Research Policy 43 (2014) 1730–1746

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Light emitting diodes and the lighting revolution: The emergence of a solid-state lighting industry

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ARTICLE INFO

Article history:
Received 1 June 2012
Received in revised form 11 October 2013
Accepted 25 April 2014
Available online 13 August 2014

Keywords:
Industry emergence
Technology evolution
Technological trajectories
Market niches
Patent litigation
Disruptive technology

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 while reducing cost and improving efficacy of LEDs. 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.

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 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,

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http://dx.doi.org/10.1016/j.respol.2014.07.011
0048-7333/

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 2010–2015 (Haitz et al., 1999). 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,b). 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. 264–268).

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. 71–74; 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