' mechanism that determines which products succeed or fail. While new products and services result from trial and error search, firms are strongly influenced by 'routines' that they developed previously. These routines provide a 'self-replication' mechanism somewhat akin to genes in biological competition. Gradual technological advances may reach thresholds or combine in ways that have radical market effects (Mokyr, 1990; Antonelli, 2008, pp.264-8).

Uncertainty, a hallmark of evolutionary theories, is thought by Nelson (1995, p.63) to be resolved only through ex-post competition. Engineers with different ideas compete to solve problems such as those described in Vincenti's (1994) study of 1920s-1930s aircraft designers. Engineers knew that the landing gear systems that attach wheels to a fuselage or wings could be improved, but it was unclear which of different possibilities would prove best, and they disagreed on where to place bets. New technologies progress from a crude form initially to something more worthwhile economically, with capabilities unforeseen at the outset and only discovered along the way (Nelson, 2005, p.30; Maggitti et al., 2013). Moreover, different new technologies may interact in surprising ways making it very difficult to predict their future value and use (Sahal, 1981, pp.71-4; Nelson, 2005, p.30). Technologies accumulate in particular trajectories, such as separate military versus commercial aircraft trajectories (Nelson, 1995, p.64), as knowledge builds up and developers seek to match market needs (Dosi, 1982).

2.2. Supply Push and Demand Pull

As Schmookler (1966) concludes, technological progress depends on both blades of the Marshallian scissors, supply and demand. Supply of science and technology, as measured through amounts and timing of activity by technical field and industry, enhances businesses' technology development and product creation (Adams, 1990; Adams et al., 2006). Technology development increases the pool of skilled labor on which it depends (Nelson, 2005, p.107). If the technology in which an industry is based has novel characteristics, new technical societies and new technical journals tend to spring up. Further, technology-oriented sciences provide a market-like environment that stimulates research and ties industries to universities through the market of people with skills and research findings that enable a technology to advance.

Demand arises in alternative market niches. Market niches provide an opportunity for firms to develop specialized products and learn by doing, typically advancing both product and process technologies (Schot and Geels, 2007). Specialized niches with distinct needs trigger the first application of the new technology and provide the impetus for further development (Levinthal, 1998). Levinthal suggests that new technological forms emerge as a result of the distinct selection criteria and the degree of resource abundance in each new domain, and a new technological form may be able to penetrate other niches and even out-compete prior technologies. For Levinthal, technological discontinuities are generally not the product of singular events but the application of existing technological know-how to a new domain (Levinthal, 1998, p.218). Creative destruction may occur when a technology that emerges from one speciation event or niche is successfully able to invade another niche. In some cases, the niches can coexist whereas in others, the technology may ultimately become viable in a mainstream market. Smith and Raven (2012) study the role of niches as protective spaces for path-breaking innovations, and identify three key properties of niches, shielding, nurturing, and empowerment. A succession of niches, or 'niche-cumulation,' may help advance a technology through a trajectory of changes (Geels, 2002). Rogers' (2003) S-curve of growing sales over time might be expected to apply within each of a series of successive niche markets, leading eventually to a possible takeover of a mainstream market.

2.3. Patents and the Appropriation of Returns to Invention and Innovation

Prospective profit encourages technology development, so long as firms' technologies are protected from excessive competition by mechanisms such as patents. Patent competition models commonly involve patent races, in which two or more competitors race to develop a technology and whoever develops the technology first captures all profits. Patent race models however fail to reflect some key features of technology competition.

First, patents are not the primary means by which successful businesses protect their profits. Surveys of managers have found that the mechanisms most useful in practice to protect profits from new technologies are not patents but lead time; learning curves; complementary manufacturing, marketing, and service efforts; and keeping process innovations secret (Levin et al., 1987; Cohen et al., 2000). Similarly, managers use mechanisms beyond just patents to deter competitive entry (Smiley, 1988). Successful technological pioneers, both individuals and firms, rarely capture anything near the full financial returns of their inventions even if they obtain patents on their technologies – for example, the difficulties of Charles Goodyear and Philo T. Farnsworth in capitalizing on their inventions in, respectively, rubber vulcanization and television have been documented extensively (Wolf and Wolf, 1936, p.309-33; Udelson, 1982; Fisher and Fisher, 1996). Patents have limited protective ability partly because firms often invent around a patent by using alternative technologies to accomplish the same goals, and also because it can be difficult to develop a patent without (often unintentionally) overlapping with another firm's patents.

Second, many patents typically pertain to a product, and firms negotiate to license use of each other's portfolios of relevant patents. Ownership of parts of the thicket of relevant patents gives firms leverage to license other firms' patents on amenable terms (Hagiu and Yoffie, 2013). Cross-licensing agreements can limit firms making high-technology products to a modest number of players, with smaller firms possessing few relevant patents finding it more difficult to participate in production of these products (Cockburn, MacGarvie, and Müller, 2010). Businesses with especially important patents should do better in this process, although costs of negotiation, lawsuits, and the large number of businesses involved may reduce the disproportionate benefits of especially important patents. Rogers (1980, p.7) argues that the uncertainty caused by patent fragmentation was a major reason for consolidation of lighting firms in the late 1800s.

Third, incentives for R&D may remain strong despite an absence or limitation of patent rights (Moser, 2013; Boldrin and Levine, 2013). Within an industry with ample opportunities for product or process improvement, firms must race to keep up technologically lest they lose their sales to faster-improving competitors. Such technological racing was crucial to firm survival in industries like automobiles, tires, television receivers, and penicillin, and occurred despite patent pools in which most firms were subject to advance agreements to license freely in three of these four industries (Klepper and Simons, 1997). One might expect such technological racing to occur also in the stepping-stone markets that lead up to development of a major product.

2.4. Invading Mainstream Markets

Despite the difficulties inherent in invading an established market, occasionally radical new technologies aid invading firms to outcompete incumbents (Cooper and Schendel, 1976; Foster, 1986). This is usually expected to result in Schumpeter's (1942) creative destruction, with innovative market entrants replacing established producers of a product. Established firms may find it most profitable to deliberately allow entrants to capture market leadership in a technological transition, and to reap profit from the existing product while it lasts (Arrow, 1962; Reinganum, 1983). Alternatively, established firms may fail to transition successfully to the new product because it involves a very different technology (Majumdar, 1982; Tushman and Anderson, 1986), because organizational structure and researchers' mindsets prevent them from understanding a different architecture in which component technologies are assembled (Henderson and Clark, 1990), because the technological trajectory of a market niche outside incumbents' scope unexpectedly surpasses prior technologies' trajectories (Christensen and Rosenbloom, 1995; Levinthal, 1998), or because the new product is best produced using a production philosophy unfamiliar to incumbents (Churella, 1998). Such technological transitions do not necessarily displace incumbents. Incumbents with general dynamic capability to adapt (Tripsas, 1997a), or with specialized complementary assets (Tripsas, 1997b; Rothaermel and Hill, 2005), may be particularly able to transition to the new technology. A mix of entrants and incumbents made the transition to previous disruptive technologies such as semiconductors (Tilton, 1971).

Once a new product industry emerges from the technology development stage, fierce competition usually follows as firms enter and seek to earn a share of the resultant profit. Most industries eventually undergo a contraction in the number of producers, or "shakeout" (Gort and Klepper, 1982, Klepper and Graddy, 1990). Substantial shakeouts are usually driven by a process of technological competition in which firms sustain their advantage and large market shares through continual innovation (Klepper and Simons, 1997, 2005). This process hints at the fierce technological competition likely to follow in technology-intensive parts of the SSL industry.

3. The Technology

Light emitting diodes are semiconductor devices that emit light. They emerged from discoveries and explorations in basic materials science and engineering. Their researchers initially had little more than pure curiosity and wild ideas about the potential for what these materials could become. To understand their story, a brief technical background will suffice.

Semiconductors are half way in between materials that conduct electricity and insulate against flow of electricity. Semiconductors of different types are composed of atoms with distinct properties that determine crystal structure and potential light emitting properties. For example silicon and carbon appear in the fourth column of the second and third rows of the periodic table of the elements, implying specific numbers of electrons in those atoms' outer orbits, so that silicon is called a *group IV semiconductor* and silicon carbide, which combines two fourth-column elements, is called a *group IV semiconductor compound*. Group IV semiconductors and compounds generally are not able to generate light. Particularly important in the development of LEDs have been *group III-V semiconductors*, materials like gallium nitride that combine atoms in the third and fifth columns of the periodic table of the elements. LED light emission from ultraviolet through the visible colors and infrared can be attained with different mixtures of various group III and V atoms.

The electrical properties of semiconductors change radically when tiny quantities of other atoms are mixed into them. When a layer of semiconductor includes a few atoms that are positive in the sense that they tend to capture free electrons, it is called a *p-type semiconductor*. When it includes a few atoms that are negative in that they easily give up extra electrons, it is called an *n-type semiconductor*. Adding these atoms to the semiconductor is called *doping*. Early experiments with semiconductors baffled scientists at Bell Labs with strange and amazing behaviors, which turned out to be driven by adjacent sections of semiconductor that accidentally had p- and n-type impurities respectively (Gertner, 2012). Two layers of p- and n-semiconductor together create a *diode*, which allows electricity to flow in only one direction. With the right elements, electricity flow through the diode will cause it to emit light, in which case it is a *light-emitting diode*. Light emitting diodes can be fabricated into laser diodes, by incorporating materials that reflect light internally within a section and thereby stimulate further light emission; laser diodes are used for example in laser pointers and optical fiber communications.

To build light emitting diodes, one needs a *substrate* on which layers of p- and n-type semiconductor can be deposited. The semiconductor layers must be deposited on top so that the substrate's and layers' atoms line up or *match* well with each other; poor alignment can cause strain and defects in the semiconductor's crystal structure and inhibit desired electronic and optical properties. Depositing the layers on top is called *epitaxy*. Among several means to perform epitaxy, a mass manufacturing approach is to surround the substrate with a hot gas, also known as a vapor, whose molecules contain atoms to be deposited in a p- or n-type layer. This approach is therefore termed *vapor-phase epitaxy* or *chemical vapor deposition*. When the vapors contain special organic chemicals carrying group III elements, the process is called *metal organic chemical vapor deposition* (MOCVD). Complex manufacturing machines that contain the substrate and control the flow of vapor over it are called *MOCVD reactors*.

Much recent work has sought to replace the *inorganic* III-V LED materials with complex electrically-conductive organic chemicals. If these materials can be manufactured and formed into reliable light-emitters inexpensively, sheets of *organic LEDs* (OLEDs) might, in the future, be printed continuously in roll-to-roll manufacturing processes at relatively low cost. OLEDs are now used in more expensive forms for certain color displays and niche lighting applications.

4. Technology Push and Market Pull: Niche Stepping Stones[1]

LED development has been characterized by slow and incremental improvements and the creation of new materials by multiple contributors over decades, many building on each other's findings. Some researchers discontinued avenues that did not seem fruitful, yet later some of these were picked up by other researchers, in the same country or continents away. Technology trajectories were not straight pathways but more like meandering paths that switched back and forth, visible only in hindsight by picking out innovations that have proved to be important. Researchers had to choose in real-time their research paths based on imperfect knowledge and a desire to advance scientific knowledge or to produce products. "Trajectories" were punctuated by many stops and starts, with initially promising technologies that led nowhere, and technologies that at first seem unpromising that led to breakthroughs. Gallium nitride (GaN) was just such an underdog technology—under-researched from 1974 until after p-doping difficulties were resolved in 1989-1991—that enabled important products such as blue LEDs, blue lasers, and white backlighting for mobile devices and televisions.

4.1. Red and Orange LEDs

Work on bulk growth of III-V semiconductor compounds began in the early 1950s, and these materials proved to be efficient light emitters and became the first foundation for the development of LEDs. Heinrich Welker, a German materials scientist who made important early contributions to the field, worked at a Westinghouse subsidiary in Paris where he developed a transistor around the same time parallel work was going on at Bell Labs. Transistors mattered, because theoretical understanding of transistors gave just the right insight to foresee the possibility of LEDs (Holonyak, 2013). From 1951 to 1961, Welker headed the solid-state

[1] Sections 4 and 5 draw primarily from Schubert (2006) and Johnstone (2007), and also from Fasol (1996) and Riordan (2005), with other sources cited in the text except where information is widely available from trade sources.

physics department of Siemens-Schuckerwerke, where he developed III-V compounds to replace silicon semiconductors. By the 1960s infrared LEDs and lasers based on gallium arsenide (GaAs) were being worked on by groups at RCA, GE, IBM, and MIT. IBM's Thomas J. Watson Research Center in Yorktown Heights, NY included many active researchers working on GaAs and combined aluminum gallium arsenide (AlGaAs) plus GaAs devices.

Researchers at these major industrial labs were motivated by scientific curiosity and by applications these new materials might enable. GE employees Nick Holonyak Jr. and Sam F. Bevacqua reported the emission of visible light in 1962 using gallium arsenide phosphide (GaAsP) LEDs. Holonyak envisioned applications for the devices including indicator lights and numeric and alphanumeric displays. The group deposited GaAsP from gaseous source chemicals on top of GaAs substrates, in a technique known as vapor-phase epitaxy, successfully creating LEDs. However these early devices had several problems including rapid degradation of the light output.

GE was first to sell small commercial quantities of GaAsP LEDs in the early 1960s for a price of $260, but it was Monsanto Corporation that developed mass production processes for LEDs. In 1968, it set up a factory that produced low-cost GaAsP. Monsanto's LEDs were based on GaAsP p-n junctions grown on GaAs substrates, and they emitted light in the visible red range. At the time, Monsanto was collaborating with Hewlett-Packard (HP) with the idea that Monsanto would provide the raw material for HP-made LEDs. However, HP worried about a single source for its raw material and started growing its own GaAsP.

Among the first applications of GaAsP LEDs was indicator lights on circuit boards, for example a status indicator for data processing on IBM System 360 mainframe computers. Texas Instruments was also active in developing LEDs for commercial use during the 1960s, but sales were low as prices for the LEDs were about $130 for a single LED. As these materials improved and dropped in price, they were used in video and audio remote controls and as sources for local area communications.

Calculators and wristwatches were important emerging markets for these early LEDs from the late 1960s to the mid-1970s, and several U.S. and Japanese firms were very active in developing LEDs and the products that used them. The first digital wristwatch with an LED display was developed by Hamilton Watch Company. Numeric displays in pocket calculators were another important early application of LEDs. However LEDs were too dim to read easily in daylight and were displaced by liquid crystal displays in watches and calculators in the 1980s.

In 1979, Monsanto, which since 1968 had made LED calculator and watch displays, sold its optoelectronics business which eventually became part of Taiwanese LED manufacturer Everlight Electronics.[2] M. George Craford, one of Monsanto's leading LED researchers, moved to HP where he became the central developer of their LED technology and business. HP was to continue to play an important role in the development of LEDs until 1999, when HP spun off its LED and scientific instrument businesses into Agilent Corporation. Agilent co-founded Lumileds Lighting Corporation in 1999 as a joint venture with Philips Corporation, and in 2005 Agilent sold its share of Lumileds to Philips. While GaAsP materials played an important role in the early LED industry, technical limitations of these material emerged and today they are used primarily for low-cost, low-brightness red LEDs for indicator lights.

Another major advance in LEDs was the development of GaP and GaAsP LEDs doped with optically active impurities. This work was pioneered at AT&T Bell Labs by a research group developing manufacturing processes for GaP-based red and green LEDs. While GaP does not emit light on its own, because of properties (indirect band gaps) similar to group IV elements, it strongly emits light when doped with certain impurities (optically active isoelectronic impurities) such as nitrogen. A group at AT&T reported the first demonstration of reproducible growth of efficient LEDs and through a series of technical advances was able to improve efficiencies by an order of magnitude over previous materials. The approach was aided by materials manufacturing innovations; by the end of the 1960s, ingots of GaP grown from

[2] The Monsanto optoelectronics business was initially sold to General Instrument, then was temporarily in the hands of private investors who named it Quality Technology, then was combined with Philips Optoelectronics and Harris Optoelectronics (formerly GE Optoelectronics) and renamed QT Optoelectronics (Rostky, 1997), and then in 2000 QT Optoelectronics was sold to Fairchild Semiconductor, which in 2006 sold its LED business to Everlight Electronics, a leading Taiwanese LED manufacturer. Although this chain of acquisitions is unusually complex, it is indicative of how companies shifted strategic investments in major optoelectronics developers as the technology's uncertain trajectories played out.

melts at high temperature and pressure were becoming available and were suitable for being cut into substrates.

Nonetheless GaP and GaAsP would not remain dominant indefinitely. In 1992, spurred (industry experts tell us) by GaAsP work and development of MOCVD reactors, aluminum gallium indium phosphide (AlInGaP) created many markets impossible with the previous GaAsP and GaP materials, as it increased light output from 1-2 to 10-20 lumens per watt of electricity. These developments opened the market for automobile taillights and later traffic lights. Bright red LEDs were briefly made with AlGaAs in the early 1990s, but today bright red and orange LEDs both are made with AlInGaP. GaP diodes are still used for many LED indicator lights.

4.2. Early Work on Green and Blue LEDs

Green LEDs were also developed, and in particular green LEDs using nitrogen-doped GaP (GaP:N) became widely used for low-brightness green indicator lights. In an early application, AT&T used green LEDs in its Trimline telephone. These green LEDs were not very bright but nonetheless began to fill out the color spectrum available from LEDs, spurring consideration of applications that spanned a greater range of colors.

RCA, one of the early radio and TV pioneers, envisioned that televisions would one day be thin enough to hang on a wall. RCA's vision for a flat panel display required the development of new light emitters that could replace cathode ray tubes that used three electron guns to display color images. A chief proponent of RCA's vision was James Tietjen, Director of RCA's Materials Research Division. Tietjen realized that red LEDs using GaAsP and green LEDs using GaP:N technology were already available, but what was needed to complete the display was a bright blue LED.

Tietjen challenged Paul Maruska, one of his young employees who had been growing GaAsP red LEDs in the lab, to find a method for growing single-crystal films of GaN using the metal-halide vapor-phase epitaxy method that Tietjen felt would yield blue LEDs.[3] The work went on at the RCA lab and at Stanford where Maruska was working on his PhD. While the RCA-Stanford team did achieve light emitting devices, these operated through a different physical mechanism than conventional LEDs and were never very efficient, yielding no

---

[3] Maruska's experience is documented in his unpublished recollection "A brief history of GaN blue light-emitting diodes" (obtained from sslighting.net).

commercial product. Another RCA researcher, Jacques Pankove, and his coworkers made in 1971 the first GaN metal-insulator-semiconductor (MIS) diodes that emitted green and blue light, but these devices also were inefficient. By 1974, RCA was suffering major losses in its business lines, and its work on blue LEDs was stopped. Elsewhere work on GaN also stopped until the late 1980s, when researchers in Japan began work on this III-V semiconductor material.

4.3. Search for a Viable Blue LED

For over 25 years before the development of methods to use GaN to make superior blue and green light emitters, most commercial and university laboratories had worked on II-VI compound semiconductors such as ZnS, ZnSe, and ZnMgS. Although large sums of money were spent on these efforts they did not yield viable commercial products, largely because of short operational lifetimes.

As we saw earlier, GaN electroluminescence diodes had been demonstrated at RCA Laboratories in the 1970s but the company dropped its research in this area as a result of competitive problems in its key businesses. Only a few groups, mostly in Japan, were trying to solve the three major problems that had stymied earlier researchers: a lack of suitable lattice-matched epitaxial substrates, thermal convection problems due to very high growth temperatures, and inability to achieve p-type doping. The most important of these researchers were Isamu Akasaki of Nagoya University (partially funded by Matsushita Electric Industrial Company) and Shuji Nakamura at Nichia.

Shuji Nakamura, a product development engineer at Nichia Chemical Industries, a small company in Anan on Japan's southern island of Shikoku, was working with GaN and indium gallium nitride (InGaN), a compound-semiconductor alloy most other researchers had dismissed as useless for LED manufacturing because of its many defects.

Akasaki and Nakamura, working separately, each developed similar technologies to achieve lower-defect GaN epitaxial growth using MOCVD methods (Amano et al., 1986; Nakamura, 1991). Akasaki chanced upon a partial solution to the long-standing failure to achieve p-type doping in GaN materials, by using a low-power beam of electrons in an electron microscope to activate magnesium, long thought to be the best impurity for making p-type GaN. Nakamura, however, solved the problem another way (Fasol, 1996). He knew that all previous GaN researchers had annealed their samples in ammonia (which is also used to grow GaN) as the samples cooled to room temperature following epitaxial growth. During that cooling process, ammonia decomposes to generate atomic hydrogen, which deactivates the p-type doping. This hydrogen passivation problem was well-known to III-V semiconductor researchers, and with their knowledge, industry experts suggested to us, the problem might have been solved ten years earlier, but the GaN LED researchers lacked their knowledge. Nakamura developed a post growth annealing process in a pure nitrogen atmosphere, driving out the hydrogen and yielding a reliable method to achieve high-quality p-type GaN materials. The result was the development of commercial GaN LEDs that were about 200 times as bright as previous blue and green LEDs. This invention also initiated a race to develop the first commercial GaN-based blue laser diodes.

In 1992, Nichia's first visible blue and green InGaN triple-layer ("double heterostructure") LED achieved efficiencies of 10%. Nakamura continued to modify industry-standard chemical vapor-deposition equipment to achieve the uniform, nanometers-thin layers needed to emit copious blue light. Later Nakamura used InGaN to produce the first pulsed and continuous blue lasers operating at room temperature, something others had thought impossible. Nichia's InGaN blue laser quickly led to commercial applications including for DVD-ROMs and Blu-ray discs, because data density could be about four times higher using the shorter wavelength of blue laser light.

The InGaN LED was a watershed for the lighting industry as it was a key enabler for white LED lighting. In addition to red, green, and blue facilitating color displays, the three colors can be mixed to create a combination perceived as white. The red and green parts of the spectrum can also be created by shining blue light onto phosphors, chemicals that convert part of the higher-energy blue light to lower-energy light of other colors including red, green, and yellow. Phosphors (primarily for early color TVs and fluorescent lighting) had been Nichia's core business, so the firm was well placed to produce white light from LEDs by combining blue LEDs with yellow phosphors – a combination of colors that is seen as white.

In 1996, Nichia introduced the first white LED, by covering a blue LED with yellow yttrium aluminum garnet (YAG) phosphor. White LEDs based on phosphors have a color distribution fixed by the phosphor thickness, eliminating the necessity for electronic controls to balance outputs of red, green, and blue LEDs. Thus, bright blue LEDs made it possible to develop a simple white LED light and take on more traditional lighting technologies that had been developed over the previous 100 years. This development triggered a series of patent disputes, described in section 5, that ultimately would end in cross-licensing agreements but only after years of bitter lawsuits.

4.4. Green Efficiency: An Ongoing Challenge

Nakamura's InGaN LEDs also demonstrated the means to produce green light much brighter than from previous GaP:N LEDs, without having to resort to phosphors. Phosphors work well to produce green and lower-frequency colors from blue or ultraviolet, but this exacts a price in terms of reduced energy efficiency. Also, one must search for a phosphor or combination of phosphors that yield a desired mixture of shades of green and nearby colors. Therefore, ideally green light would be emitted directly from LEDs, and fortunately InGaN and GaN LEDs can be tailored to cover the entire range of green. An ongoing challenge however is the so-called "green gap," in which green light output efficiency falls especially rapidly with electrical current. The green gap is an active focus of research today. Nonetheless, the red, green, and blue LEDs now available can be used either with or without phosphors for both color displays and general illumination white-light applications.

4.5. Stepping Stones: LED Product Niches

LEDs have now effectively substituted earlier lighting technologies in a successive list of product categories. Many of these product categories are documented in Table 1. LEDs found application as indicator lights, calculator displays, signage, flashlights, headlamps, traffic lights, and emergency lights, and they are increasingly being used in streetlights, outdoor lights, architectural lighting, and backlighting for mobile devices and TVs. Traffic signals were an early LED application as LED traffic lights promised an extended lifetime, reducing the frequency of difficult bulb changes, and would not burn out suddenly. Other hostile outdoor environments such as architectural lighting have also been early adopters of LEDs.

Today, LED lighting systems are, at least technically, capable of replacing just about every conventional (incandescent and fluorescent) lighting source in use. Estimates for 2010 market penetration of LEDs as the type of lighting appear in Figure 1, for market niches broken out by Strategies Unlimited.[4] In exit signs, LEDs were well along the S-curve of product

[4] Market penetration differs by geographic region and application, and is affected by government policies, energy prices, and events such as the 2011 tsunami in Japan.

diffusion, with over 90% of sales, and in flashlights LEDs were nearing 90% diffusion. In entertainment (particularly liquid crystal televisions), architectural lighting, and retail refrigerator displays, LEDs were well into the middle of the diffusion curve. White LED lights were gaining sales in more standard lighting applications, with around 5% of outdoor area lighting and commercial and industrial lighting sales, but in some applications such as solar-powered street lighting and, most notably, residential lighting, LED sales were just beginning as of 2010. Diffusion has been especially rapid in China, with national subsidies to purchase SSL streetlights, and Japan, which after the March 2011 tsunami experienced electricity shortages.

5. Patent Wars and Nitride LED Competition

Once the creation of commercially viable blue LEDs became known, many companies contacted Nichia to license this important new technology. In the past, Nichia had developed novel technologies only to have larger companies take most of the market. To protect itself from competition from larger companies with greater access to resources and market experience, Nichia refused to license its LED innovations to other companies. Based on the work of Nakamura and his associates, Nichia took the lead in commercializing nitride-based LEDs, introducing its first devices in 1993.

Nichia had a first-mover advantage as a result of Nakamura's important inventions, and the firm decided to invest in MOCVD reactors to produce the LEDs in-house. Their decision to go it alone coincided with the explosive popularity of mobile phones with color liquid crystal displays, which required white backlights, and the subsequent demand for the inclusion of white LEDs in mobile phones created high sales and profits (Kishi and Takahashi, 2010). Using their experience in producing phosphors to complement their work in LEDs, Nichia had a virtual monopoly on white LED demand and an overwhelming share of the white LED market, at least initially. But their refusal to license their blue LEDs led to a backlash among firms that thought they had a right to produce blue LEDs based on their own research.

Toyoda Gosei started developing GaN LEDs in 1986, working in part with Nagoya University and its fellow Toyota group companies. The company developed methods similar to Nichia's at almost the same time. Toyoda Gosei applied its LEDs quickly to automobile applications, with blue (in 1991), green, purple, and high-brightness white LEDs (Stettier and Leslie, 2010). Its blue LEDs were developed in 1991 after five years of effort, and reached mass production in 1995. This triggered, in August 1996, a legal response by Nichia.

Nichia filed with the Tokyo District Court a series of patent infringement lawsuits, the 1996 suit plus five more in 1998, alleging that Toyoda Gosei violated its blue LED patents. The Court found Toyoda Gosei in violation and ordered it to stop manufacture and sale of its LED products and provide compensation of 104.86 million yen to Nichia. However, countersuits and appeals by Toyoda Gosei prevented a simple win for Nichia.

Other cases followed, including Nichia's 1999 patent infringement suit against Cree, and Nichia suits against Epistar, Everlight, and Seoul Semiconductor. However, some judgments significantly weakened Nichia's legal position, and lawsuits often led to countersuits, deterring the incentive to sue. Countersuits were aided by the fact that more than one LED technology might be relevant to a product, and this increased the potential for countersuits, whether obviously relevant or not. Cree countersued forcefully on the basis of an earlier GaN patent licensed from Boston University. Patent-related lawsuits were common among developers of the technology, and while Nichia's case stands out, other major firms also filed against each other.

Many such cases eventually resulted in settlements with agreements to cross-license most of the relevant patents. Nichia and Toyoda Gosei's September 2002 settlement effectively permitted use of each other's patents, but with Toyoda Gosei paying royalties to Nichia for production of white LEDs using YAG phosphor. Nichia and Cree's November 2002 settlement allowed use of all GaN patents, including high-brightness LED and blue laser technologies, but excluded other technologies including Cree's silicon carbide LED patents, which are relevant to different LED types. Nichia signed a broad cross-licensing agreement with (Philips) Lumileds in October 2002, and a more narrow agreement for InGaN patents and related packaging technology with Osram in June 2002. Osram and Nichia had cross-licensed many core LED technologies earlier, after Osram obtained rights in 1996-7 to a Fraunhofer Institute patent with a priority date near Nichia's covering the same white light LED technology that Nichia patented.[5]

[5] Prior patents also used phosphors for visible-light LEDs, starting with a patent filed in 1969 by Bell Labs.

6. Institutions Leading in LED Technology Development

The meandering paths of technology development coincided with a shifting group of universities, firms, and government laboratories carrying out LED research. Organizational rankings by citations of inorganic LED-related papers are shown in Table 2 (see Appendix A for methodology). Organizations' activity sometimes resulted because of interests or chance discoveries of their researchers, but usually the organizations had made strategic decisions about their research areas. Bell Labs, for example, had long sought solid-state devices to replace vacuum tubes as amplifiers for telephone signals, and considered new materials as means to create and improve the many components of telephone systems. This led directly to its work on semiconductors, diodes including light emitting diodes, the transistor, and solar cells (Gertner, 2012). Hence Bell Labs appears at the top of Table 2 as the most-cited institution for work done during 1945-1981. RCA's role has been mentioned earlier, driven by the dream of thin televisions that could hang on a wall, and RCA appears second in the list for 1945-1981. Other institutions highly active during 1945-1981 include firms active in telephony, computing, electronics, semiconductors, and chemicals, as well as universities.

During later periods, shifts in the most-cited organizations show that work later perceived as particularly important occurred in different institutions. Firms soon showed less frequent journal publication, not because they ceased research on LEDs but because they increasingly relied not on journal publications but on patents. A few firms are exceptions, with Nichia propelled into the ranking in 1982-1991 by Nakamura's groundbreaking 1991 paper, and continuing to appear in 1992-2001 and 2002-2006 with his continuing work, and Samsung appearing in 2007-2012. University work on LEDs has been most prominent at strong technological universities, among them the Massachusetts Institute of Technology (MIT), the University of Illinois at Urbana-Champaign, North Carolina State University, Rensselaer Polytechnic Institute, and – most prominently in recent years – the University of California at Santa Barbara. At North Carolina State University, Robert Davis was the most-cited inorganic LED researcher during 1982-1991, and three students and a research assistant from Davis's lab started the leading U.S. LED chip manufacturer, Cree. The University of California at Santa Barbara's faculty includes Nakamura, who moved away from Nichia (Johnstone, 2007), and several other well-known LED researchers including Steven DenBaars. These highly respected researchers recently established a startup firm, Soraa, which achieved strong sales of a common light bulb type, the MR-16, through an unconventional approach: GaN substrates at the base of its LEDs enhance crystalline quality and hence light output at high electric current, allowing the high expense of GaN substrates to be offset by carving wafers into many small high-current LED chips. Activity leading to publications also grew more international over time, and in the most recent decade, entrants in Taiwan, China, and Korea became especially prominent in LED science.

As time went on, the annual number of LED-related publications grew exponentially. From about 25 publications per year in the mid-1950s, the publication rate grew to about 125 per year in the mid-1970s, 614 in 1992, and 4,181 in 2011. This growth in publications is apparent in Figure 2, for which the vertical axis is logarithmic. Growth in publications reflected a spiraling of the number of researchers involved as increasingly many scientists, engineers, and businesses grew interested in the technology. A similar exponential growth is apparent in patents, for which the growth rate from the mid-1950s to the late 1980s was about 10% annually, similar to the growth rate in publications. Growth in publications and especially patents accelerated in the 1990s and 2000s as commercial applications intensified.

Publications indicate where basic science initially developed, but product development innovation is measured better through patents. Patents are filed by all businesses that need to defend intellectual property rights to their technologies, whereas articles are published only by some firms. Leading patenting institutions are listed in Table 3 (see Appendix A for methodology), for the same time periods as Table 2 by date of application, except that the latter two periods are combined (otherwise international differences in delays between patent application and granting would bias results in the most recent period which would have small numbers). Patent quality is measured by multinational patent filing and patent grants, since firms rarely pay the expense of filing for a patent in multiple nations unless that patent is likely to have commercial value. The table is ordered, therefore, by the number of patents granted in multiple nations. To show when firms' recent technological strength built up, older organizations are reported under the names of their current parent firms, so figures for Philips include Color Kinetics, and figures for Siemens include Osram and Sylvania.

The major four traditional lighting firms' pursuit of LED technologies is apparent since Philips, Siemens, GE, and Toshiba are prominent in Table 3. During the earliest period, 1945 to 1981, many of the same early technology developers who published frequently, IBM, AT&T,

RCA, and Westinghouse, also received patents for their LED technologies. Several Japanese electronics and lighting firms also played a prominent role during that early period. The role of the Japanese firms grew in the 1980s and 1990s as Japanese firms became dominant producers of LEDs. The three traditional lighting firms remained important, although GE quickly slipped below the top ten ranking. Two Korean firms, Samsung and LG, invested heavily in LED technology in 2002-2010, with Samsung catapulting to the top of the patent ranking, as firms prepared for rapid SSL commercialization.

7. SSL Technology Trends, Potential, and Market Emergence

The decades-long aim of a solid-state replacement for white light has been a long time coming. In an assessment of the possible future rate of progress of SSL technology, Haitz and Tsao (2011, p.19) write,

> … SSL application needs are currently met by existing lighting technologies, but at a high level of energy consumption. SSL has only a chance to disrupt the entrenched technologies by supplying the same flux and quality of light as currently used at a significantly lower energy consumption.

However, there is also much reason for optimism. Not only are LED replacement bulbs already selling in stores at prices attractive to some buyers, but also the technology behind those replacement bulbs is improving rapidly.

7.1. Technology Trends

Haitz et al. (1999) document graphically a gradual but quite steady advance from 1968 to 1999 in light output and cost-per-lumen of LEDs. For red LEDs, their figure suggests a thirty-fold (later adjusted to twenty-fold) increase in light output per LED lamp per decade, and a ten-fold reduction in cost per decade. This trend has become widely known as Haitz's law. Haitz and Tsao (2011, p.19) update this figure to include white LED lights in 2000-2010, and for white LED lamps the corresponding improvements in light output and cost have been slightly faster than was observed for red LEDs. The data imply a mean 35% annual increase in LED light output and 20% annual decrease in LED lamp cost per lumen. Light output stems from both electrical current and efficiency, and at least for red LEDs efficiency improvements occurred steadily, albeit at a gradually decreasing growth rate as efficiency headed toward 100%, during

1968-2003 (Haitz, 2003, p.43). (White LEDs may have had a more discontinuous jump following Nakamura's work.) Given that energy savings and quality already make some LED lights attractive replacements for many buyers, the potential for LED lighting to replace existing forms of lighting, including fluorescent and incandescent, is apparent.

Haitz and Tsao reflect on this ongoing development of LED technology. They observe an "underlying see-saw dynamic between technological advance pulled by the promise of new markets, and the opening of new markets pushed by technological advance." In other words, not only does market potential pull technological advance, but also technological advance spurs new demand, particularly to the extent the technology creates new uses. These pull and push effects are expected by Haitz and Tsao to occur for perhaps a decade, but to slow as SSL efficiency approaches theoretical limits.[6] It might be added, however, that cost improvement may prove slower to reach diminishing returns and could intensify use and spur novel uses of lighting.

7.2. Competition with Conventional Lighting

Conventional light bulb technologies have had poor conversion efficiency from electric energy to visible light, ranging from 5% for incandescent light bulbs to 28% for fluorescent tubes (Haitz and Tsao, 1999, 2011). Given limits in the capabilities of conventional lighting technologies, these technologies seem unable to make any significant jump in conversion efficiency in the foreseeable future. Thus the traditional lighting industry might face a "sitting-duck scenario similar to that of the horse carriage and the vacuum tube" (Haitz and Tsao, 2011, p.21). In contrast, by 1999 LEDs had established a spectacular improvement in efficacy for red lamps, and LEDs and lasers had conversion efficiencies of 50-60% in the infrared and red parts of the spectrum. Hence "if SSL could achieve such a performance over the entire visible spectrum, then light sources with conversion efficiencies of >50% looked plausible" from the vantage of 1999 (Haitz and Tsao, 2011, p.21). The ongoing improvement since then has indeed realized large gains and has made SSL competitive for many applications.

The cost-efficiency tradeoff between SSL and conventional light bulbs depends on purchase cost, electricity cost, and replacement cost. For light bulbs in use three hours per day at average electricity prices in the U.S. (and allowing 3% annual discounting), the up-front costs of

---

[6] Another limit Haitz and Tsao identify, LED chips becoming too bright to look at, has already been mitigated by optical technologies that spread out light.

choosing SSL instead of incandescent bulbs are paid back in 1.8 years if SSL bulbs cost $12 (as available now), and from fluorescent to SSL in 17.0 years if the SSL bulb cost falls to $6 (see Appendix B). In areas with higher electricity prices, as in New York City or Japan, and for bulbs used eight hours per day, the higher SSL bulb price of $12 is paid for in 4 months versus incandescent or at $6 in 2.4 years versus compact fluorescent. Prices for LED bulbs are declining rapidly, and well-rated SSL replacements for standard 60-watt incandescent bulbs sold as of March 2013 on Amazon's website for $10.99. Data on bulb price trends are unavailable, but for packaged LED chips (before assembly into bulbs), prices fell from $32 per kilolumen in 2007 to $3.45 in 2012, while light output rose from 70 to 139 lumens per watt (using Strategies Unlimited data for one-watt cool white LED packages). The established conventional lighting industry thus seems very unlikely to crush the emerging SSL technology, and it is no surprise that the incumbent major lighting firms of the Western hemisphere each established an SSL joint venture in 1999 and then acquired the joint venture during 2001 to 2006 (Sanderson et al., 2008).

8. Growth of the SSL Industry

Starting about 2005, large numbers of firms began to enter the SSL industry, creating myriad new products. Entry was limited by patents only in selected supply chain segments. North America's major lighting trade show, LightFair, in 2010 and 2011 went from very few SSL products shown previously to SSL being the dominant type of lighting exhibited by firms, as all sorts of lighting firms developed plans to enter this new market. In the United States, LED bulbs began appearing in most home supply stores in 2012, and by late January 2013 Amazon's internet store advertised for sale nearly 15,000 different LED bulb products. Another indicator of the industry's growth is a trade directory published by *LEDs Magazine*, catering to the needs of the industry by listing large numbers of firms that could assist in SSL product and manufacturing development as well as firms making SSL products. Tables 4 and 5 document the number of firms listed in the magazine's directory at the time information was collected, around the latter part of each year 2005 through 2011, for publication early in the subsequent year.

Firms are categorized in Table 4 by country, and in Table 5 by industry segment. Worldwide, the number of firms listed grew from 127 in 2005 to 891 in 2011. Actual numbers are much higher, since many relevant firms were not recorded in the directory. In North America, where the data are more representative than in most other parts of the world, the number of firms grew from 60 in 2005 to 455 in 2011. In the U.K., also an English-speaking nation and with fairly systematic data, the number of firms grew from 23 in 2005 to 110 in 2007. Numbers of U.K. firms listed in the directory fell subsequently, but as many of the firms deleted continued to advertise their services on internet websites, this decrease seems a limitation of the directory rather than a true characteristic of the U.K. industry. Despite the English-language nature of the directory, many firms appear from other European nations and from Asian nations. Here the numbers that appear are definitely undercounts, judging from data we have obtained about firms and trade organizations in various nations, but nonetheless they are indicative of the worldwide scope of the industry and of the burgeoning activity in Asian rim nations including Japan, Taiwan, and China.

The data by industry segment in Table 5 illustrates the supply chain and applications for this emerging industry. The number of firms in each industry segment (firms often appear in multiple segments) is given for the years 2005 through 2011, whenever the directory included a section for the relevant segment. Supply chain components include LED chips and the packages that encapsulate those chips; arrays of LEDs and electrical modules incorporating LEDs to produce light; light-management optics; heat sinks to remove excess heat from LEDs; test and measurement devices and services; electronics to drive, connect, and control LED lighting; and services to design and manufacture LED chips. Each of these exhibits a rapid growth in number of firms through at least 2009; after that date the directory has a drop in the number of firms included but as mentioned above it is not clear this apparent drop is realistic. The key applications are lighting plus large displays and signs, but in some years other applications are also listed including some of the stepping-stone applications of LEDs mentioned earlier: medical and industrial lights, backlights for mobile appliances, signal lights, and vehicle lights. Separate sections were included in some years for sales and distribution networks and for industry services. While it should be emphasized that the precise numbers given here, and particularly decreases in numbers in some years, are not necessarily meaningful, nevertheless the data give a sense of the broad scope of the market, its worldwide nature, and its rapid growth.

National policy has played an important role in the development of the industry in several nations, including the U.S., Japan, and Taiwan, but particularly in China. As was revealed to us in many expert interviews, the Chinese government has invested billions of dollars to support the growth of an indigenous manufacturing capability for SSL. These vast sums have been used to pay for manufacturing facilities, subsidize by half the cost of the MOCVD reactors used to manufacture LED chips, and subsidize the purchase by provinces and localities of enormous numbers of SSL fixtures and lamps (which had to be at least 70%, by value added, made in China to be eligible for subsidies) for street lighting and other uses. Whether this strategy will allow Chinese manufacturers to become permanently competitive with leading international producers remains unclear. Quality concerns arose from initial provincial and local SSL purchases, but these concerns have been addressed by restricting subsidies to about 6-7 large SSL manufacturers (a consolidation consistent with China's Twelfth Five-Year Plan) and by requiring that quality and performance tests be passed before payment to manufacturers.[7] The government has also heavily invested in SSL research by the Chinese Academy of Sciences, a fact indicated in Table 2 by the Academy's leading ranking in publications in 2007-2012. The enormous investment by the Chinese government is apparent, as they seek to develop an industry that is a national priority to help solve the country's energy problems and build a much-needed lighting infrastructure, and that might incidentally be a valuable investment for future export reasons.

With the SSL industry in its infancy, its future is difficult to foresee, and many SSL firms' managers are struggling to make appropriate decisions in this highly competitive and complex industry. Some of the many uncertainties include which firms will be able to remain leading players in the industry, how the competition will vary by industry segment, potential market saturation exacerbated by long product lifetimes, the development and effects of standards, and future applications of SSL including with integrated controls and communications. The industry faces an exciting and challenging evolution to come, just as the automobile and mobile phone industries went from early years with much design experimentation before gradually developing characteristics and features that have come to be accepted as commonplace.

[7] China's subsidies, an industry expert explained to us, take the form of national green-energy tax breaks to localities, which otherwise must submit taxes to the national government. Local governments therefore are incentivized to help cover costs to develop local LED manufacturing and to purchase SSL streetlights.

9. Discussion and Synthesis

The findings reported above suggest a series of lessons that can be compared to the evidence from other emerging technologies and industries. Several stylized facts or patterns seem to constitute a prototypical process by which evolving technologies spawn or contribute to the development of products and industries. The technology evolution process is influenced by scientists and engineers, firms, and national policies, as well as markets that serve as stepping stones to finance development and provide avenues for learning. This is particularly important in helping to improve product performance and bring down manufacturing costs. Improved performance and reduced costs support a proliferation of market applications and niches, and strengthen firms that successfully participate in niche markets, preparing them for a confrontation with incumbents whose product is displaced by the new technology.

How does the emergence of SSL fit with stylized facts of prototypical product emergence from evolving technologies? Most of our findings below confirm ideas from prior work, although some departures from common views occur in findings 9, 10, and 13 below.

9.1. Unpredictable Paths of Technology Evolution

Technological advance is gradual (1). SSL development took a half-century from the 1950s at least until the availability of white light from blue LEDs with phosphors in 1997, with continued development of more advanced LED lamps thereafter.[8] Work on LED technologies with commercial promise occurred for over three and one half decades, including Holonyak's success in 1962. Outstanding breakthroughs built on prior developments that had proceeded over decades. Efficiency improved gradually toward 100% from 1968 through 2003, and cost per lumen improved steadily from 1968 through 2010.

Technological advance takes many paths and is difficult to predict (2). In SSL, one example is GaN's intermittent development: GaN LED R&D occurred early at RCA, but GaN was subsequently abandoned by almost all researchers and other, seemingly more promising, materials were pursued, until the 1980s and 1990s when the underdog material GaN finally achieved spectacular success. Similar branching of activity and difficulty of prediction occurred at a smaller scale within individual research projects.

[8] Chance discoveries came earlier, with electroluminescence seen in 1907 by Henry Round (1907), and light emission from crystal diodes in 1927 by Oleg Losev.

Duplication of inventive activity is common, but the multiple activities may differ in their specifics and each may have limited chance of success (3). For SSL, even unpopular approaches (such as GaN) tended to have multiple researchers, so that if one researcher did not work on a general topic, another would. This duplication of inventive activity can be helpful: each researcher has only a probability of success, the results of the research usually differ in important ways such as methods and tools, and skills acquired through the research aid the researchers' future work (Schmookler, 1966, pp.189-95).

Key individuals succeed through perseverance, combined with skill, method, and luck (4). In SSL, major successes required many steps, each a mini-invention or discovery of its own. These steps were frequently difficult to attain, nonobvious, even surprising. They often required learning new skills such as how to build and modify an MOCVD reactor or how to work with particular materials. Method involved, for example, using science and intuition to generate new ideas, and systematically experimenting with new variations, approaches and chance trials until one proved successful. Maintaining willpower to keep working despite many setbacks was crucial.

Technologies are often developed by a mix of firms and institutions including universities and public laboratories (5). In SSL, firms, universities, and government laboratories all contributed to basic research, while applied product and process development occurred primarily in firms. Researchers sometimes moved between firms and universities, as with Holonyak and Akasaki, and universities sometimes supported continuing work when business projects closed, as with Pankove.

Persistence of corporate R&D was necessary to achieve commercially viable invention success (6). In contrast, companies sometimes shut down research programs part way through because of financial pressures, even if technological potential seemed strong. This was more likely when short- or moderate-term market prospects for a technology were unclear. RCA shut down its early work on GaN LEDs in 1974, just after building an MOCVD reactor and weak blue and violet LEDs, after the company experienced corporate-wide financial losses. Texas Instruments abandoned LED work under market pressure.

9.2. Supply Push and Demand Pull

Technological knowledge spread, pushed by the efforts of scientists and engineers, facilitates the creation of products (7). In SSL, which required lengthy development of a major technology, the number of researchers involved in developing the technology and its initial commercial applications was considerable. Close to 100,000 publication authors and a similar number of patent inventors, all creators of publications and patents analyzed in Tables 2 and 3, participated in development of the technology.[9] Without these researchers, LEDs and SSL could not have advanced.

The supply of scientists and engineers working on a topic tends to increase as knowledge spreads and commercial potential becomes apparent (8). In SSL, the number of publications per annum grew exponentially, as was seen in Figure 2, and the number of researchers authoring these publications grew similarly.

Technologies are usually applied first in market niches, and a succession of niche markets may commonly support any major application (9). In SSL, the first application of indicator lights preceded a succession of other applications such as traffic lights, exit signs, outdoor video displays, architectural lighting, backlights for flat panel (television and computer) displays, flashlights, and refrigerator lights, leading up to the recent application of indoor and outdoor white lights. Although prior researchers have indicated that a market niche may spawn firms capable with a new technology, the large number of successive niches leading up to SSL for general illumination is remarkable. In light of this pattern, it would be useful to reevaluate past industry cases to examine the extent to which there were large numbers of market niches, each with distinct demand characteristics that drove product needs. While SSL may be exceptional, perhaps due to the broad scope of applicability of the technology, we suspect that very many new technologies have large numbers of distinctive market niches and that these niches typically provide stepping stones to more general commercialization.

Niches support the development of the technology but not necessarily specific companies, as few companies may participate in many niches (10). Prior studies have not carefully examined the phenomenon of many market niches leading to product development, so the

[9] Numbers of authors and inventors reported here are approximate because of difficulties matching names across publications and across patents. Using last names and first initials to distinguish authors, 78,242 authors appear (20% with at least 3 articles and 11% with at least 5 articles), but there might have been up to 111,226 authors judging from full names (which yield 16% and 7% with at least 3 and 5 articles respectively).

number of niches in which companies participate remains a topic for future study. In SSL, Osram and Sharp persisted over most of the history of SSL's commercial development and spanned several niches, but their experience was very unusual. More commonly, firms spanned up to two niches, rarely progressing from one niche to another. However, experience in a niche market often helped in developing products suitable for the emerging market in SSL, as LED backlights helped Samsung develop into SSL and colored LED Christmas lights helped Neo-Neon enter SSL.

9.3. Patents and the Appropriation of Returns to Invention and Innovation

In typical products with substantial potential for patented technology, firms develop thickets of many patents related to a product, and negotiate cross-licensing agreements (11). In SSL, major producers of LED chips and integrated SSL manufacturers held portfolios of hundreds or even thousands of relevant patents, and conflict and eventual cross-licensing within this group of producers was the norm. Licensing also occurred to other makers of SSL products, depending on the specific products made. Although Nakamura's race with Akasaki to develop a bright blue GaN LED could be modeled as a traditional patent race (but with Akasaki unaware of Nakamura's competition), the race's outcome must be understood in the context of patent thickets.

Patents are very important in a high-technology industry's birth, when lawsuits and cross-licensing arrangements are being negotiated, as a tool to help protect firms' future profit streams (12). Although for typical products patenting is just one of several methods to protect profits of technological innovation, patents may be a particularly important source of competitive advantage in the years leading up to emergence of a major industry. In SSL, this is when major patent lawsuits were fought and many licenses negotiated. The findings here do not address whether patents are socially beneficial or harmful, only how they matter competitively.

9.4. Invading Mainstream Markets

When radical disruptive technologies arise, incumbent firms may anticipate the new technology and act aggressively to transition to it, yet still be faced with stiff competition from new entrants and potentially lose their market leadership (13). The shift in technology from traditional lighting to SSL fits all the major hallmarks identified for disruptive technological shifts – a new product based on different areas of science and technology, architecturally different in its components and their assembly, starting out in niche markets, with entirely different production technologies. It is a rebuke to established theories of disruption, then, that the leading lighting firms all transitioned early to the new technology, and did so relatively successfully (so far). Incumbents' success in transitioning to the new technology apparently involved openness to change, perhaps stemming from dynamic capabilities of the firms. In any case, the incumbents' preemptive activity could prove insufficient to remain the market leaders given entry by large numbers of new competitors also establishing strong capabilities in SSL.

After creation of a new industry that has strong potential for continued technological advance, a race to keep up technologically results in continued exit of less able firms, and eventual near-cessation of entry, yielding after the initial buildup in firms an eventual drop-off, or shakeout, in firm numbers (14). In SSL, manufacturers are already wary of the uncertainties involved and the competition to come. Integrated firms are already considering bailing out of LED chip production amid uncertainties about whether giant integrated manufacturers such as Samsung, or subsidized manufacturers in China, will outcompete them on costs. These concerns are exacerbated by the slow transition of household consumers to SSL (coupled with the recent macroeconomic downturn) and by concerns that sales may fall substantially after the market is saturated. For firms to be successful in SSL supply chain segments that will experience lasting competitive shakeouts, past industry cases suggest that it is crucial for firms to enter early, grow their sales, and establish low-cost manufacturing processes and high-quality products.

Firms' competitive advantage often results from differentiation through novel product characteristics and features (15). Some SSL manufacturers are pioneering new products such as color-changing SSL systems with readily programmable interfaces, LED-based devices to promote health and affect Circadian rhythm and sleep, and SSL communication systems that transmit data to devices within rooms.

10. Conclusions

The bulk of economic growth stems from technological advance, to an extent not measured in past price indices and output statistics. Technology's unmeasured role is illustrated by Nordhaus's (1996) analysis of lighting technologies from stone-age fires and torches to oil and kerosene lamps, gas lamps, electric light, and fluorescent bulbs. A next leap in this succession of lighting technology is in progress, the switch to solid-state lighting. SSL again promises an important jump in the quality and efficiency of lighting, this time with novel features including color control and data communication.

This study yields valuable evidence in that studies of industry emergence have been few and hampered by the difficulty of tracking not only technological trajectories but also the complex interplay between those technologies and the decisions and actions of individual researchers and organizations involved in technology development. This study has deliberately taken a descriptive approach and a broad view, to move beyond network analyses of patents or publications to a more comprehensive analysis of processes at work leading to successful industry emergence. This study focuses on a single case, the newly emerged SSL industry, but the lessons drawn are compared to previous findings to yield general stylized facts of industry emergence.

Key findings pertain to the nature of technology development, to the individuals and organizations involved, and to the way in which organizations successfully navigated the development phase to enter the emergent industry. Technology development was drawn out and consisted of enormous numbers of small technological changes, with occasional major technological breakthroughs that enlarged the practical and commercial potential of the technology. Tens of thousands of scientists and engineers were involved in this development process, and some of them stood out as having particularly important capabilities and unusual approaches that allowed them to make major breakthroughs. Some firms continued development of the technology and used stepping-stone markets to help develop their products and fund continuing development work, while other firms failed to develop stepping-stone markets and exited LED technology development. Many types of firms, startups and international multi-product behemoths, traditional lighting firms, and entrants from related industries like controls and lighting fixtures, all have been entering the newly-emerged industry and bringing with them varied advantages and capabilities that may constrain them to particular segments of the new industry. Today another complex challenge faces firms as they develop new products and processes, improve light quality and product features, and drive down costs to remain competitive and appeal to a large number of customers. Making the best strategic decisions is a formidable challenge in this complex, rapidly changing, and difficult-to-analyze new industry.

Appendix A. Data Sources

Data were required on the development of LED and SSL technologies, the people and organizations that developed these technologies, the companies in the recently emerged SSL industry and those companies' products and services, and the history of major SSL companies to date including leading traditional lighting firms and major diversifying firms and entrepreneurial startups. To achieve these requirements, data were drawn from several sources. To study technological development, worldwide databases of publications and patents were used. Organizations (and people) involved in technology development were revealed through their publications and patents. Companies now involved in SSL were also identified using a recent annual buyer's guide on the LED industry. Industry reports and extensive discussions with industry experts informed the analysis.

A.1. Publications Data

Publications data pertain to articles listed in the Science Citation Index and its companion index of conference proceedings. Relevant publications were identified using the same search criteria employed by another group with leading expertise in SSL (Boyack et al., 2009). The search criteria were developed through an iterative process and were tested by those authors against lists of publications by key LED researchers and institutions, yielding estimated precision and recall of 70-90%, by no means perfect but reasonable for the analyses used here (Lundberg et al., 2006). To further ensure key articles analyzed are relevant, the top 100 articles by citation counts in each period 1945-1981, 1982-1991, and 1992-2001 were checked manually, and off-topic and irrelevant articles were removed from the data. After 2001, when the large number of publications being generated tend to reduce noise in citation counts, citations within articles in the dataset were computed as a metric that provides little or no weight to irrelevant articles, which were mainly burgeoning applications of LEDs and their materials to medicine and the sciences. Additional criteria described by Boyack et al. (2009) were used to classify publications as pertaining to inorganic versus organic LEDs. Each article's authors, author affiliations, and number of citations were recorded. Where the source data lacked information on author affiliations (particularly in early years), data for all journal issues in the authors' university library (90% of all missing data) were compiled by hand. The organizational affiliations of authors were matched manually to ensure that alternate spellings and (most carefully for leading organizations) subsidiaries were treated each as a single organization.

A.2. Patent Data

Patent data are drawn from the European Patent Office's EPO Worldwide Patent Statistical Database. This global database not only includes applicants worldwide, but importantly it also covers patents granted by most substantial patent authorities worldwide. About sixty national and regional patent authorities, covering almost all nations with substantial LED activity as well as the world's major multi-nation patent authorities, are included. For Taiwan, only limited national patent data are available. For mainland China data are available from 1985, for South Korea from 1978, for Japan and Australia from 1973, and for Canada from 1970. Use of patent data from virtually all granting authorities, not just the U.S. or Europe, avoids a Western-centric bias that would otherwise be substantial for LED-related technologies.

Applications data, available in more recent years (the number of years varies by nation), provide a measure of recent technological activity. Application evaluation often occurs over multiple years before a patent is granted, so applications provide a relatively leading-edge understanding of recent developments in LED industries. Neither applications nor granted patents provide a totally up-to-date metric, however, because national laws dictate a period of privacy before a patent application's full specifications are published, and because of delays in granting decisions, in the provision of bibliographic data from national patent offices to the EPO, and in the EPO's preparation of its biannual database. Applications cannot be reliably attributed as being patent versus utility model applications, given limitations of the publication type data provided to the EPO by many national patent offices, so applications include those for utility models (not to be confused with patents of utility) as well as regular patents, for countries that grant utility models. An application filed in multiple nations, or multiple times in the same nation, as measured by an INPADOC family, is herein counted only once.

LED-related documents (patents, utility models, and their applications) were identified by developing a series of distinctive title keywords and international patent classification (IPC) codes, through a successive iteration between identification and discussion with industry experts. A list of title keywords and IPC codes used to identify relevant patents is available in Simons and Sanderson (2011), except that the search term "electroluminescent" has been added here. The codes are designed to capture a large portion of LED-related documents while excluding almost every non-LED-related document. An analysis of patents applied for by three companies that focus mainly on LED technologies revealed that approximately half of each of these companies' patents are caught by our patent search (50% for Color Kinetics, 41% for Cree, and 58% for Nichia). Similarly, an analysis of U.S. patents in U.S. class 362/800, which is a light-emitting diode cross-reference art collection, showed that 45% of these LED-related patents are caught by our search method. Inorganic LED patents and applications were identified by excluding any that matched the organic LED identification criteria documented in Simons and Sanderson (2011).

Applicant organizations were coded to match records with different names for the same organization. These differences result from typos, variant names used by different national patent offices, and variant names used within a patent office. Parts of larger organizations, such as Philips and its subsidiaries, were combined with the parent organization, and headquarters nationalities of organizations were likewise recorded based on the location of head offices of the parent organization.

A.3. Industry Directory

LEDs Magazine's LED Suppliers Directory, published annually from March 2006 through January 2012, lists manufacturers, service providers for manufacturers, and suppliers of numerous LED-related components and products. The 2012 directory is divided into ten sections, which detail which companies supply each of a range of more specific product types. Most but not all of these sections had information similarly catalogued from 2006 onward.

The directory unfortunately does not distinguish pure suppliers from companies that design or build their own products or that provide services to aid LED lighting or product design. We therefore evaluated each company based on information reported in the directory and on its website (or past website where available for defunct companies) and eliminated from our analysis all companies that apparently are pure suppliers.

The *LEDs Magazine* data are global. That said, *LEDs Magazine* is published in English, and edited in Great Britain and the United States. Hence English-language companies, particularly British and U.S. companies, are likely to be relatively highly represented. Small firms in other nations, particularly non-English speaking nations, are less likely to have placed their data in *LEDs Magazine*'s directory.

Directory listings are free of charge, and the publishers attempt to keep the information up to date and accurate through an ongoing review process and solicitations of updated information. Company representatives can add or update their listings using an Internet-based system, and since the magazine is the leading LED-related trade publication, the directory apparently captures many or most companies that are selling LED-related products or services. These companies gain business by being listed in the directory and therefore have an incentive to ensure that they are listed in it (this may be less true for companies that seek no business from English-speaking customers). Nonetheless, many relevant firms do not appear in the directory, and its editors seem to have carried out periodic culls of the firms included in which many relevant firms were eliminated, possibly because they failed to submit updated information.

A.4. Industry Experts

We coupled the above quantitative sources with in-depth discussion with experts in the U.S. and worldwide. Experts from industry, academia, and government were interviewed over the period 2006-2012 as the authors attended LED and SSL conferences run by the U.S. Department of Energy, LightFair, SPIE (optics and photonics engineers), the University of California at Santa Barbara, Rensselaer Polytechnic Institute, and Boston University; meetings with executives from Philips, Osram-Sylvania, General Electric, Color Kinetics, Walsin Lihwa, San'an, and other organizations; meetings with government policy makers at the U.S. Department of Energy and Taiwan's Industrial Technology Research Institute; and meetings and informal interactions of the NSF Smart Lighting Engineering Research Center, in which the authors study the development and impacts of SSL, smart lighting, and their emerging industries.

Appendix B. Relative Cost of Alternative Light Bulbs

SSL bulbs currently cost more than incandescent and compact fluorescent light bulbs, but use less electricity and last longer. It is desired to analyze the recent relative costs of these light bulb types.

The expected discounted financial cost to buy a light bulb of type *i*, operate it for *T* years, and replace it when needed is $C_i = p_i + \int_0^T e^{-\rho t}(kw_i h365/1000)\,dt + \int_0^T e^{-\rho t} p_i(365h/L_i)\,dt$, where p_i is the bulb's purchase price, *k* is the cost of electricity per kilowatt-hour, w_i is electricity consumption in watts, h is hours operated per day, L_i is the bulb's expected lifetime in hours, and ρ is the purchaser's real discount rate. The bulb price and electricity price are assumed to be constant. The figure 365 is the number of days per year, while 1000 is the number of watts per kilowatt. The first term in C_i is the purchase price, the second term is the discounted cost of electricity, and the third term is the discounted cost of replacing burned-out light bulbs. C_i simplifies to $p_i + m_i(1 - e^{-\rho T})$ where $m_i = (h365/\rho)(kw_i/1000 + p_i/L_i)$. Letting $i = 0$ denote a reference bulb type (incandescent or compact fluorescent), the time T^* until the expected extra cost of an SSL bulb of type 1 (compared to a type 0 bulb) is paid back is found by solving $C_1 = C_0$ for $T = T^*$. This yields $T^* = \frac{-1}{\rho}\ln(1 - \frac{p_1 - p_0}{m_0 - m_1})$.

Comparisons are based on hypothetical reference bulbs: a \$1.00 incandescent bulb emitting 800 lumens with 60 watts of electricity for an expected life of 1,000 hours (compare to GE 41208: \$6.99 per four-pack, 800 lumens, 60 watts, 1,000-hour rated life); a \$1.30 compact fluorescent bulb emitting 800 lumens with 12.6 watts for 8,000 hours (compare to GE 383330: \$10.34 per eight-pack, 825 lumens, 13 watts, 8,000-hour rated life); and a \$12.00 SSL bulb emitting 800 lumens with 9 watts of electricity for 30,000 hours (compare to Lighting EVER 100022-DW: \$10.99 each, 630 lumens, 7 watts, 30,000-hour rated life; or to Philips 423244: \$26.77 each, 940 lumens, 10 watts, 30,000-hour rated life). Comparators are major sellers with roughly comparable specifications and standard (A19 or common compact fluorescent) Edison-base bulb shape on Amazon's internet store as of March 15, 2013, and Amazon's retail price is used since manufacturer suggested retail prices include widely varying margins.

For $T = \infty$, $C_i = p_i + m_i$. Using the U.S. average household electricity cost of \$0.10 per kilowatt-hour, a typical usage of 3 hours per day, and a 3% real discount rate, the infinite-horizon expected discounted cost is \$256.50 for the incandescent bulb, \$53.22 for the compact fluorescent bulb, or \$59.45 for the SSL bulb. The time T^* for SSL to recoup its price differential is 1.8 years compared to incandescent, but never compared to compact fluorescent. At the average New York City area or Japanese household electricity cost of \$0.20 per kilowatt-hour and 8 hours per day, T^* is 4 months compared to incandescent or 8.6 years compared to compact fluorescent. If the SSL bulb price falls to \$6, T^* falls to 2 months or 2.4 years.

Acknowledgements

This work was supported primarily by the Engineering Research Centers Program (ERC) of the National Science Foundation under NSF Cooperative Agreement No. EEC-0812056 and in part by New York State under NYSTAR contract C090145. These funding sources did not affect study design, data, writing, or journal submission. We thank three anonymous referees and Bob Karlicek for helpful comments, and many industry experts for valuable discussions.

References

Adams, J.D., 1990. Fundamental stocks of knowledge and productivity growth. Journal of Political Economy 98 (4), 673-702.

Adams, J.D., Clemmons, J.R., Stephan, P.E., 2006. How rapidly does science leak out?, NBER Working Paper 11997.

Amano, H., Sawaki, N., Akasaki, I., Toyoda, Y., 1986. Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer. Applied Physics Letters 48 (5), 353-5.

Antonelli, C., 2008. Localised Technological Change: Towards the Economics of Complexity. Routledge, London.

Arthur, W.B., 1988a. Competing technologies: An overview, in: Freeman, C., Nelson, R., Silverberg, G., Soete, L. (Eds), Technical Change and Economic Theory. Pinter Publishers, London, pp. 590-607.

Arthur, W.B., 1988b. Self-reinforcing mechanisms in economics, in: Anderson, P.W., Arrow, K.J., Pines, D. (Eds), The Economy as an Evolving Complex System. Addison-Wesley, Redwood City, pp. 9-31.

Arrow, K., 1962. Economic welfare and the allocation of resources for invention, in: National Bureau of Economic Research (Ed), The Rate and Direction of Inventive Activity. Princeton University Press, Princeton, pp. 609-25.

Basalla, G., 1988. The Evolution of Technology. Cambridge University Press, Cambridge.

Boldrin, M., Levine, D.K., 2013. The case against patents. Journal of Economic Perspectives 27 (1), 3-22.

Boyack, K.W., Tsao, J.Y., Miksovic, A., Huey, M., 2009. A recursive process for mapping and clustering technology literatures: Case study in solid-state lighting. International Journal of Technology Transfer and Commercialisation 8 (1), 51-87.

Christensen, C., Rosenbloom, R., 1995. Explaining the attacker's advantage: Technological paradigms, organizational dynamics, and the value network. Research Policy 24, 233-57.

Churella, A.J., 1998. From steam to diesel: Managerial customs and organizational capabilities in the twentieth-century American locomotive industry. Princeton University Press, Princeton.

Cockburn, I.M., MacGarvie, M.J., Müller, E., 2010. Patent thickets, licensing and innovative performance. Industrial and Corporate Change 19 (3). 899-925.

Cohen, W.M., Nelson, R.R., Walsh, J.P., 2000. Protecting their intellectual assets: Appropriability conditions and why U.S. manufacturing firms patent (or not), NBER Working Paper 7552.

Cooper, A.C., Schendel, D., 1976. Strategic responses to technological threats. Business Horizons 19 (1), 61-9.

David, P., 1985. Clio and the economics of QWERTY. American Economic Review 75 (2): 332-7.

Dosi, G., 1982, Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. Research Policy 11 (3), 147-62.

Fasol, G., 1996. Room-temperature blue gallium nitride laser diode. Science 272 (5269), 1751-2.

Fisher, D.E., Fisher, M.J., 1996. Tube: The Invention of Television. Counterpoint, Washington, D.C.

Foster, R.N., 1986. Innovation: The Attacker's Advantage. Summit Books, New York.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Research Policy 31, 1257-74.

Gertner, J., 2012. The Idea Factory: Bell Labs and the Great Age of American Innovation. Penguin Press, New York.

Gort, M., Klepper, S., 1982. Time paths in the diffusion of product innovations. Economic Journal 92 (3), 630-53.

Hagiu, A., Yoffie, D.B., 2013. The new patent intermediaries: Platforms, defensive aggregators, and super-aggregators. Journal of Economic Perspectives 27 (1), 45-66.

Haitz, R., 2003. Another semiconductor revolution: This time it's lighting! Advances in Solid State Physics 43, 35-50.

Haitz, R, Kish, F., Tsao, J., Nelson, J., 1999. The case for a national research program on semiconductor lighting, Sandia National Laboratories Report SAND 2000-1612 (downloaded on 1 March 2013 from http://www.sandia.gov/~jytsao/hpsnl_sand_report_2000.pdf).

Haitz, R., Tsao, J.Y., 2011. Solid-state lighting: 'The case' 10 years after and future prospects. Physica Status Solidi A 208 (1), 17-29.

Henderson, R.M. Clark, K.B., 1990. Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. Administrative Science Quarterly 35, 9-30.

Holonyak, N., Jr., 2013. The III-V alloy p-n diode laser and LED ultimate lamp. Proceedings of the IEEE 101 (10), 2158-2169.

Johnstone, B., 2007. Brilliant! Shuji Nakamura and the Revolution in Lighting Technology. Prometheus Books, Amherst NY.

Kishi, N., Takahashi, N., 2010. Licensing strategy of Japanese firms and competitive advantage. Annals of Business Administrative Science 9 (1), 1-12.

Klepper, S., Graddy, E., 1990. The evolution of new industries and the determinants of market structure. RAND Journal of Economics 21 (1), 27-44.

Klepper, S., Simons, K.L., 1997. Technological extinctions of industrial firms: An inquiry into their nature and causes. Industrial and Corporate Change 6 (2), 379-460.

Klepper, S., Simons, K.L., 2005. Industry shakeouts and technological change. International Journal of Industrial Organization 23 (1-2), 23-43.

Levin, R.C., Klevorick, A.K., Nelson, R.R., Winter, S.G., 1987. Appropriating the returns from industrial research and development. Brookings Papers on Economic Activity 1987 (3) Special Issue on Microeconomics, 783-831.

Levinthal, D.A., 1998. The slow pace of rapid technological change: Gradualism and punctuation in technological change. Industrial and Corporate Change 7 (2), 217-47.

Lundberg, J., Fransson, A., Brommels, M., Skar, J., Lundkvist, I., 2006. Is it better or just the same? Article identification strategies impact bibliometric assessments. Scientometrics 66 (1), 183-97.

Maggitti, P.G., Smith, K.G., Katila, R., 2013. The complex search process of invention. Research Policy 42, 90-100.

Majumdar, B.A., 1982. Innovations, Product Developments, and Technology Transfers: An Empirical Study of Dynamic Competitive Advantage, the Case of Electronic Calculators. University Press of America, Washington, D.C.

Merton, R.K., 1963. Resistance to the systematic study of multiple discoveries in science. European Journal of Sociology 4 (2), 237-82.

Mokyr, J., 1990. Punctuated equilibria and technological progress. American Economic Review (papers & proceeding) 80 (2), 350-4.

Moser, P., 2013. Patents and innovation: Evidence from economic history. Journal of Economic Perspectives 27 (1), 23-44.

Nakamura, S., 1991. GaN growth using GaN buffer layer. Japanese Journal of Applied Physics 30 (10A), L1705-7.

Nelson, R.R., 1995. Recent evolutionary theorizing about economic change. Journal of Economic Literature 33 (1), 48-90.

Nelson, R.R., 2005. Technology Institutions and Economic Growth. Harvard University Press, Cambridge, Mass.

Nelson, R.R., Winter, S.G., 1974. Neoclassical vs. evolutionary theories of economic growth: Critique and prospectus. Economic Journal 84 (336), 886-905.

Nelson, R.R., Winter, S.G., 1982. An Evolutionary Theory of Economic Change. Harvard University Press, Cambridge, Mass.

Nordhaus, W.D., 1996. Do real-output and real-wage measures capture reality? The history of lighting suggests not, in: Bresnahan, T.F., Gordon, R.J. (Eds), The Economics of New Goods. University of Chicago Press, Chicago, 27-70.

Pinch, T.J., Bijker, W.E., 1984. The social construction of facts and artefacts: Or how the sociology of science and the sociology of technology might benefit each other. Social Studies of Science 14, 399-441.

Reinganum, J.F., 1983. Uncertain innovation and the persistence of monopoly. American Economic Review 73 (4), 741-8.

Riordan, M., 2005. How Europe missed the transistor: The most important invention of the 20th century was conceived not just once, but twice. IEEE Spectrum 42 (11), 52-7.

Rogers, E.M., 2003. Diffusion of Innovations, 5th ed. Free Press, Glencoe.

Rogers, R.P., 1980. Staff Report on the Development and Structure of the U.S. Electric Lamp Industry. U.S. Government Printing Office, Washington D.C.

Rostky, G., 1997. LEDs cast Monsanto in unfamiliar role. Electronic Engineering Times 944 (March 10), 24.

Rothaermel, F.T., Hill, C.W.L., 2005. Technological discontinuities and complementary assets: A longitudinal study of industry and firm performance. Organization Science 16 (1), 52-70.

Round, H.J., 1907. A note on carborundum. Electrical World 19 (6), 309.

Sahal, D., 1981. Patterns of Technological Innovation. Addison-Wesley, Reading, Mass.

Sanderson, S.W., Simons, K.L., Walls, J.L., Lai, Y., 2008. Lighting, in: Macher, J.T., Mowery, D.C. (Eds), Innovation in Global Industries: U.S. Firms Competing in a New World. National Academies Press, Washington D.C., pp. 163-205.

Schmookler, J., 1966. *Invention and Economic Growth*. Harvard University Press, Cambridge, Mass.

Schot, J., Geels, F.W., 2007. Niches in evolutionary theories of technical change: A critical survey of the literature. Journal of Evolutionary Economics 17, 605-22.

Schubert, E.F., 2006. Light-Emitting Diodes, 2nd ed. Cambridge University Press, Cambridge.

Schumpeter, J.A., 1942. Capitalism, Socialism, and Democracy. London: Allen and Unwin.

Simons, K.L., Sanderson, S.W., 2011. Global technology development in solid state lighting technologies. International Journal of High Speed Electronics and Systems 20 (2), 359-82.

Smiley, R., 1988. Empirical evidence on strategic entry deterrence. *International Journal of Industrial Organization* 6, 167-80.

Smith, A., Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. Research Policy 41 (6), 1025-36.

Stettier, J., Leslie, A., 2010. The Future of Lighting: Who Will Win? New Street Research, London.

Tilton, J., 1971. International Diffusion of Technology: The Case of Semiconductors. Brookings Institution, Washington D.C.

Tripsas, M., 1997a. Surviving radical technological change through dynamic capability: Evidence from the typesetter industry. Industrial and Corporate Change 6 (2), 341-377.

Tripsas, M., 1997b. Unraveling the process of creative destruction: Complementary assets and incumbent survival in the typesetter industry. Strategic Management Journal 18 (Special Summer Issue), 119-142.

Tushman, M.L., Anderson, P., 1986. Technological discontinuities and organizational environments. Administrative Science Quarterly 31 (3), 439-65.

Udelson, J.H., 1982. The Great Television Race: A History of the American Television Industry 1925-1941. University of Alabama Press, University, Alabama.

Vincenti, W. 1994. The retractable airplane landing gear and the Northrup `anomaly': Variation-selection and the shaping of technology. Technology and Culture 35 (1): 1-33.

Wolf, H., Wolf, R., 1936. Rubber: A Story of Glory and Greed. Covici Friede, New York.

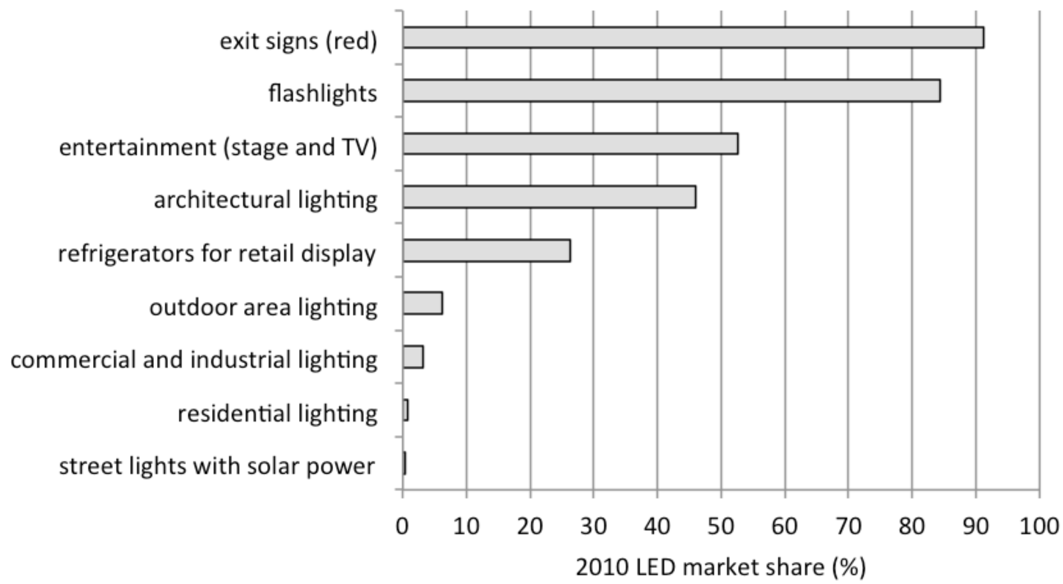

Figure 1. Diffusion of LEDs by Market Niche, 2010 (estimates from Strategies Unlimited).

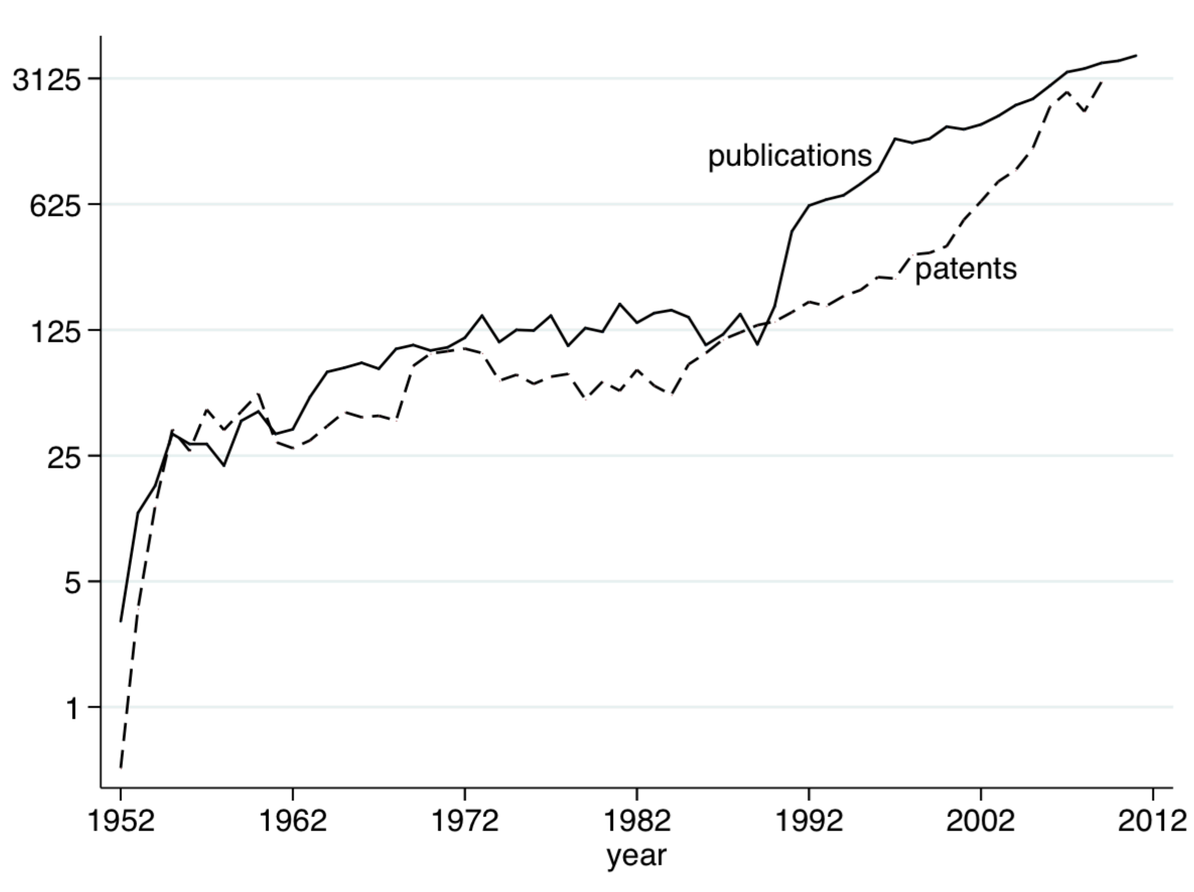

Figure 2. Inorganic LED Publications and Patents by Year. Source: See Appendix A.

Table 1. Selected Stepping-Stone Market Niches Culminating in Solid-State Lighting

Introduced	Application/Market	Pioneer
1962	Circuit board indicator lights	Texas Instruments
1962	Alpha-numeric displays	GE
1967	Indicator lights	Monsanto/HP
1968	Early electronic display	HP
1970	LED watch (Pulsar)	Hamilton Watch Co
1977	LED TV screen (B&W)	
1981	Early LED traffic lights	Electro-Tech's
Late 1980s-1990s	Auto interior lighting, early color LED displays	Siemens, Sanyo, and later Cree
1993	Bright blue LED, enabling electronic device backlighting	Nichia, Toyoda Gosei
1990s	Bright white LEDs; LED streetlights, flashlights, traffic lights	Nichia, Lumileds (Philips), Cree
1997	Architectural lighting	Color Kinetics (acquired by Philips)
2000s	LED light bulbs	Various
2004	Commercial LED daylight auto headlamp	Audi/Lumileds
2004	AC LED (low power)	Industrial Technology Research Institute, and 23 firms, in Taiwan
2007	OLED television	Sony

Table 2. Top Ten Institutions Most Cited for Inorganic LED Publications, By Time Period

		Raw Counts			Age-Adjusted	
Institution	Country	Cites	W-Cites	Papers	Cites	W-Cites
1945 to 1981						
Bell Labs	U.S.	3226.0	16.0	131.0	3226.0	16.0
RCA Corp	U.S.	1425.0	3.0	76.1	1425.0	3.0
IBM	U.S.	1277.0	0.0	58.0	1277.0	0.0
GE Co	U.S.	878.5	23.0	31.5	878.5	23.0
Westinghouse Electric Corp	U.S.	858.5	13.0	59.2	858.5	13.0
GTE Sylvania Inc	U.S.	513.0	2.0	35.0	513.0	2.0
Monsanto Co	U.S.	428.0	0.0	13.3	428.0	0.0
Fujitsu	Japan	310.5	0.0	12.5	310.5	0.0
Univ Illinois Urbana-Champaign	U.S.	265.0	0.0	3.9	265.0	0.0
Kyoto Univ	Japan	264.0	0.0	15.0	264.0	0.0
1982 to 1991						
Osaka Univ	Japan	1562.0	31.0	23.5	1572.1	31.1
Fraunhofer Inst Appl S-S Physics	Germany	829.4	0.0	3.2	830.0	0.0
Bell Labs	U.S.	598.9	7.0	41.2	600.0	7.0
Nichia Corp	Japan	430.0	0.0	1.0	433.7	0.0
MIT	U.S.	403.0	1.0	7.0	403.5	1.0
NTT Corp	Japan	354.0	10.0	34.0	355.3	10.1
Univ Joseph Fourier	France	349.0	0.0	1.0	352.0	0.0
Univ of Texas at Austin	U.S.	346.0	9.0	9.0	348.2	9.1
Univ of Toronto	Canada	325.0	2.0	2.0	327.8	2.0
North Carolina State Univ	U.S.	323.0	46.0	3.0	325.8	46.4
1992 to 2001						
Nichia Corp	Japan	7589.1	448.5	71.4	8057.2	498.5
Univ Illinois Urbana-Champaign	U.S.	6565.3	419.2	66.1	6846.1	443.3
Bell Labs	U.S.	4630.6	375.8	72.1	4824.2	395.0
MIT	U.S.	4583.1	413.0	68.9	5210.8	459.8
Univ of Calif Santa Barbara	U.S.	4057.9	293.3	58.0	4526.6	338.0
Univ of Calif Berkeley	U.S.	3958.9	321.4	36.0	4644.4	378.0
Harvard Univ	U.S.	3186.0	171.8	14.6	3882.6	213.6
Tohoku Univ	Japan	3041.6	106.9	61.2	3365.2	123.0
Xerox Corp	U.S.	2516.4	338.0	33.3	2767.4	367.0
Univ of Cambridge	U.K.	2257.6	93.4	47.9	2437.4	106.3
2002 to 2006						
Univ of Calif Santa Barbara	U.S.	3534.0	2003.4	78.5	5952.1	3350.0
Rensselaer Polytechnic Inst	U.S.	1988.1	1441.3	82.9	3330.5	2462.8
Univ of South Carolina	U.S.	1542.9	1127.7	59.7	2326.8	1684.2
Chinese Academy of Sciences	China	3114.2	988.2	211.9	5279.5	1681.9

Institution	Country	Raw Counts Cites	W-Cites	Papers	Age-Adjusted Cites	W-Cites
National Cheng Kung Univ	Taiwan	2029.6	945.9	100.3	3087.8	1492.3
National Chiao Tung Univ	Taiwan	1346.3	943.3	88.9	2312.2	1639.5
Nichia Corp	Japan	1394.4	833.0	33.6	2135.1	1247.0
National Tsing Hua Univ	Taiwan	1057.4	714.6	42.2	1663.2	1112.6
National Central Univ	Taiwan	839.0	604.2	55.0	1282.0	911.2
Yonsei Univ	S. Korea	1031.5	600.2	27.2	1726.8	1006.9
2007 to early March 2012						
Chinese Academy of Sciences	China	3340.2	1148.9	540.3	11979.7	4107.5
National Taiwan Univ	Taiwan	1480.2	853.7	263.7	5076.0	2897.3
Univ of Calif Santa Barbara	U.S.	1909.2	796.3	149.7	6479.0	2902.0
National Chiao Tung Univ	Taiwan	1079.9	726.8	239.7	4050.8	2663.4
Lehigh Univ	U.S.	921.7	695.5	79.9	3973.7	2983.3
Sun Yat Sen University	China	930.9	585.0	120.3	3198.0	1963.0
Samsung	S. Korea	905.8	556.9	128.0	3108.9	1944.4
National Inst for Materials Sci	Japan	1033.5	517.4	89.5	3443.3	1607.4
National Cheng Kung Univ	Taiwan	948.5	503.7	249.1	3691.7	1878.2
Rensselaer Polytechnic Inst	U.S.	645.6	449.1	102.6	2257.3	1582.7

Notes: Institutions are ranked by all citations through 2001, while papers and citations tend to be few, and are ranked by within-dataset citations thereafter, to screen out many recent off-topic publications including applications of LEDs to medicine and science. Through 2001 off-topic publications with high citation counts were identified and excluded manually. Data pertain to articles in the Science Citation Index and its conference proceedings companion, and therefore tend to undercount non-English language publications. All counts are divided by the number of institutional affiliations of authors on a paper, or for papers with information on all authors' affiliations, counts are divided by the number of authors and then credit is apportioned to each author's institution. For example a three-author paper with authors at three different institutions counts as 1/3 of a paper for each institution, and its number of citations is divided by three when crediting each institution. "Cites" is the total number of citations recorded in the citation indices, "W-Cites" is within-database citations for which LED-related papers cite other LED-related papers (this reduces citation counts related to external applications such as medical uses of LEDs), and "Papers" is a count of papers published. The last two columns contain age-adjusted versions of the citation metrics, using a best-fit quadratic citation lag function. Time periods are defined based on year of publication.

Table 3. Top Ten Institutions with Most Multi-Country Inorganic LED Patents, By Time Period

Institution	Country	Applications	Patents	M-Applications	M-Patents
1945 to 1981					
Philips	Netherlands	214.5	185.1	99.5	94.1
IBM	U.S.	92.9	86.6	70.9	61.6
Siemens	Germany	322.6	255.7	69.1	54.7
AT&T	U.S.	61.4	53.0	58.4	49.5
Panasonic	Japan	167.8	119.5	38.8	35.5
GE	U.S.	183.3	169.9	37.8	33.3
RCA	U.S.	99.4	99.1	33.4	32.1
Westinghouse	U.S.	174.5	161.1	27.5	23.1
Sharp	Japan	205.4	172.0	22.4	21.0
Hitachi	Japan	129.0	65.5	35.8	20.3
1982 to 1991					
Sharp	Japan	448.1	205.8	86.1	68.3
Toshiba	Japan	553.7	135.8	54.7	47.3
AT&T	U.S.	59.6	56.2	53.6	46.7
Mitsubishi	Japan	435.8	91.6	41.0	28.3
NEC	Japan	771.7	125.8	30.2	26.3
Hitachi	Japan	569.4	90.4	33.6	23.9
Panasonic	Japan	856.1	225.3	30.4	20.5
Siemens	Germany	79.8	48.3	45.8	20.3
Philips	Netherlands	34.4	27.7	24.4	18.7
Fujitsu	Japan	897.4	122.4	15.5	15.0
1992 to 2001					
Philips	Netherlands	190.2	188.9	160.7	144.4
Sharp	Japan	652.6	370.7	130.2	102.9
Semiconductor Energy Lab	Japan	191.7	127.2	123.7	80.4
Sony	Japan	564.2	210.8	128.8	79.0
NEC	Japan	282.1	198.7	101.2	78.7
Siemens	Germany	192.3	134.1	107.5	76.8
Seiko	Japan	383.1	209.3	84.1	71.1
Toshiba	Japan	532.9	207.5	92.7	68.4
Panasonic	Japan	799.7	238.2	82.9	65.8
Sanyo	Japan	354.7	142.6	73.3	60.1
2002 to 2010					
Samsung	Korea	3077.4	1876.5	1044.0	483.4
Seiko	Japan	2549.9	819.6	610.3	401.5
Semiconductor Energy Lab	Japan	1160.0	550.7	641.0	256.4
Philips	Netherlands	886.6	523.0	618.3	218.8
Sanyo	Japan	546.5	228.6	220.5	145.0
Sharp	Japan	835.8	332.9	262.8	127.7
Sony	Japan	1494.4	326.3	463.1	124.6
LG	Korea	1717.9	688.8	316.2	109.2
Panasonic	Japan	1404.2	341.0	235.3	108.0

Siemens	Germany	801.2	347.5	334.3	98.9

Notes: Institutions are ranked by LED patents granted in multiple nations, as a metric of quality. Data pertain to patents granted in patent authorities worldwide (see Appendix A for details). For patents with multiple authors at different institutions, credit is divided equally among the authors and assigned to each author's institutional affiliation. "Applications" includes LED patents applied for but not necessarily granted, and is subject to non-availability of data on non-granted patent applications in early periods in most nations. "Patents" are only granted patents. "M-Applications" and "M-Patents" are applications filed in, and patents granted in, multiple nations.

Table 4. Number of Firms in *LEDs Magazine* Industry Directory by Nation and Year

Nation	2005	2006	2007	2008	2009	2010	2011
United States of America	56	74	263	345	462	274	406
Canada	4	5	34	39	47	32	46
North America Total	*60*	*80*	*298*	*384*	*510*	*308*	*455*
United Kingdom	23	36	110	92	105	40	55
Germany	6	13	40	39	44	23	35
Netherlands	2	4	11	11	17	10	12
France	2	0	10	8	12	9	9
Italy	4	3	10	12	12	3	4
Other European nations	16	15	59	68	71	50	54
Europe Total	*53*	*71*	*240*	*230*	*261*	*135*	*169*
China	1	5	51	51	86	94	133
Taiwan	6	15	53	49	67	46	59
India	1	2	11	9	10	8	19
South Korea	0	3	6	9	20	6	12
Japan	4	4	13	12	13	6	6
Other Asian Rim nations	0	0	17	13	16	6	10
Asian Rim Total	*12*	*29*	*151*	*143*	*212*	*166*	*239*
Other Total	*2*	*1*	*21*	*21*	*18*	*19*	*28*
World Total	127	181	710	778	1,001	628	891

Notes: Numbers for non-English-speaking nations, or nations outside the U.S. and U.K., may be most severely undercounted, since *LEDs Magazine* is published in English and edited out of the U.S. and U.K. All nations with 12 or more firms in any year are listed. Distributor-only firms (subjectively identified) are excluded, where information about the firms could be found on the internet. Listings were published in April 2006, March 2007 through 2010, and January 2011 through 2012, and the year in the table is the preceding year, when most data were collected.

Table 5. Number of Firms in *LEDs Magazine* Industry Directory by Industry Segment and Year

Industry Segment	2005	2006	2007	2008	2009	2010	2011
Chips & packages	65	61	149	130	154	88	117
Arrays, light engines, modules	64	82	288	319	380	146	190
Optics, packaging, thermal mgmt.	62	60	219	248	297	130	171
Test & measurement	10	18	51	61	73	31	51
Drivers, controls, connectors	53	58	213	272	349	140	193
Chip design & manufacture		11	33	44	64	24	42
Networks & distributors			16	32	30	14	23
Lighting	61	77	317	425	594	306	410
Displays & signs	49	84	289	300	45	133	184
Other applications	59	76	267	279			
Industry services	6						

Notes: Firms typically participate in multiple segments. Blank cells occur in years when *LEDs Magazine*'s industry directory did not contain data for the specified industry segment. Distributor-only firms (subjectively identified) are excluded, where information about the firms could be found on the internet. Listings were published in April 2006, March 2007 through 2010, and January 2011 through 2012, and the year in the table is the preceding year, when most data were collected.