ISSN 1862-6300
Phys. Status Solidi A
208 · No. 1 January
1–224 (2011)

physica status solidi a

www.pss-a.com

applications and materials science

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2011

Expert Opinion

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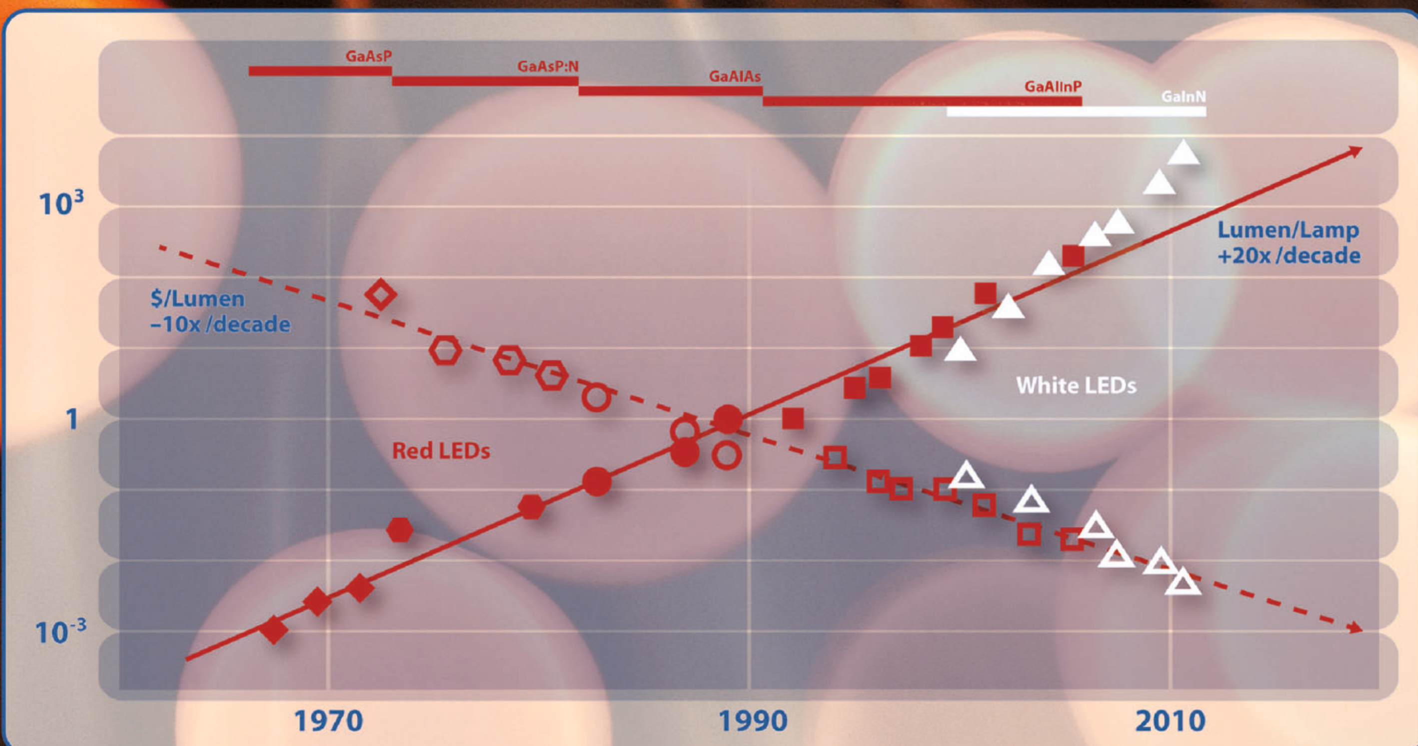

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Phys. Status Solidi A 208, No. 1, 17–29 (2011) / DOI 10.1002/pssa.201026349

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Solid-state lighting: 'The case' 10 years after and future prospects

Expert Opinion

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Received 24 June 2010, revised 28 August 2010
Published online 28 September 2010

Keywords Haitz' Law, lighting, light emitting diodes, solid-state lighting, disruptive innovation

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Ten years ago, a white paper titled "The Case for a National Research Program on Semiconductor Lighting" outlined the promise and potential of semiconductor light-emitting diodes (LEDs) for general illumination. Since then, investments in the now-renamed field of solid-state lighting (SSL) have accelerated and considerable progress has been made, not always in the directions envisioned at the time. In this paper, two of the original four authors comment on the white paper's hits and misses, while making the original white paper available archivally as supplemental online material. Finally, we make new predictions for the coming 10–20 years.

1 Introduction Ten years ago, four authors from Hewlett-Packard/Lumileds and Sandia National Laboratories wrote a white paper [1] entitled "The Case for a National Research Program on Semiconductor Lighting." That paper outlined, for the first time in a comprehensive manner, the promise and potential of semiconductor light-emitting diodes (LEDs) for general illumination.[1] In doing so, the white paper helped trigger enthusiasm and investments in the technology by industries and governments on a global scale.

The paper was first presented on October 6, 1999 in Washington, DC at the annual Forum of the Optoelectronics Industry Development Association (OIDA) to a restricted audience of OIDA members and representatives of the Defense Advanced Research Projects Agency (DARPA) and the Department of Energy (DOE). It was first presented to the public at large at Strategies in Light 2000, the first of a series of annual conferences organized by Strategies Unlimited [2]. It was never published in an archival journal and has up until now only been accessible on the web sites of OIDA and Sandia National Laboratories (but is provided here as Supporting Information, online at www.pss-a.com).

Since then, considerable progress has been made [3], to the point where there is little doubt that semiconductor LEDs will eventually displace virtually all traditional (kerosene, incandescent, fluorescent, high-intensity-discharge) lamps for general illumination [4]. In broad outline, then, the original white paper's predictions have been born out.

On closer examination, however, the progress that was made was not always in directions envisioned in the white paper. In part, this is to be expected: the future is inherently difficult to predict. In part, though, this was also because the perspectives of the four original authors reflected a narrow background rooted in the semiconductor industry. The original authors' understanding of the needs and demands of lighting applications (e.g., color control, flux and color stability, color rendering, and lighting standards) was rudimentary at best.

In this article, two of the original four authors still active in SSL provide comments on the white paper through the lens of 10 years of progress. We discuss trends that the white paper forecast correctly and those that it forecast incorrectly, and make a set of new predictions for the coming 10–20 years. Finally, we take this opportunity to make the original white paper available archivally as supplemental online material to this article.

[1] The expression "solid-state lighting" (SSL) is now commonly used in the U.S. and Japan to describe this area. It is analogous to the expression "solid-state electronics" which became common in the 1950's and 1960's to describe the semiconductor-transistor-based technologies that were then displacing vacuum tubes for electronics. Other, perhaps more descriptive, expressions are often used in other languages: e.g., "LED lighting" in Korean, Russian and German, and "semiconductor lighting" in Chinese. In these Comments, we will interchangeably use these various expressions.

2 Red LEDs point the way: Haitz' Law At the heart of the white paper was its prediction of a revolution in the 130-year-old electric lighting industry, an industry that consumes approximately 6.5% of global energy. Such a prediction faced a number of challenges.

The first challenge was that the forecast had to take into account the anticipated performance improvements of the incumbent lighting technologies. Fortuitively, a 1995 EPRI-sponsored review [5] concluded that all current lighting technologies faced fundamental physics-based limitations. For instance, the efficacy of the venerable incandescent lamp had been practically flat for nearly a century and was limited by the laws governing a blackbody radiator. A 2800 K filament emits 95% of its energy in the infrared and only 5% in the visible part of the spectrum. Increasing the filament temperature in the construction of a halogen lamp brought the efficiency up to around 7%. The efficacy of other lighting technologies faced similar issues limiting their performance to only small incremental improvements over the foreseeable future.

The second challenge was that the forecast had to project *far* into the future – at least 20 years, since it was clear to us in 1999 that SSL would not achieve any significant penetration in less than 15 years (see Tables 4 and 5 in Ref. [1]). SSL lamp costs in 1999 were three orders of magnitude higher than those of incandescent lamps, even before accounting for a power converter and Edison-socket-compatible lamp housings. Moreover, the forecast had to be well founded on historical data and on the current state of the applied technologies and their scientific base. Only if it were so founded would the forecast be convincing enough to trigger substantial investments by industries and governments on a global scale over the first 10 years.

In order to credibly project ahead 20 years, we needed a history that went back in time for a comparable period. Fortunately, one of us (RH) had collected relevant historical data on LED technology, in particular red LED technology, back to its first commercial use in 1968. This data set allowed us to graph (Fig. 4 of Ref. [1]) the historical evolution of two quantities: light flux (in lm/lamp) of the most powerful red lamp commercially available in a given year; and the original equipment manufacturers (OEM) cost of that light flux (in \$/lm) when purchased at high volume as a simple lamp element. The resulting graph has since come to be known as "Haitz' Law".

2.1 1999 performance and trends That graphical history of 30 years of LED performance for commercially available lamps, and their implications for the potential future competitiveness of LEDs with incandescent light bulbs, can be summarized as follows.

First, the best red and yellow LED flux/lamp of around 40 lm/lamp in 1999 was only a factor of 25x lower than the typical 1 klm/lamp flux of a typical 60 W incandescent light bulb. That absolute value combined with the trend line indicated that LEDs might reach a competitive flux/lamp within a decade.

Second, at a 1999 cost of \$0.1/lm, the high volume LED price of \$100/klm was 200x higher than the retail price of a light bulb. It would be higher in retrofit Edison-socket installations where one would need for the LED lamp a 110/220 V power converter, a heat sink, and an Edison-socket-compatible package. It would be higher still if one were to take into account additional mark-ups in the wholesale and retail channels. In total, the LED lamp had a 3-4 order-of-magnitude cost handicap against the incandescent light bulb in 1999. The trend line for red LEDs promised a cost reduction of 10x/decade, a significant step in the right direction, but insufficient without help from reduced operating cost (as discussed in Section 3).

In other words, lm/lamp was on a course to be competitive with incandescent lamps within a decade, but \$/lm was in serious need of help from lowered operating costs through reduced energy consumption.

2.2 2003 and 2010 updates and trends Since 1999, the Haitz' Law graph has been updated regularly.

In 2003, the first significant update occurred. Two points were deleted that could not be supported by written records and several new points were added that were found in those records. In addition, we eliminated the yellow lm/lamp point for 1999 so as not to mix technologies, and added red lm/lamp points for the years 1999–2003. The resulting graph, published in 2003 as Fig. 5 of Ref. [6], represented 35 years of red lm/lamp and 30 years of red \$/lm data. The slope of the red lm/lamp trend line changed from 30x/decade in the 1999 graph to 20x/decade in the 2003 graph. The slope of the red \$/lm trend line remained unchanged at −10x/decade.

Also in 2003, having established a clean data set and trend lines for red LEDs, Haitz [6] argued that red performance should be a good predictor for white. The argument was based on the observation that (a) the human eye response to red light is close to the average of the human eye responses to green and blue light and (b) red optical power is about half the total optical power of white light. This is not very scientific, but red turned out to be a good predictor for white as was demonstrated by superimposing the lm/lamp and \$/lm data from the first cool-white power lamps on top of the red data set [6].

The most current version of the graph, as of early 2010, is shown in Fig. 1. The data points (white triangles) for white LEDs are plotted over the trend lines drawn through the data points (red diamonds, triangles, circles, and squares) for red LEDs. Note that the white data is based on the currently dominant cool-white blue-pumped phosphor lamps with color temperatures in the range of 5000–8000 K. Only after 2005 did warm-white LED lamps generate commercial interest. For future comparisons we will use only cool-white data until warm-white lamps become comparable in flux and cost performance.

Note that, although the order of magnitude of the lm/lamp data for white LEDs is predicted by the red LED trend line, the increase in lm/lamp data has been steeper. The first white lamps of Fig. 1 started at 10 lm/lamp in 2000, a factor

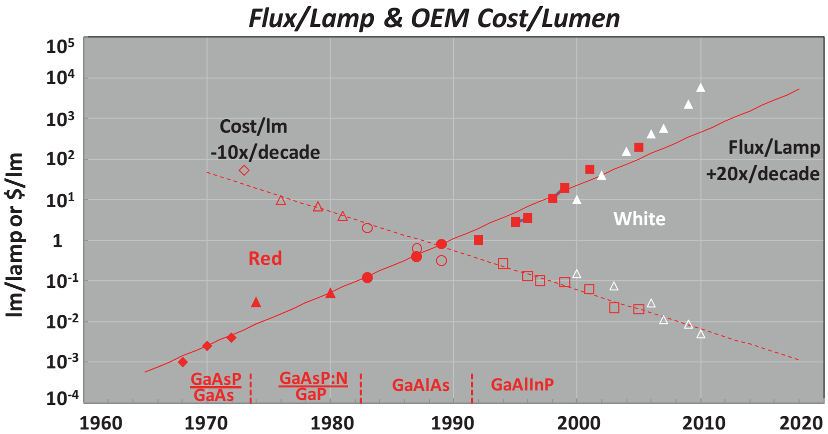

Figure 1 (online color at: www.pss-a.com) This Haitz' Law figure shows two sets of data: The flux/lamp set describes the highest flux red or cool-white lamp that could be commercially purchased in a given year between 1968 and 2010. The OEM cost/lm set describes the lowest costs per lumen for red or cool-white lamps that were commercially offered in a given year between 1973 and 2010. The lamps in the flux/lamp set may or may not be the same lamps entered into the cost/lumen set. The two trend lines are based on red data only, with the white data superimposed on the red trend lines. The different red symbols correspond to the different red materials technologies indicated in the labels at the bottom of the graph.

of 2 below the red LED trend line. Very quickly, however, the lm/lamp of the best white LEDs caught up with, and exceeded, the red LED trend line. By 2010, as forecast in Ref. [6], white LED lm/lamp is 20x above the red trend line.

Is this slope change for real? In one sense the answer is yes, while in another it is no. We will address this issue in Section 2.3.

2.3 Comparison of Haitz' and Moore's Laws

Before going further, we should comment on the superficial and often-noted similarity between Haitz' and Moore's Laws.

On the one hand, the two laws are similar in the sense that they predict steady exponential changes in measurable technological quantities over time. On the other hand, the two laws are not laws in the physical sense, but are simply reflections of 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. As such, they have different limits imposed upon them by their respective technologies and markets.

For Moore's Law and solid-state electronics, the see-saw dynamic has been well documented. Investments in technology that enable increases in transistors per chip are driven by the promise of ever-expanding market needs for computation. These market needs, in turn, are opened by the lower cost of computation enabled by increased transistor count per chip.

What determines the rate of progress – transistor count per chip or market demand? There is a practically unlimited demand for more computational power at lower cost[2]. For nearly five decades, the semiconductor industry has struggled to meet that demand by increasing transistor count utilizing two technology drivers: feature size and defect density. Smaller geometries yield more transistors per unit area and lower defect density allows the production of larger chips to be economically feasible. There is an important side benefit in energy consumption per unit of computation: Smaller transistors have less parasitic capacitance and must be operated at ever decreasing voltages thus reducing the energy consumption per clock cycle. Although the end of Moore's Law is often predicted in each technology generation due to seemingly obvious limitations on continued decrease in feature size, today, at a feature size of 32 nm, Moore's Law is still alive and well. Indeed, its ultimate limit may well be determined by the size scale of silicon atoms.

For Haitz' Law and SSL there is a similar see-saw dynamic but with a different set of boundary conditions and ultimate limits imposed by both technology and market needs.

As Haitz' Law evolved over the last decade, it reflected the conversion of LEDs from small signal indicators to power lamps. One branch saw the flux per lamp increase from 10 lm in 1999 to 6 klm in 2010 driven by increases in efficacy and input power. The second branch described the cost per lumen dropping from $150/klm in 2000 to $5/klm in 2010 for cool white. The drivers behind this cost reduction included improvements in efficacy, increases in power per package, larger chips, better yields, higher volumes, *etc.*

Unlike computing, 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. To achieve this goal, we need power lamps in the 0.1–10 klm category with a conversion efficacy of 150–200 lm/W.

Limits on conversion efficacy: Power conversion from electrical to optical power cannot exceed 100% and, after optimal matching of that optical power with the human eye, this 100% conversion corresponds to a maximum luminous efficacy of 400 lm/W. Thus, conversion efficiency is limited by the first law of thermodynamics and will approach the point of diminishing return within the current decade (see Section 4 for predictions). Then, energy consumption will

[2] Note that, unlike Haitz' Law, Moore's Law does not specify cost. But it is well recognized that Moore's Law has been the driver behind the enormous reduction in the cost of computing, in the range of 70%/year for the last three decades. With the continued insatiable demand for computing power at steadily reduced cost, Moore's Law does not face a foreseeable application-based limit.

increase in proportion to flux. Moore's Law does not face such a limit; the energy consumption per unit of computation will continue to decrease.

Limited flux needs: The flux needs of lighting applications are currently met by existing technologies and exceeding these flux levels with SSL is undesirable (blinding, glare, light pollution) and costly (see above comment on conversion limits). The sweet spot for residential lamps will remain in the 300–3000 lm range and for commercial lighting in the 1–30 klm range, respectively.[3] Even the most demanding applications, such as HD TV broadcasting in sports stadiums, require only 10–20 Mlm. Such applications will be served most cost effectively with 10–50 klm LED modules, not by an LED replica of a 180 klm metal halide lamp.

Considering these limitations, we anticipate a saturation in the flux part of Haitz' Law. The lm/lamp performance will remain relevant only for establishing "bragging rights" by smaller suppliers to niche segments of the SSL market. Again, Moore's Law does not face such a limitation: The need for more computing power will remain insatiable over the next few decades.

3 What does it take to win a revolution? During the last two millennia, human society has seen many fledgling revolutions with a broad spectrum of outcomes, from unquestioned success to marginal survival to utter failure. Even in the more narrowly defined topic of technical revolutions, human society has seen a broad spectrum of outcomes. What are the necessary and sufficient ingredients that determine success or failure of a technology driven revolution?

The most common ingredient is benefit to the user. This benefit can be measured in performance, cost, convenience, or environmental factors. But benefit alone is not sufficient as shown by two of the examples below. The path to successful revolution must provide at least two additional ingredients [7]: (1) The existence of stepping-stone markets to finance the required investments and to hone manufacturing processes to the required performance; and (2) the targeted technology must be mature and/or incapable of reacting to the attack in a timely fashion.

Two examples of successful revolutions are the automobile and the semiconductor transistor.

The benefits of the automobile over the horse carriage were: speed, range, maintenance, instant readiness, and reduced pollution (horse apples per mile *vs.* grams of CO_2/km). Moreover, there was sufficient time to build the road, refueling and maintenance infrastructure and reduce the cost. After Henry Ford, the automobile could do everything the horse carriage could do, but better, faster, more cheaply, and more conveniently. The domesticated horse had matured over millions of years and could not get stronger or run faster to keep up with the challenge. The horse carriage was thus relegated to niche applications: delivery of beer in Bavaria, royal parades in London, nostalgia in tourist hot spots, and daily use in Amish country!

The benefits of the semiconductor transistor over the vacuum tube were: size, energy consumption, operating life, footprint, *etc*. Progress of vacuum tubes against these metrics was nearly (though not quite) as slow as that of horse carriages against their own metrics. The volume of the vacuum enclosure had shrunk from 300 ml to 10 ml in 5 decades. This pace corresponded to a 3x decrease in linear dimensions over the same 5 decades. Tubes represented a mature technology with little chance of accelerating their performance pace. In contrast, during the early days of Moore's Law transistors reduced their linear feature size by 3x every 6 years and are still maintaining that pace 5 decades later. By eliminating the high power consumption (~2 W) of the hot cathode, the glass bottle, the corroding pin/socket problem, the short operating life, *etc*., the transistor had sealed the fate of the vacuum tube shortly after the tenth anniversary of its invention. The final nail in the coffin was transistor integration: first a few, then 1 K and now >100 M transistors in a single chip. Tubes represented a *de facto* sitting target, giving transistors enough time to win. Moreover, transistors had practically an infinite number of stepping-stone applications, most of them impossible to implement with tubes. By the transistor's 20th anniversary, the battle was over. Today, tubes are relegated to a few specialty applications in daily life such as magnetrons in microwave ovens, power tubes in AM and FM radio transmitters, *etc*.

Two examples of partially successful (or unsuccessful) revolutions are GaAs integrated circuits and the field-emission display (FED).

The benefits of GaAs or similar III–V compounds over silicon as a transistor material were similar to those of silicon over germanium. Because of its lower temperature sensitivity and higher speed GaAs was predicted to replace silicon just as silicon had replaced germanium. But, though GaAs transistors were always at the forefront of performance, in most cases silicon transistors reached a "good enough" performance 3–5 years later, at a small fraction of the cost. Thus, GaAs had 5 decades and numerous stepping-stones to complete its revolution, but silicon was too agile a target to beat. The wisdom of the early 1960s still holds: "GaAs always was, always is and always will be the semiconductor material of the future," except for those applications where the laws of physics prevent silicon from doing the job: efficient generation of light and transistor performance at the extremes of low noise, high speed, and high power.

The benefits of the FED over the active-matrix liquid-crystal display (LCD) screen were superior visual quality along with a well-documented manufacturing process simplification that should have resulted in a decisive cost advantage. Television sets and computer monitors were dominated from their start by cathode-ray tubes (CRTs), a

[3] One might argue that the trend towards greater flux/lamp may ultimately reverse, if finer control over the temporal and spatial placement of light is desired, since such control is facilitated by larger numbers of spatially distributed but lower-flux lamps.

venerable glass bottle from the 19th century. Three decades ago, small LCDs started to make inroads into computer displays, ultimately using their size and power advantage to dominate portable computers, the most important stepping stone to larger flat panel displays. Around 1990, a new flat panel display technology, the FED, was developed by Candescent, a Silicon Valley start-up company. Candescent had Hewlett-Packard (HP) both as its lead investor and its largest potential customer. The Candescent FEDs matched the visual performance of CRTs and outperformed LCDs. Since the FED manufacturing technology built upon the more mature production processes of LCDs, HP insisted that Candescent bring one of the leading LCD manufacturers on board as a partner. This prudent requirement was based on the FED's lack of stepping-stone markets which could gradually develop the technology. FEDs had to be cost competitive with LCDs from the start in the rapidly growing notebook computer market. Candescent's first FED factory could only come in one shoe size: the current nth generation of LCD production equipment and factory layout costing around \$1.0–1.5 B in 1999. None of the leading LCD manufacturers were willing to sign up for a technology gamble that directly competed with their own expensive investments in LCD. Without the process know-how of a top LCD manufacturing partner, any forced go-it-alone approach would have been doomed to fail. Around 2000, HP pulled out of the deal and Candescent became the most expensive investment debacle in the history of Silicon Valley. The intended display revolution with around \$600–700 M in sunk investments went up in smoke in spite of FED's unquestionable technical advantages. The scrap value of a decade of brilliant and hard work was the fire sale of some used equipment and a pile of, most likely, useless patents. The missing stepping-stones and the agility of LCD technology were the root causes of this failed revolution!

This brings us to lighting. The proposal made in the white paper [1] outlined a revolution against the well entrenched and mighty lighting industry, with its venerable Edison light bulbs and their derivatives from halogen to high-intensity discharge (HID) to fluorescent lamps. In formulating the proposal, a multitude of tough questions arose. Could SSL meet or beat the performance and cost targets set by the entrenched technologies? How agile would be the entrenched technologies in meeting the challenge? Did we have the time and stepping-stones to finance and develop the SSL infrastructure to a competitive level or would SSL be crushed before getting off the ground? In 1999, we had only prototypes of an off-white lamp with a 10 lm flux. Everything else was nothing but promises and hope. Did this constitute a smoke-and-mirrors illusion or a core foundation to build upon? Would SSL become a silicon-transistor-like success story or only a partial success like GaAs? We were confident that SSL could beat the incandescent and halogen bulbs with their low energy-conversion efficiency. But the remaining technologies, in particular the fluorescent tubes, presented a much bigger challenge. To succeed against those technologies, SSL had to deliver conversion efficacies in the range of 150–200 lm/W and retail lamp costs of ~\$5/klm. These performance targets required multi-billion dollar investments in R&D and manufacturing capacity over the following decade.

The Achilles heel of the conventional light bulb technologies was well recognized by industry leaders, energy economists, university researchers, and government funding agencies. The conversion efficiency from electric energy to visible light ranged from 5% for incandescent light bulbs to 28% for fluorescent tubes. This performance range seemed to leave a lot of room for improvement. However, a 1995 industry wide study by EPRI [5] concluded that none of the conventional lighting technologies would be able to make a significant jump in conversion efficiency in the foreseeable future. That revelation provided an early indication of the existence of a sitting-duck scenario similar to that of the horse carriage and the vacuum tube.

By 1999, LEDs had established a spectacular improvement in efficacy for red lamps, and LEDs and lasers had demonstrated conversion efficiencies of 50–60% in the IR and red part of the spectrum. If SSL could achieve such a performance over the entire visible spectrum, then light sources with conversion efficiencies of >50% looked plausible. Doubling or tripling the conversion efficacy of light sources would reduce the energy consumption for lighting by 50–75% and potentially reduce generation capacity by 30–45 GW in the US alone. That 1999 recognition resonated around the world!

But substantially higher conversion efficacy is only a necessary criterion for success of the lighting revolution. It is not sufficient. Let's look at some of the other performance and investment criteria that are necessary for success. Without acceptable cost and quality of light, even the most efficient light source will not find many buyers. The SSL light source has to be priced low enough for the user to recover its cost through energy savings in a reasonable amount of time. The quality of light must meet certain currently used color standards and must be stable over its rated operating life. The operating life of an SSL light source has to meet or exceed the best conventional technology. These conditions represent another set of necessary but not yet sufficient criteria for success. In addition, we need R&D resources generated by stepping-stone market opportunities or by committed investors.

After we have met all these necessary criteria, we are still left with one simple question: Might the established conventional lighting industry still crush the embryonic SSL technology? This question can only be answered indirectly. SSL has two ways to succeed: SSL can either convince the conventional lighting industry that it is in its own best interest to join the revolution, or the SSL industry has to raise enough capital to build its own infrastructure, marketing channels, *etc*. and kill the conventional industry. The first path depends on the quality of the arguments for SSL. The second path requires that the SSL industry succeed in generating the resources to go it alone. So far, the SSL industry has been able to play with a winning hand. It developed a series of monochromatic or white-light stepping-stone applications and won every battle against conventional technology from traffic lights to car tail-lights to decorative landmark lighting. By 2010, the threat of an FED-like scenario has passed and the conventional lighting industry has chosen the path of joining the revolution. The only question remaining is: Will SSL repeat the success of the transistor over the tube, or will it be only a partial success with a substantial fraction of the conventional lighting technologies avoiding their trip to the museum?

In the following four subsections we examine the issues of efficacy, cost, quality of light, and generation of sufficient R&D resources. We will examine these issues and point to important stepping-stones as well as to psychologically important factors in building confidence for the relatively large and risky investments. From our 2010 perspective, we can say that these necessary criteria have been or will be met before the end of the current decade. These considerations, together with our future outlook discussed in Section 4, give us confidence that SSL has assembled a winning set of necessary and sufficient criteria to create a transistor-like revolution of the lighting industry.

3.1 Efficacy improvement: the shift in mindset to phosphor conversion In 1999, the only white LED lamps commercially available used a blue LED to pump a phosphor to generate white light. These lamps had a low flux of <3 lm/lamp, a poorly controlled bluish-white color, and significant angular color variation. White LED lamps based on color mixing of individual red, green, and blue LEDs existed only as engineering prototypes or early pre-production devices, mainly as vehicles to demonstrate the large color gamut that could be achieved with SSL. Using the efficacies of Fig. 2 of Ref. [1], a color-mixed 20 lm RGB lamp could have been made in 1999, but such a lamp would not have met our definition of a "commercially available product" and could not have been entered as a data point in Fig. 4 of Ref. [1].

Nevertheless, it was generally recognized that the latter approach of color mixing was the *preferred* approach to generating white light. This approach avoids the 20–25% loss associated with the Stokes shift from a blue pump to longer wavelengths of light. Indeed, at that time we thought the Stokes loss could only be tolerated for small lumen applications in the range of 3–100 lm/lamp. For these devices, one blue-pumped package suffices and the cost of multiple chips and packages would be prohibitive. For applications requiring >100 lm/lamp we recognized the need for multiple lamp packages and we thought that the Stokes loss would be a decisive detriment.

Thus far, however, we have been proven wrong: phosphor conversion has continued its dominance over color mixing as the preferred approach to white LEDs. There are at least five reasons for this.

First, efficiency improvements have been uneven across the visible spectrum. While the efficiency of blue pump LEDs increased by 5x since 1999, the efficiency of direct-generated red, yellow, and green LEDs at 85 °C increased only 2x–3x, compared to the data in Fig. 5 in Ref. [1].

Second, progress in power package development was more rapid than expected, and is enabling useful, 1 klm amounts of light to be easily produced from single-LED lamps. In particular, a blue-pumped cool-white LED lamp with a 2×2 mm^2 chip can now be operated at 10 W with an efficacy of 100 lm/W, giving a flux of 1 klm and an operating life of 50 khr. For applications requiring only a 3 khr life, this lamp can be operated at 25 W delivering 2 klm of flux. Indeed, a single power-LED package with four densely packed 3×3 mm^2 chips can handle input powers approaching 100 W, generate a flux of over 6 klm, and still meet an expected operating life of 50 khr. With expected efficacy improvements discussed below, this technology can readily be extended to 20 klm for applications requiring an operating life of 3 khr.

Third, we underestimated the importance of white-LED color stability. The human visual system is extremely sensitive to the exact chromaticity of white light. Color-mixed white LEDs with 4–6 sources therefore must take into account 4–6 different temperature dependencies to achieve a temperature independent color point. This requires 4–6 independently controlled feedback loops and current drivers. The blue pump and the conversion phosphors are far less temperature dependent than the red and yellow LEDs. In addition, the pump and phosphors can operate at temperatures well above 100 °C. These features allow for the design of blue-pumped phosphor lamps with color and flux stability over temperature ranges acceptable to a large range of high volume applications. The lack of a good understanding of such lighting requirements by the original authors was responsible for this oversight.

Fourth, since conventional lighting technologies do not accommodate color tuning, there are no significant or urgent needs for this feature. SSL suppliers are still struggling with flux, cost, and quality of light requirements and users are currently concentrating on "good enough white only" solutions.

Fifth, phosphors with very high internal quantum efficiency and good thermal and environmental stability have been developed throughout the green-to-red wavelength range. Some of these phosphors are not inexpensive, in part because of licensing fees and in part due to the need to amortize development costs. However, very small amounts of phosphor are used compared to the amounts used in compact fluorescent lamps and fluorescent tubes. Hence, if experience with these other technologies is a guide, phosphor costs expressed as \$/klm are likely to be a negligible fraction of the overall cost of SSL lamps.

Today, the blue-pumped phosphor conversion LED has relegated the color mixing approach to the specialty market niche requiring real-time chromaticity tuning. Moreover, it is clear that this will also be the case for the immediate future. *We emphasize, though, that the longer term future is unclear.* One of the current disadvantages of color-mixed white LEDs – the complexity and cost of a feedback loop – could turn to an advantage if digital control of chromaticity becomes a feature to be desired. Moreover, although such a feedback loop would now be considered too costly to implement, it may not be so in the future. As $/lm continues to drop, the cost of the lamp may at some point become insignificant compared to the cost of operating the lamp. Then, the lighting industry will be looking to add new features so they can charge more for their lamps. Chromaticity control may be one such feature (see Section 4.3).

3.2 Cost reduction: non-lighting applications lead the way The cost per lumen of the early cool-white lamps came in at 2x–3x above the red trend line of Fig. 1. This cost performance should not be surprising. During the 2000–2006 period, white lamps first encountered the market's demands for color quality: control, stability, and rendering. The associated testing reduced production yield and increased cost. During the last 3 years, however, cost per lumen has crossed below the red trend line. This decrease in cost per lumen for white is remarkable considering that the cost for red flux was driven by one of the most demanding markets: automobiles. How could white LEDs in such a short time catch up with red on the $/lm metric?

In the white paper [1] we outlined the cost gap between early white LEDs and the well entrenched conventional light bulbs. To succeed, white LEDs needed to meet and follow the red cost/lumen trend line for at least 2 decades. Only then would lower energy consumption make up for the cost difference between LEDs and conventional lamps in cost-sensitive consumer applications.

To achieve this goal, the LED industry needed a series of high-volume power-LED applications, at any color, to act as stepping-stones for an expanded LED manufacturing infrastructure. Indeed, the importance of such non-lighting stepping-stone markets in driving down the cost of previous generations of LEDs was pointed out in our white paper. As discussed later in this section, subsequent non-lighting stepping-stone markets were no less important, and continued to significantly expand the high-brightness (HB) manufacturing infrastructure and to reduce cost per lumen.

The early, pre-1999 stepping-stone markets were documented in the white paper. The first stepping-stone market, in 1968, was alphanumeric displays and indicator lamps, followed by optocouplers, optical encoders, fiber-optic transceivers, blood-oxygen monitors, and even giant outdoor display screens. By 1994, a joint project between HP and Philips Lighting began to explore the potential of LEDs in lighting applications; by 1996 a joint venture between the two companies, Lumileds, was formed; and by 1999, the new opportunity for LEDs was becoming widely recognized and the team from HP/Lumileds and Sandia National Laboratories (SNL) started to quantify the energy savings potential for a conversion of the lighting industry from its traditional and fairly inefficient light bulbs to the new LED-based SSL technology.

Between 1999 and now, additional stepping-stone markets opened up. Traffic lights have been converted to LEDs in all new construction and replacement of existing traffic lights is progressing rapidly. The automotive market is in the middle of a complete conversion to LED lamps, including headlights. LED designs have taken over large segments of the outdoor display and sign market. The last few years have witnessed the first transitions in commercial lighting applications such as streetlights and architectural lighting. The first consumer lighting applications such as hand-held flashlights and camera flash bulbs are in the process of converting to LED lamps.

In 2010, the $/lm figure-of-merit for white LEDs is lowest in the mid-power lamps sold into the market for LCD backlights. A 100 lm lamp sold in volume at $0.50 represents the $0.005/lm data point in Fig. 1. Lamps with a higher flux of 1 klm are selling at OEM volumes at twice this $/lm figure. LED lamps equivalent to a 60 W incandescent lamp with an integrated Edison socket, internal power converter and heat sink retail at widely varying prices centered around $0.05/lm. Complete flashlights with a 900 lm rating are selling for $70 to $100 in retail stores. Thus, LED lamps intended to replace incandescent lamps are still a factor of 10x in purchase price from directly competing with 1 klm CFL lamps. Nevertheless, the market for LED-backlit LCD panels is exploding, and it appears to us extremely likely that the cost reductions necessary for general illumination will be achieved.

3.3 Quality of light: what's that? In 1999, the four semiconductor physicists that authored the white paper [1] recognized the purely technological problems that had to be conquered before LEDs could take over the world of lighting. As discussed above, these were efficacy, klm flux packages and, most of all, cost. All three are interdependent and not meeting any one of them was equivalent to failure.

We were aware of other issues such as color rendering, color control, flux stability, and operating life. We knew that LEDs had a much longer operating life than any existing light bulb, so there were no concerns on this issue. Using our favored approach to white light, the mixing of 4–6 equally spaced colors controlled by an active feedback loop was supposed to take care of the three color issues. In the age of silicon chips with 10 M transistors or kW controllers, a six-channel feedback loop looked like a minor hurdle.

But the issues discussed in Section 3.1 upset our color-control strategy. The industry did not solve the yellow-green efficacy hole as expected and pumping a phosphor with a blue LED became the technology of choice. The color-control game changed from a software solution to a physical hardware headache. Now the LED manufacturer had to select a narrow pump wavelength and match it to a particular phosphor mixture to obtain the targeted color point. Small and unavoidable process variations limit the test yield and significantly add to product cost. In addition, variations in ambient temperature and drive current result in a significant color shift. Fortunately, the nitride system has some unique properties never seen before in the history of LEDs. Both blue pump and conversion phosphor are relatively insensitive to temperature variations and allow the production of white lamps that are "good enough" in color control and acceptable in cost for a large range of market needs.[4,5]

Improvements in efficacy and color control are still some of the hottest issues of the industry. But recent progress has been quite encouraging, giving us the confidence that blue-pump phosphor-conversion path will meet the stringent color-control requirements of the general lighting market at the cost targets expected during the next decade.

3.4 Driving progress: sources of R&D funds The global LED market in 1999 amounted to 2100M$ and was dominated by small-signal indicators and seven-segment displays. It included an embryonic 400M$ segment of first-generation power-signaling devices used mostly in secondary automotive brake lights and traffic lights. The part of the market controlled by US-based companies was in the range of 15–20%. For 2000, we estimated that total R&D spending funded by US industry, government, and universities would be \$60–80 M with the industry spending close to 20% of its revenue. This modest R&D resource had to be seen in the context of the technical challenges and the energy savings potential.

The first white lamp to exceed an arbitrary lighting threshold of 10 lm was a product from Lumileds in 2000. It had a cost structure consistent with high-volume pricing in the \$1.50–2.00 range. This state-of-the-art was so primitive that, looking back, it took a lot of imagination and courage to extrapolate from these early beginnings to a revolution of the mighty lighting industry. Nevertheless, we did so. In Fig. 2 of Ref. [1] we made a daring forecast for the evolution of the efficacy of SSL. It consisted of two scenarios.

The first (conservative) scenario was based on an R&D investment self-financed by the small LED industry as it existed in 1999. We predicted gradual efficacy increases from 10 lm/W in 2000 to 50 lm/W in 2010 and then a leveling off. Such an efficacy evolution would have allowed an attack on traditional incandescent and halogen lamp markets, but fluorescent and other high-efficacy lamp technologies would have been out of reach. This limited market was still an attractive target since it consumed around 40% of the electricity used in lighting. While this first scenario basically limited itself to the low hanging fruits, it whetted our appetite for more.

The second (accelerated) scenario was based on a much larger R&D investment. After we convinced ourselves about the energy-savings potential, we pondered the next two questions: How far can we take SSL in efficacy and what would it take to do it faster? This second scenario required a leap of faith: We assumed that we could eventually replicate the 50% wall plug efficiencies – then demonstrated only in the deep red and near infrared – at any visible wavelength. Under this assumption we would be able to approach 200 lm/W, a target that clearly would revolutionize the 130-year-old lighting industry as we knew it. This Herculean task looked unreachable with the modest R&D investments that the US LED industry could muster on its own. Moreover, though the potential energy savings looked gargantuan, those savings would benefit the consumer and not the SSL industry, therefore justifying the "case" for a national research program. As a consequence, we proposed a US government investment program into SSL research of \$500 M over 10 years with the goal of reaching efficacies for white light in the range of 150–200 lm/W.

Soon thereafter, Senator Jeff Bingaman, D-NM introduced the Next Generation Lighting Initiative in July of 2001 as SB 2060. It became part of the omnibus energy bill and was approved by Congress in 2003. However, the tail of the Dot-Com recession and the looming sub-prime mortgage bubble slowed down the appropriation of funds and to date only ~\$200 M have been disbursed [8]. And, although not originally considered by the authors of the white paper, companies that were researching organic LEDs – a different technology which at that time had much lower luminous efficacies and dauntingly short device lifetimes – were successful in getting organic LEDs included in the initiative, effectively reducing the funding for semiconductor LED research by a factor of 2.

While Congress was considering support for SSL research, the rest of the world quickly recognized the potential of this disruptive new technology. The white paper became the blue print for aggressive government support in South Korea, Taiwan, China and Japan. Even countries like Great Britain and France that had made great contributions to the compound semiconductor technology in the 1960s but missed out on the development of the optoelectronic industry, came back with strong research programs in universities and government labs and with support for start-up companies in SSL-related fields.

But by far the largest incentive to this global investment momentum came from the rare opportunity of revolutionizing an industry with revenues of \$15B/year for the light bulbs only. Five decades previously, the nascent semiconductor technology demonstrated how to kill a 50-year-old glass bottle, the vacuum tube. Now, a subset of the mighty semiconductor industry, the much smaller compound semiconductor industry, saw another opportunity to beat the next glass bottle, Edison's 130 year-old light bulb and its derivatives. And the white paper showed a clear path in Table C3 of Ref. [1]: Grow the light source market to a much larger size than \$15 B and pay for this growth with huge reductions

[4] The color-mixing approach preferred in the white paper could have used a broad production distribution of LEDs of any of the selected 4–6 colors. Ambient temperature variations and its corresponding color shift, flux stability over time, differential aging, *etc*. could all have been corrected for with drive current changes controlled by an active feedback loop. If digital color tuning becomes a market need, then this approach to color control may have to be implemented (see Section 4.3).

[5] Color mixing will play a role in niche sections of the lighting market where limited or extensive color variations are needed. Its market share will depend on progress in efficacy improvements in red, yellow and green and on a satisfactory design of the feedback loops. Currently the cost of the power converter/driver is comparable to the cost of the basic high-volume LED lamp. Even if the power converter can be shared for all colors, the cost of 4–6 independent drivers will present a significant cost hurdle.

in energy costs. This recognition did not directly provide R&D funds but it loosened purse strings from board rooms to venture capitalists to government agencies around the globe. The white paper became the blue print for many investment decision makers, especially in Asia.

How did R&D spending evolve over the last 10 years? For 2000, we estimated the US R&D spending by industry, universities, and National Labs at \$60–80 M [1]. In retrospect, we now estimate the global R&D spending in 2000 at \$200–250 M. Since then, the HB LED market grew by 18% annually from \$1.2 B to \$5.3 B in 2009 [9]. The non-HB LED market probably shrank somewhat from its \$1 B level of 1999, bringing the total LED market to ~\$6 B in 2009 and ~\$7.5 B in 2010, with ~20% coming from US based companies. The latest available data from Cree for the recession year 2009 shows a revenue of \$567 M and R&D investments of \$71 M. The current momentum in the HB market [9] should carry Cree to a revenue of > \$700 M and an R&D investment of ~\$100 M in calendar year 2010. Adding the comparably sized Philips-Lumileds and several small start-ups and university research brings the US R&D investment to \$250–300 M in 2010. This investment is twice as high as the \$130–150 M level projected in the conservative scenario of [1] for 2010. Global R&D investments are harder to estimate but probably show a similar trend.

What caused this sustained high level of R&D investments bridging two global recessions? There are six separate considerations that influenced the minds of investment decision makers: (1) the potential for a sustained high market growth rate that would be enabled by the non-lighting stepping-stones outlined in Ref. [1]; (2) the increasing global interest in reduced carbon emissions and the opportunity to make a significant lighting-based contribution to that reduction; (3) government incentives for R&D investments in "green" technologies; (4) the recognition that this disruptive technology might revolutionize the lighting industry and provide opportunities for market entry and growth; (5) the ability to sell relatively high-priced replacement products for conventional light bulbs and still provide an incentive for the customer through much reduced operating cost; and (6) the fear of missing the boat by not investing aggressively enough. For this combination of reasons, the money flowed, investments were made during a tough economic decade, and the results speak for themselves.

A common denominator of all the arguments above is that they can be found in Ref. [1]. The white paper provided a well-founded rationale for a revolution, outlined a strategy, and left the tactics to the market. In the next section we discuss the accuracy with which our predictions have come to pass at the time of this writing.

4 Forecast for the next 10–20 years Based on the excellent progress in blue pump efficiency and in adapting mature phosphor technologies, the 2010 efficacy performance of 100–120 lm/W for cool white and 80–100 lm/W for warm white have met our optimistic predictions (the accelerated scenario in [1]). We do note, though, that these efficacies must be qualified to some extent. They are based on an operating current of 350 mA in a 1 mm^2 chip at room temperature. There is a 10% reduction in efficacy for state-of-the-art devices operating at 85 °C. There are similar reductions in efficacy for state-of-the-art devices (e.g., the recently introduced Cree XP-G cool-white lamp) operating at higher currents: around 17% at 700 mA and around 35% at 1500 mA. However, these reductions in efficacy at high current densities have gradually been improved over the last 3–5 years and additional performance improvements are expected.

Indeed, there is every reason to believe that progress will continue. Government investment in R&D is now ramping up and is poised to make significant contributions. Most importantly, industry investment in R&D continues to grow, following the continuing opening of new and ever-larger stepping-stone markets for HB LEDs.

In particular, Strategies Unlimited [9] predicts a 31% compounded growth rate for all HB LED lamps over the next 5 years. This growth will be dominated by backlights for LCDs for hand-held appliances, notebook computers, computer monitors and, increasingly, flat TV screens. Indeed, this backlight segment is projected to grow from a small fraction of today's \$400 M LED display market to around \$10 B in 2014.

Although the conversion from fluorescent-tube-based backlights to LEDs is expected to approach completion by 2014, after which its growth rate will slow down dramatically, by then the market for general lighting will be poised to finally take over. The market for general illumination is predicted to grow from \$600 M in 2009 to \$4.5 B in 2014.[6] Together, these two market segments will increase from 25% of the \$5.3 B HB LED market in 2009 to 75% of the \$20 B market in 2014, with growth shifting from backlights to general illumination. Growth rates during this 5-year period by market segment are anticipated to be: display backlights 90%, lighting 50%, and the remaining market 6%. Near the end of this period, the growth rates will change significantly, to display backlights 10%, lighting 30% and the rest unchanged at 6%.[7]

4.1 2010 to 2020 With this backdrop of continuing and aggressive government and industry R&D investment, the two authors of this paper venture to make average performance predictions for the coming 10 years for SSL

[6] Market forecasts during a rapid technology-driven conversion have to be taken with a grain of salt. Economic hiccups in consumer markets are notorious and faster-than-expected price erosions resulting from over-investments in an industry boom are a classic problem in the semiconductor industry.

[7] Please note that these market numbers refer to simple packaged LED lamps only, without secondary optics, drivers, sockets, etc. This phenomenal growth has to be seen in the context of the fairly static \$15B/year market for all conventional light bulbs during the last 15 years. This conventional light bulb market will start shrinking as SSL takes over and may eventually disappear nearly completely!

Table 1 Five- and ten-year forecasts for cool- and warm-white SSL lamp efficacies, street prices, and payback times at assumed operating conditions and electricity costs.

year	color temperature	junction temperature	current density	luminous efficacy	street price	electricity cost	payback time *vs.* incandescent	payback time *vs.* compact fluorescent
		°C	A/cm^2	lm/W	\$/klm	\$/kWh	operating hours	operating hours
2015	cool white	120	100	150	5	0.15	500	2000
	warm white	120	100	125				
2020	cool white	150	150	180	2.5	0.2	200	800
	warm white	150	150	150				

lamps, specifically for products that are *designed for and sold into the general lighting market*. This distinction is necessary to differentiate these lighting products from the lower performing products (efficacy, flux, color, CRI, operating life, *etc*.) that will be relegated to less demanding applications. These predictions are shown in Table 1, following and somewhat exceeding Haitz' Law.

By 2020, we predict luminous efficacies of 150–180 lm/W. SSL lamps will thus beat all mainstream conventional lamp technologies by factors of 2x to 10x in efficacy. Such a performance advantage represents a necessary condition for a revolution of the lighting market. Also by 2020, a straight extrapolation of the red trend line of Fig. 1 suggests an OEM price for cool white of \$2/klm in 2015 and \$0.6/klm in 2020. We believe that cool-white LEDs in 2015 will beat this trend line substantially.

Progress will not be smooth, however, due to the bust-boom cycles typical of industries, such as semiconductors, that are heavily reliant on capital investments requiring long lead times. The accelerated growth anticipated over the next 4 years in the backlight market is already straining supply. Current production processes have trouble meeting the demands for tight performance specifications in the backlight market. The industry is reacting in a fashion typical of the semiconductor industry: higher or stagnant prices and rapid increase of production capacity to compensate for low yield. By 2012, the yield will have improved, right at the time when backlight growth will be slowing down. The resulting overcapacity will decrease prices, just at the time when the general lighting market is exploding. By the middle of the decade we expect a rebalance of supply and demand with an OEM price in 2015 of \$0.5-1/klm, a factor of 2x–4x below the red trend line. By 2020, the price will level off at < \$0.5/klm.[8]

We can also comment on other aspects of the evolution of SSL.

One aspect is the retrofit market for Edison-socket incandescent and compact fluorescent lamps, expected to still be very large, even in 2015 and 2020. For this mostly residential market, the high-volume OEM price of a basic LED lamp is only one aspect of the price. A lamp manufacturer buys a basic LED element and adds a power converter, driver, secondary optics, socket, and heat sink. Then the replacement lamp enters a two-step distribution channel for wholesale and retail before some users buy it at "list price." Often more important is the "street price," usually a heavily discounted price from the retail "list price" for various reasons: government subsidies to encourage energy savings, a heavily advertised price leader to generate store traffic, *etc*. This "street price" makes or breaks the success of many consumer products. For instance, early CFL lamps retailed for around \$15 in 1990 and were roundly rejected by residential users for two reasons: too bluish and too expensive. After more than a decade of performance improvements and substantial government-driven price subsidies, only now are CFL lamps finally being accepted by residential customers.

Because of the mercury content and an inferior efficacy of CFLs relative to LEDs, government incentives will shift from CFL to LED lamps as soon as LED lamps are widely available at a retail list price approaching the current list price of CFL lamps. This switch is expected to happen around 2015 and by 2020 the LED street price will be around \$2-3/klm (see Table 1). By that time, the CFL lamps will suffer the fate of the Edison lamp, banned for a variety of reasons, from issues around hazardous waste disposal (due to mercury content) to high energy consumption. This will be the beginning of the end for traditional lamps in all applications.[9]

Note that the payback calculations of Table 1 assume an incandescent lamp cost of \$0.50 and a CFL cost of \$2.50 in 2015 and \$1.50 in 2020. Also note that incandescent lamps may no longer be available in 2015 or later and that CFL lamps will lose their current subsidies, thus reducing their assumed cost advantage over SSL. In other words, payback time may essentially disappear or go negative by 2020 making SSL lamps the preferred choice with regard to purchase, operating, maintenance, and disposal cost!

[8] We note that these prices are consistent with U.S. DOE forecasts. Jim Brodrick recently presented DOE's expectations on SSL relative costs for the 2009-2015 time frame [10]. DOE expects a cost reduction for the LED element of 8x for the 6-year window. The red trend line cost for 2009 of Fig. 1 is \$8/klm. A reduction by 8x in 2015 gets to the same range that we predict in Fig. 1.

[9] In 2003, Haitz [6] predicted that by 2015 LED lamps start to compete for any electricity based light source application on earth, even sports stadiums with TV coverage. In a recent press release (http://www.philipslumileds.com/newsandevents/releases/PR128.pdf), Philips announced solar/battery based lighting systems for small soccer training fields in remote areas without access to an electricity grid.

A second aspect is that buildings and homes are of course now wired for medium-voltage AC power, but LED lamps run on low-voltage DC power. There will thus be a battle between wiring modified to route DC power *versus* lamps modified to run on AC power.

At the first extreme, one could install a separate "DC power" grid at 12, 24, or 48 V either in newly constructed buildings or in conjunction with major building remodeling. Such a grid would require only one or a small number of power converters per building plus a single current driver for each light fixture.

At the opposite extreme, there are numerous ways to construct "AC lamps." The simplest is to add a power converter. However, a power converter from AC line voltage to low voltage DC is a non-trivial cost element in a lamp retailing at a $5 "street price." Instead, LED lamps can also be designed to be operated directly from 110/220 V AC power lines. Integrating multiple p–n junctions and connecting them in series increases the drive voltage and reduces the drive current for a given flux. Taking this concept to an extreme, one can design a blue pump chip with two anti-parallel chains of LED junctions that can operate both as light source and rectifier in a lamp directly connected to an AC line. This is easier said than done: one has to re-engineer all the manufacturing processes to meet the quality-of-light arguments discussed above. But in a large enough market with the proper performance and cost incentives, this could be a winning proposition. This approach is of particular interest to small candle-shaped replacement applications for which the spatial volume necessary for a power converter is incompatible with the compactness of the lamp base.

In between these two extremes are integrated light fixtures. The current fluorescent-tube-based ceiling lights with a flux of 3–10 klm could be integrated as an AC system with two chains of series-connected individual DC lamp elements or it could be designed with a similar number of DC-operated lamps driven by a single power converter/driver.

At this time, it is too difficult to predict the outcome of the battle between DC wiring and AC lamps. This battle will be fought more than a decade from now and will most likely end in a draw. The two approaches will coexist and the user will be able to select the best solution for particular needs. For instance, residential lighting might employ AC lamps using existing AC wiring while commercial applications may pick DC wiring for reasons of best efficacy and lowest life-time system cost. In the long run, though, AC lamps may slowly lose out against integrated fixtures and DC wiring as remodeling incentives, driven by other energy conservation issues, rework the existing residential base. Integrated fixtures and DC grid could dominate the commercial lighting market after 2020.

4.2 Near-term technical challenges Throughout this paper we have mentioned various technical challenges, some going back for a decade and some surfacing only recently. Various technology roadmaps sponsored by OIDA, DOE, and others have identified these issues and we briefly summarize here the most relevant.

Droop: In Section 4 we referred to a state-of-the-art Cree lamp that shows a ~17% drop in efficacy when the current is doubled from 350 to 700 mA, and another ~17% when doubled again to 1500 mA. This effect is certainly not caused by an increase in junction temperature but seems to be related to carrier or photon flux density. Several mechanisms have been proposed but LED scientists have not yet settled on a definitive explanation. This droop has serious economic consequences since it results in a corresponding increase in energy consumption. One mitigating attempt is based on a significant reduction of the LED wafer cost per unit area. Doubling the chip area allows a doubling of the drive current without a penalty in efficacy.

Narrow-band red Phosphor: In the current generation of warm-white lamps there is a significant efficacy loss caused by the wide spectral distribution of conventional red phosphors. Phosphors with a narrower line width or unconventional light converters such as quantum dots could reduce the efficacy loss in the long-wavelength red and near infrared parts of the spectrum. In addition, such phosphors should absorb well at the blue wavelength (~460 nm) that best optimizes the trade-off between human visual sensitivity and color rendering index.

Phosphor heating by Stokes shift: In all current lamp designs, one side of the chip has to be mounted on a metal heat sink allowing light to exit the chip only from the top. Modern chip designs have reduced side emission substantially. Thus the phosphor must cover the top of the chip and the heat generated by the Stokes loss must be transmitted from the phosphor to the chip. The phosphor consists of a small grain powder held together with a transparent organic binder material. All transparent organic materials have a poor thermal conductivity resulting in substantial self-heating of the phosphor and a corresponding reduction in light conversion efficiency. The Philips-Lumileds design using Lumiramic (phosphor embedded in a ceramic material) helps somewhat, but the phosphor material is still the hottest part of the lamp.

Red to green efficacy gap: The efficiency of red, yellow, and green direct-generation LEDs is far lower than the efficiency of blue pumps (Section 3.1). Closing this gap, especially at the higher junction temperatures needed for power LEDs would open up the color-mixing approach and avoid the ~25% energy loss caused by the Stokes shift. This breakthrough would also make color tuning more attractive and mitigate the phosphor heating addressed above.

Flicker of AC lamps: LED lamps operated directly from AC lines (Section 4.1) without the use of an AC-DC converter will exhibit 50/60 Hz or 100/120 Hz flicker. This issue is surfacing only recently and should not be any worse than the flicker associated with conventional fluorescent or CFL lamps. For flicker sensitive applications, DC operation is the obvious choice.

4.3 Beyond 2020 Finally, we comment on what might happen beyond 2020. Here, the two authors of these Comments have created a dilemma by going on record with two significantly different long-range expectations on efficacy and cost performance. Here is a summary of our diverging views.

RH, on the one hand, believes in a pragmatic or "good enough" compromise between long-term efficacy and cost as illustrated in Table 1. Further efficacy improvements would require endless variations of process parameters that tend to increase cost and reduce yield. Haitz believes that the cost of the basic LED lamp element will become insignificant compared with other cost factors such as the cost of metals, plastic, distribution, inventory, government mandates, *etc*. By the end of the decade, the OEM cost of light will drop to < 0.5\$/klm and disappear into the fog of other unrelated cost issues. That will bring the cost line of Haitz' Law to an end. Eventually, "light splurging taxes" imposed by fiscally strained governments from federal to municipal levels may approach or even exceed the cost of the basic lamp element.

The flux line of Haitz' Law will expire even faster. High-flux lamps will run out of market needs in the 20–50 klm range, as outlined in Section 2.3. During the next decade to 2020, the flux part of the graph will be used mainly by lesser LED manufacturers to establish "bragging rights." But these high-flux products will only be used in niches with small economic significance.

JYT, on the other hand, believes that efficacy will continue to increase, eventually saturating at a level closer to 250–300 lm/W than to 200 lm/W. The reasons for this belief are threefold.

First, the capital cost of light associated with the white LED lamp will decrease to the point where the ownership cost of light is dominated by the operating cost of light. The consumer will thus be willing to purchase a slightly more expensive lamp if that lamp is more efficient and will save him or her enough in the cost of energy burned within a reasonable time.

Second, as efficacy increases, less waste heat is generated (per unit light flux produced) and lamp packaging will become easier and less expensive (again per unit light flux produced).[10]

Third, and perhaps most importantly, because of the rich set of functional and integration possibilities that semiconductor technologies offer at low cost, *additional features beyond simply the production of light will likely become important* [11]. These include digital tuning of both the chromaticity and the temporal/spatial placement of light within the environment that is being lit. The benefits of such features will drive the development of electroluminescence in the shallow red, with higher efficacy due to a reduced Stokes loss a side benefit.

[10] Note that this is not to imply that thermal issues will disappear. It will always be advantageous to drive LEDs as hard as possible so as to amortize LED cost over greater lumens produced. In the absence of 100% efficiency, thermal issues will generally be the factor that limits how hard LEDs can be driven.

5 Summary In retrospect, the global resonance to the white paper [1] far exceeded our expectations. It described an emerging lighting technology that had the potential to revolutionize the industry given sufficient time, resources, and other ingredients of success such as stepping-stone markets to self-finance growth. Ten years later, SSL has met or exceeded the efficacy and cost goals set in 1999 and discussed in Section 3, while also meeting the market's expectations for color control, stability, and operating life. The forecasts for the next decade are consistent with the criteria necessary for a revolution in lighting: compelling benefits to user, economy, and environment !

While our initial interest focused on generating support from the US government to accelerate the conversion to SSL, we were not surprised that these compelling arguments triggered the amazing global response by industry and governments to this truly disruptive technology.

Since Edison's first installation of electric lights over 130 years ago, the industry developed half a dozen new electricity-based lighting technologies, each improving efficacy, cost, or quality of light. Over the next decade SSL will approach the end of the efficacy ladder and meet or exceed the market's needs with respect to cost and quality. There will be little room left to justify the substantial investments needed to develop an alternative newer technology. The series of revolutions in lighting covering the entire history of mankind from campfire to candles to light bulbs to SSL will come to an end. The revolutions in lighting will be over!

Acknowledgements We are grateful to Jerry Simmons for careful edits and comments, though we of course take responsibility for remaining deficiencies. We are also grateful for helpful input from Mike Coltrin, Sasha Neumann, Daniel Noh, Taisuke Ohta, Ines Waldmueller, and Bob Walker. Work at Sandia National Laboratories was supported by Sandia's Solid-State-Lighting Science Energy Frontier Research Center, funded by the U. S. Department of Energy, Office of Basic Energy Sciences. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract No. DE-AC04-94AL85000.

References

[1] R. Haitz, F. Kish, J. Tsao, and J. Nelson, The Case for a National Research Program on Semiconductor Lighting, presented at the Annual Forum of the Optoelectronics Industry Development Association, Washington DC (1999).

[2] R. Haitz, F. Kish, J. Tsao, and J. Nelson, The Case for a National Research Program on Semiconductor Lighting, presented at: Strategies in Light, Burlingame, CA (2000).

[3] M. R. Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, J. Display Technol. **3**, 160–175 (2007).

[4] J. Y. Tsao, M. E. Coltrin, M. H. Crawford, and J. A. Simmons, Proc. IEEE **98**(7), 1162–1179 (2010).
[5] A. B. Gough, in: ALITE '95 Workshop, Electric Power Research Institute (EPRI), Rochester, NY, 1995, Proc. ALITE '95 Workshop, EPRI-TR-106022.
[6] R. Haitz, Another Semiconductor Revolution: This Time It's Lighting!, in: Advances in Solid State Physics, edited by B. Kramer, Vol. 43 (Springer-Verlag, Berlin, 2003), pp. 35–50.
[7] C. M. Christensen, The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail (Harvard Business School Press, Boston, 1997).
[8] EERE, Solid-State Lighting Multi-Year Program Plan FY'10-FY'16, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy Building Technologies Program, (2010).
[9] R. Steele, High-Brightness LED Market Review and Forecast, in: Strategies in Light (Strategies Unlimited, Santa Clara, CA, 2010).
[10] J. Brodrick, DOE SSL Roadmap, in: Strategies in Light (San Jose, Santa Clara, CA, 2010).
[11] E. F. Schubert and J. K. Kim, Science **308**, 1274–1278 (2005).

THE CASE FOR A NATIONAL RESEARCH PROGRAM ON SEMICONDUCTOR LIGHTING[1,2]

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EXECUTIVE SUMMARY

Dramatic changes are unfolding in lighting technology. Semiconductor light emitting diodes (LEDs), until recently used mainly as simple indicator lamps in electronics and toys, have become as bright and efficient as incandescent bulbs, at nearly all visible wavelengths. They have already begun to displace incandescent bulbs in many applications, particularly those requiring durability, compactness, cool operation and/or directionality (e.g., traffic, automotive, display, and architectural/directed-area lighting).

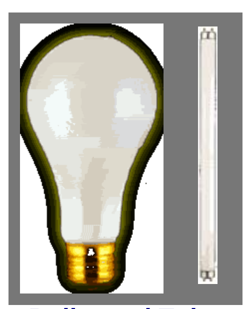
Further major improvements in this technology are believed achievable. Recently, external electrical-to-optical energy conversion efficiencies exceeding 50% have been achieved in infrared light emitting devices. If similar efficiencies are achieved in the visible, the result would be the holy grail of lighting: a 200*lm/W* white light source two times more efficient than fluorescent lamps, and ten times more efficient than incandescent lamps.

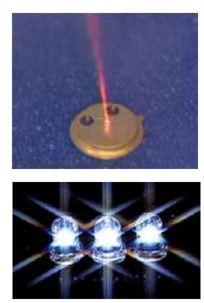
This new white light source would change the way we live, and the way we consume energy. The worldwide amount of electricity consumed by lighting would decrease by more than 50%, and total worldwide consumption of electricity would decrease by more than 10%. The global savings would be more than 1,000*TWh/yr* of electricity at a value of about US$100B/year, along with the approximately 200 million tons of carbon emissions created during the generation of that electricity. Moreover, more than 125*GW* of electricity generating capacity would be freed for other uses or would not need to be created, a savings of over US$50B of construction cost.

Bringing about such revolutionary improvements in performance will require a concerted national effort, of the order $0.5B over ten years, tackling a broad set of issues in semiconductor lighting technology. The effort would also require harnessing the most advanced high-technology companies, the best national laboratory resources, and the most creative university researchers in this area.


Fire


Candles and Lamps


Bulbs and Tubes


Semiconductors

1 This white paper was first presented publicly at the 1999 Optoelectronics Industry Development Association (OIDA) forum in Washington DC on October 6, 1999.

2 Revision B:03/30/1999

1 INTRODUCTION

Energy is the lifeblood of our economy, and a critical building block for global peace and security. Its generation incurs huge costs: both direct economic costs as well as indirect environmental costs (smog and particulate emissions, acid rain, global warming, waste disposal, etc). And, the direct economic costs will only increase as concern heightens over how to reduce the indirect environmental costs.[3] As a consequence, there is great benefit to enhancing the efficiency with which energy is used -- virtually all major energy consumers from transportation to heating to the various users of electricity are constantly being examined for energy saving opportunities.

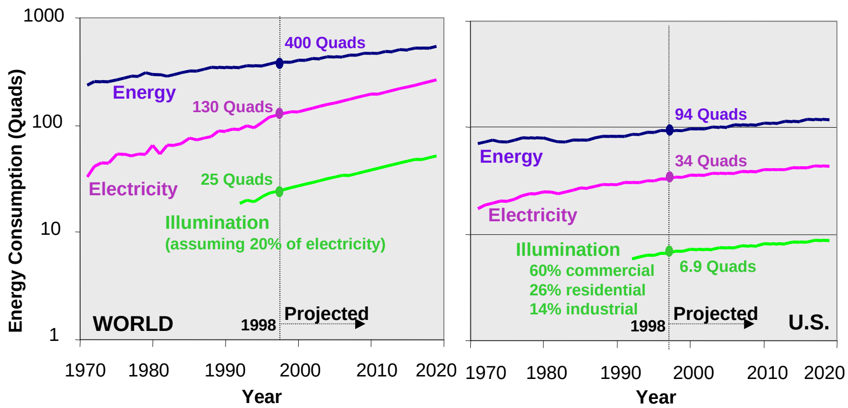


Figure 1. World (left) and U.S. (right) consumption of energy for use in all forms (blue), for use in electricity generation (pink), and for use in illumination (green).[4] One Quad (one quadrillion BTUs) of primary energy consumed is roughly equivalent, after energy conversion and transmission losses, to 92TWh of electricity at the wall plug.

Among the most widespread, important, and *growing* uses of energy is the electricity used for lighting. As illustrated in Figure 1, in the U.S., about 20% of all electricity consumed,[5] and about 7.2% of all energy consumed, can be estimated to be used for lighting. In 1998, the cost was about 6.9 quads of primary fuel energy (with an associated 112 million tons of carbon emissions), and about 637*TWh* of actual electricity consumed at a cost of about US$63B. Worldwide, about 3.4% of all energy consumed can be estimated to be used for lighting, a percentage that is expected to increase with standard of living. In 1998, the worldwide cost was about 25 quads of primary fuel energy (with an associated 410 million tons of carbon emissions), and about 2,350*TWh* of actual electricity consumed at a cost of about US$230B.

Because of this large contribution of lighting to worldwide energy consumption, it is no wonder that the lighting industry receives its fair share of inquiries regarding energy reduction. In 1995, the three major US lighting manufacturers – GE Lighting, Osram/Sylvania and North American Philips

[3] In the Kyoto Protocol of 1997, e.g., the developed nations agreed to limit their greenhouse gas emissions, relative to the levels emitted in 1990. The United States agreed to reduce emissions from 1990 levels by 7% during the period 2008 to 2012.

[4] World data taken from the International Energy Agency (http://www.iea.org), and assuming projected energy, electricity and illumination growth rates of 1.6%, 3.5% and 3.5%. U.S. data taken from the Energy Information Administration (http://www.eia.doe.gov), and assuming projected energy, electricity and illumination growth rates of 1.2%. We acknowledge Gerald Hendrickson and Arnold Baker at Sandia National Laboratories for assistance interpreting the data.

[5] According to a recent EPRI report (TR-106196), the four top electricity-consuming applications in the U.S. in 1995 were: electric motors (24%), cooling/refrigeration (18%), lighting (17%), and space/water heating (16%). These percentages include the three major market segments -- residential, commercial and industrial -- but not street lights, traffic signals, nor the use of electricity to remove the heat generated by lighting in air-conditioned buildings. The Industrial Lighting handbook estimates that it takes 1 kW of electricity in the air-conditioning system to remove 3 kW of heat generated by lighting. After including the above omissions, it is safe to say that, in the U.S., lighting consumes at least 20% of electricity and ranks a close second to the 24% consumed by electric motors.

– sponsored a three-day workshop to identify promising research areas for improving the efficiency of white light sources. This workshop confirmed that "lighting consumes about 20% of the electric power production of the nation." One of the most revealing figures in the resulting EPRI report[6] is a graph of luminous efficiency vs. time for the major "true" white light sources: incandescent, halogen, and fluorescent lamps. As illustrated in Figure 2, none of these workhorse technologies has shown any significant efficiency improvements during the preceding 20 years!

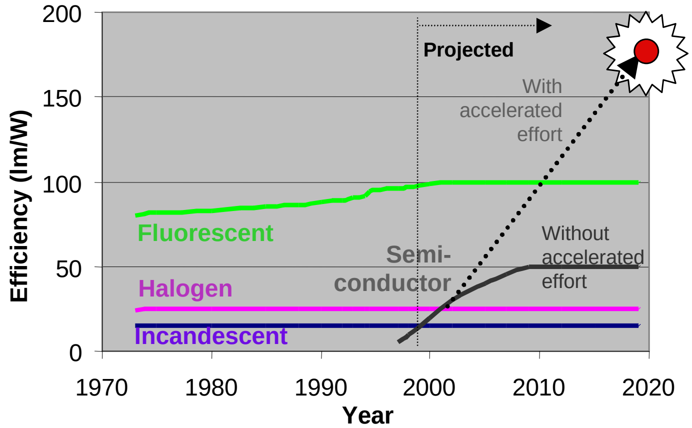


Figure 2. Condensed history and projection of efficiencies (in lm/W) of vacuum tube (incandescent, halogen and fluorescent) and semiconductor (LED) white lighting technologies.

There is, however, one striking exception. Light emitting diodes (LEDs), a 40-year-old semiconductor technology, have steadily improved their efficiencies and power levels to the point where they are knocking incandescent and halogen lamps out of such traditional monochrome lighting applications sockets as traffic lights and automotive tail lights. And, a recent breakthrough in the green and blue makes LEDs a serious contender for conventional white lighting.

It is the purpose of this white paper to call attention to this new lighting technology and to the potential impact of a concerted national effort to advance it further. Such an effort would fill a need identified by the U.S. Department of Energy for research in advanced lighting technologies.[7] And, such an effort would target the technology we believe has the highest potential to create an ideal lighting source, both in quality and in cost. LEDs and their semiconductor variants are visually appealing, convenient and environmentally friendly, and it is our assessment that they have a realistic shot at reaching the industry nirvana of an efficiency of 200*lm/W*.

If semiconductor lighting can achieve this goal through a concerted national effort, the lighting industry would be revolutionized. An efficiency of 200*lm/W* would be more than 2x better than that of fluorescent lamps (80*lm/W*), and more than 10x better than that of incandescent lamps (15*lm/W*). If current lighting, with an aggregate efficiency of roughly 50*lm/W* (in between the efficiencies of fluorescent and incandescent lamps), were replaced by semiconductor lighting with an aggregate efficiency of 150*lm/W* (somewhat less than the target), then the electricity currently used for illumination would decrease by a factor of three, from 2,350*TWh* to 780*TWh*. This would represent a decrease in global electricity use of about 13%, and a decrease in global energy use and associated carbon emissions of 2.3%.

In some ways such a revolution in lighting could be compared to the revolution in electronics that began 50 years ago and is only now reaching maturity. Just as for electronics, glass bulbs and tubes would give way to semiconductors. And, just as for electronics, the increased integrability, density, performance, and mass manufacturability of semiconductors may drive an explosion of additional, not-yet-thought-of uses for lighting. One can even speculate on visionary concepts in

[6] The workshop is summarized in EPRI report TR-106022.

[7] This need has been identified in the Department of Energy's ongoing "Vision 2020" lighting technology roadmapping activity. It has also been identified separately by the Department of Energy's Office of Building Technology, State and Community Programs, whose program plan consists of three overall goals: (1) Accelerate the introduction of highly efficient technologies and practices through research and development; (2) Increase minimum efficiency of buildings/equipment through codes, standards and guidelines; and (3) Encourage use of energy efficient technology through technology transfer and financial assistance.

which information and illumination technologies combine to create ultra-fast wireless local-area networks that are mediated through building lights!

We begin this white paper in Section 2 with a brief history of LED technology, and compare its current and projected performance and cost with those of conventional technology. In Section 3, we discuss its penetration (and replacement of conventional technology) in signaling and lighting applications. We expect LED penetration into signaling applications, currently dominated by inefficient filtered incandescent lamps, to be rapid, and to drive continued improvements in performance and cost. These improvements will, in turn, enable gradual penetration of LEDs into lighting applications, currently dominated by a mix of incandescent and fluorescent lamps. Although the penetration will be gradual, its global impact will already be very significant, since lighting represents such a large fraction of global energy consumption. In Section 4, we describe an economic model for that global impact.

We believe much more dramatic improvements to be possible. In Section 5 we discuss such improvements, the resulting acceleration of the penetration of semiconductor lamps into lighting applications, and the resulting huge impact on global energy consumption. Finally, in Section 6 we discuss in general terms the daunting technical challenges, and the magnitude and nature of a national research program that might enable these challenges to be overcome.

2 History and Projection of LED Performance and Comparison with Conventional Lamps

LEDs have had a "colorful" history, alternately pushed by technology advances and pulled by key applications. The first demonstration was in 1962 by General Electric. The first products were introduced in 1968: indicator lamps by Monsanto and the first truly electronic display (a successor to the awkward Nixie tube) by Hewlett-Packard. The initial performance of these products was poor, around 1*mlm* at 20*mA*, and the only color available was a deep red.[8] Steady progress in efficiency made LEDs viewable in bright ambient light, even in sunlight, and the color range was extended to orange, yellow and yellow/green. Within a few years, LEDs replaced incandescent bulbs for indicator lamps, and LED displays killed the Nixie tube.

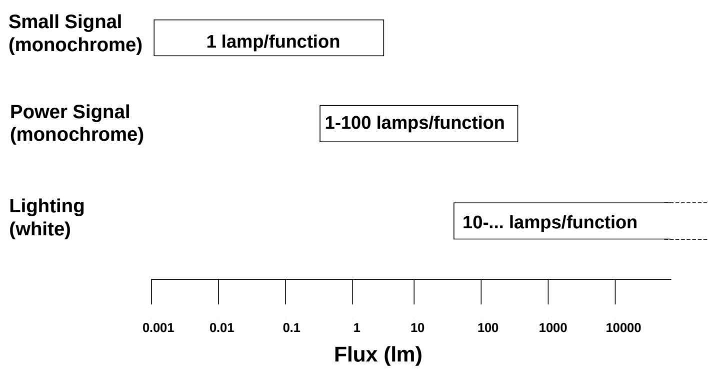


Figure 3. Flux and numbers of lamps required for various classes of LED applications: low-medium-flux "signaling" applications, in which lamps are viewed directly, and medium-high-flux "lighting" applications, in which lamps are used to illuminate objects. Current LED lamps emit 0.01-10lm of light.

Until 1985, LEDs were limited to small-signal applications requiring less than 100*mlm* of flux per indicator function or display pixel. Around 1985, LEDs started to step beyond these low-flux small signal applications and to enter the medium-flux power signaling applications with flux requirements of 1-100*lm* (see Figure 3). The first application was the newly required center high-mount stop light (CHMSL) in automobiles. The first solutions were crude and brute-force: 75 indicator lamps in a row or in a two-dimensional array. It did not take long to realize that more powerful lamps could reduce the lamp count, a significant cost advantage. *This was the first situation where efficiency became an*

[8] For comparison, a 60*W* incandescent lamp emits 6 orders of magnitude higher light flux (about 900*lm*).

issue and for which the market was willing to pay a premium.[9] So, in the late 1980's, we saw the first horse race for efficiency improvements. By 1990, efficiencies reached 10*lm/W* in the GaAlAs materials system, for the first time exceeding that of equivalent red filtered incandescent lamps. Nevertheless, even higher efficiencies were desired to continue to decrease the number of lamps required per vehicle. Plus, the GaAlAs system was limited in color to a deep red, above 640*nm*.

This horse race triggered the exploration of new materials system with still higher efficiency and a wider color range. First emerged GaAlInP materials, covering the range of red to yellow/green and quickly exceeded 20*lm/W* in the 620*nm* red/orange part of the spectrum. In 1995, Hewlett-Packard projected a room-temperature efficiency of 50*lm/W* by the Year 2000, with a theoretically possible efficiency of 150*lm/W* that could challenge that of even the most efficient conventional light source, the yellow low-pressure sodium lamp. This projection spawned a joint venture with Philips, and accelerated the use of LEDs in power signaling applications.

In 1993, there was another breakthrough in LED technology. Based on work at several universities, both in the US and Japan, Nichia Chemical Corporation in Japan announced a fairly efficient blue material, GaN. Efficiency improvements followed quickly, together with an extension of the color range from blue to green (430-530*nm*). Now, LEDs could cover practically the entire visible spectrum, enabling their entry into additional power signaling applications such as traffic lights.

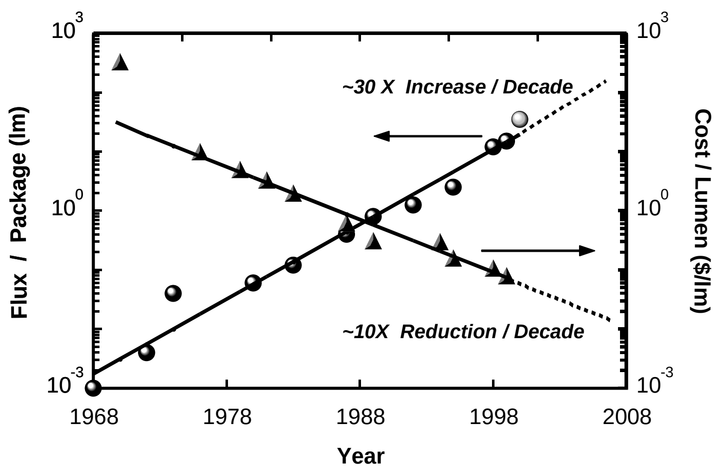


Figure 4. Historical and projected evolution of the performance (lm/package) and cost ($/lm) for commercially available red LEDs. This data was compiled by R. Haitz from HP historical records.

Before going on, we want to emphasize here the importance of the power signaling market on LED evolution. The penetration of LEDs into this market depended (and continues to depend) critically on performance and cost. Solutions based on large numbers of small-signal lamps are too expensive, thus demanding the development of higher-power LEDs. This evolution is illustrated in Figure 4 covering the period from first LED sales in 1968, projected to 2008. In a Moore's-law-like fashion, flux per unit has been increasing 30x per decade, and crossed the 10*lm* level in 1998. Similarly, the cost per unit flux – the price charged by the LED supplier to OEM manufacturers – has been decreasing 10x per decade and will reach 6*cents/lm* in 2000. At this price, the LEDs in a typical 20-30-lm CHMSL contribute only $1.50 to the cost of the complete unit![10] In other words, the power signaling market drove, and continues to drive, improvements in the design and manufacturing infrastructure of the compound semiconductor materials and devices on which LEDs are based.

These improvements have led to the LED efficiencies summarized in Figure 5 for the visible wavelength range 450-650*nm*. Because the efficiencies vary with temperature, the data shown refer to

[9] Back in the small signal days where one lamp was used per function, a 2x improvement in efficiency did not allow customers to use half a lamp. And, to reduce the drive current of an indicator lamp from 20*mA* to 10*mA* did not matter very much in an instrument that used 10-100*W* for other electronic functions.

[10] Although this cost is higher than that of an incandescent light bulb, it is low enough that other factors, such as compactness, styling freedom and absence of warranty cost, easily make up the difference.

a junction temperature of 85°C. For the GaAlInP material system (red to yellow), we show efficiency data for: (a) the expected Year 2000 production capability of the industry, (b) the expected Year 2005 production capability, and (c) the best results reported as of 1999, shown to substantiate our confidence in the Year 2005 forecast. For the GaInN material system (green to blue), we show efficiency data for: (a) current average production performance of the industry leader, Nichia, and (b) a curve that is 50% higher. According to Nichia, their best results seem to be 50% above their average, and we assume that these best results will become average industry production within five-six years (by the Year 2005).

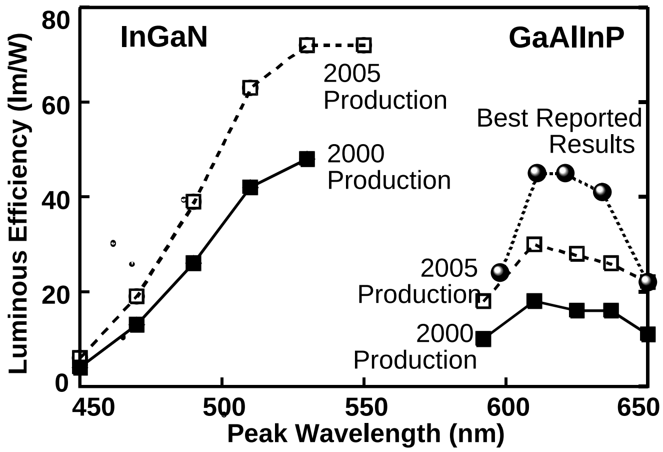


Figure 5. LED efficiency at an 85°C junction temperature as a function of wavelength. For the two dominant materials systems (GaAlInP and GaInN) we show current production data and our best estimate for Year 2005 production.

At this point, LEDs of reasonable efficiency span virtually the entire visible wavelength range (with the exception of a narrow window in the yellow-green), and it is possible to create white light sources. One approach, which gives white light sources with excellent color rendering properties, involves combining 3-6 LEDs of different colors. Another approach involves combining a blue LED with down-conversion phosphors in a relatively inexpensive package. Both of these approaches involve some losses (color mixing in the former and photon down-conversion in the latter), but nevertheless can achieve good overall efficiencies. In fact, assuming the efficiencies of Figure 5, and a color mixing loss of 15%, semiconductor white light sources made with red, yellow, green and blue LEDs will already exceed that of standard 60-100*W* incandescent lamps in the Year 2000.

Lamp Type	Power (W)	Efficiency (lm/W)	Lifetime (hrs)
Standard Incandescent	15	8	1,000
Standard Incandescent	100	15	1,000
Long Life Incandescent	135	12	5,000
Halogen	20	12	3,000
Halogen	300	24	3,000
Compact Halogen	50	12	2,500
Compact Fluorescent	11	50	10,000
Standard Fluorescent	30	80	20,000
White LED 2000	Any	20	100,000
White LED 2002	Any	30	100,000
White LED 2005	Any	40	100,000
White LED 2010	Any	50	100,000

Table 1. Efficiencies and lifetimes of various conventional and semiconductor white light sources. Similar to Figure 5, the semiconductor white light sources refer to a junction temperature of 85°C.

This is illustrated in Table 1, which compares current and projected efficiencies of white LED-based lamps with those of the most widely used conventional white light lamps. The most popular incandescent lamps with a power rating of 60-100*W* have an efficiency of around 15*lm*/*W* and a rated life of 1,000 hours. The efficiency of incandescent lamps drops off at lower power ratings or for lamps with a longer 3,000-6,000 hour rated life. Halogen lamps show a similar pattern covering the range of 12-24*lm*/*W*. Fluorescent lamps at 80*lm*/*W* are the most efficient white light sources and dominate commercial and industrial lighting applications.

In comparison, using the projections shown in Figure 5, LED-based white light sources will have efficiencies of 20*lm*/*W* in the Year 2000, should reach 40*lm*/*W* in the Year 2005, eventually leveling off in the 40-60*lm*/*W* range by the Year 2010. These efficiencies exceed significantly those of standard 60-100*W* incandescent lamps.

Moreover, the comparison between LED and incandescent lamp efficiencies favors LEDs even more in the case of monochrome applications. For these applications, there are no color-mixing losses for the LEDs, but there are additional filtering losses for incandescent lamps. [11] As shown in Table 2, LED efficiencies exceed those of filtered incandescent lamps by a large margin over the entire visible wavelength range except for yellow, where the two technologies are close to parity.

Color	Filtered Long-Life Incandescent Efficiency (lm/W)	Year 2000 LED Production (lm/W)
Red	1-6	16
Yellow	4-8	10
Green	3-10	48
Blue	1-4	13
White	12	20

Table 2. Current (Year 2000) LED efficiencies in broad color ranges as compared to those of filtered long-life incandescent lamps. The LED efficiencies refer to a junction temperature of 85°C.

3 LED PENETRATION INTO POWER SIGNALING AND LIGHTING APPLICATIONS

The penetration of LEDs into the signaling and lighting markets is a complex issue. Like in any new technology, in the early years LED solutions will be considerably more expensive than conventional solutions. To justify their selection, the higher initial cost has to be compensated with lower operating costs or other tangible benefits.

With the dramatic progress that has been made in LED performance and cost over the past decades, however, LEDs have already begun to penetrate a number of monochrome signaling applications. We describe several of these applications in Appendix A, which include traffic and automotive lights, and large-screen outdoor TVs. Energy savings are the driving force for traffic lights; ruggedness, long life and styling are important factors in automotive tail lights; and lamp density and integrability are the key factors in TV screens with 3,000,000 pixels over an area of 600m^2.

The penetration of LEDs into white light applications will be much more difficult. A comparison between Table 2 (monochrome efficiencies) and Table 1 (white light efficiencies) shows why. At Year 2000-2005 performance levels, an LED-based red traffic light consumes 10x less power than its filtered incandescent alternative, while an LED-based white light consumes only 2x less power than its standard incandescent alternative, and about 2-3x *more* power than its fluorescent alternative.

As a consequence, in the very near term, the white light applications that can realistically be attacked will be lower-flux "specialty" lighting applications in the 50-500*lm* range, currently dominated by incandescent and compact halogen lamps with relatively modest efficiencies in the range of 8-12*lm/W*. We describe several of these applications in Appendix A, which include accent and landscape lights, and flashlights.

General lighting of residential, office, retail or industrial buildings, which consumes much more total energy than either signaling or specialty white lighting, will be much more difficult to penetrate for several reasons, the foremost being cost. <u>Lamp cost</u>: a 100 W incandescent lamp delivering a

[11] Note that this comparison does require some caution, due to the variability in efficiency of the filters used to produce various colors. For instance, the filter used in a red traffic light absorbs 90% of the white light and results in a deep red color. The red filter of an automobile taillight has a wider transmission band and yields an orange-red color. Yellow and green filters are fairly efficient and transmit a large fraction of the white spectrum. Blue filters are comparable to the transmission of red filters. Nevertheless, filtered incandescent color sources will always be less efficient than unfiltered white sources, while LEDs are inherently monochrome and do not suffer filtering losses.

flux of 1.5*klm* costs only \$0.50, or \$0.33/*klm*, while a comparable LED-based light source would cost over \$150, or roughly \$100/*klm*. Efficiency: Incandescent lamps with a rating of 60-150*W* have an efficiency of 14-16*lm*/*W*. To recover the initial difference in lamp cost in a reasonable time, today's white LED efficiency of 20*lm*/*W* is insufficient. White LEDs will not cross the critical threshold of 30*lm*/*W* before 2002. Maintenance labor cost: The majority of incandescent lamps are used in residential buildings where the cost of maintenance labor is not an issue.

Penetration into these higher-flux general lighting markets thus depends on continued efficiency improvements to the point where the energy savings pay back the initial cost penalty in a reasonable time, i.e. in six years or less. To quantify this, we define a "breakeven" time, which is the period over which energy savings equal the difference in initial lamp costs. A simple calculation of breakeven times is given in Appendix B for a standard 100 W incandescent lamp and an LED lamp of equivalent flux. For example, in the Year 2002, when LED lamp retail prices are expected to be of the order 100\$/*klm* with an efficiency of 30*lm*/*W*, the breakeven time for a daily operating time of 12 hours is just about six years. This is a marginal payback situation and penetration will be quite limited. But continued improvements in LED cost and efficiency should gradually expand the penetration.

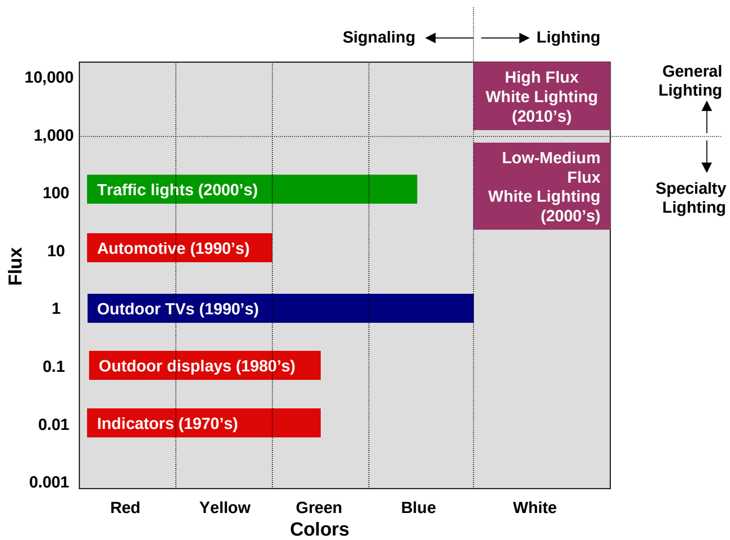


Figure 6: The stepping stones from LED indicators to LED illumination over half a century from 1970 to 2020. Signaling applications are mostly monochrome; lighting applications are mostly white. Specialty lighting includes monochrome and low/medium flux white lighting and is dominated by incandescent lamps. General lighting includes high flux white lighting and is dominated by a combination of incandescent and fluorescent lamps.

It is helpful at this point to remind ourselves that these improvements will almost certainly continue at a rapid rate, due to the pressure that has been, and will continue to be, supplied by the power signaling market. To emphasize this, we show in Figure 6 the key stepping stones in the cost evolution of LEDs. Large outdoor displays with thousands of LED lamps made sense only after the growing volume for indicator lamps had reached hundreds of millions of units per month at a price of 10 cents or less per unit. LEDs in automotive rear combination lamps will not make economic sense until the cost/lumen approaches 5*cents*/*lm*. Replacing a red traffic light with 12-18 LEDs has created LED power packages that can handle a heat dissipation of several Watts at a reasonable cost. In turn, such a capability is needed for the front turn indicators which are mounted close to the head lamps of the car. The cost sensitive and potentially huge automotive market will force the industry along a steep cost learning curve. And, it is this cost pressure that will enable white LEDs to cross the critical threshold of 100\$/*klm* and 30*lm*/*W* that we estimate will be achieved in the Year 2002.

When this critical threshold is achieved, LED-based white lamps will begin to replace incandescent and compact halogen lamps in the following situations:

Highly directional lamps: Our prototype work with Philips has shown that LED-based lamps are far more effective in distributing light to where it is needed rather than trapping light within the luminaire or sending part of it into undesirable directions ("light pollution"). In one particular example that we studied extensively, the difference was 2x over a conventional light source. If this advantage can be realized in many applications, then a 25*W* LED lamp with an efficiency of 30*lm/W* can do the job of a 100W incandescent lamp with its 15*lm/W* efficiency. In this case the break-even point for a daily operation of 12 hours is a respectable two years!

<u>High Maintenance Cost</u>: In all commercial applications the cost of maintenance labor is real. A regular incandescent lamp with 750-1000 hours operating life has to be replaced 25 times over 5 years if it is operated 12 hours/day. Depending on the situation, the maintenance cost could be comparable to the initial cost of an LED based lamp. Some applications have very high maintenance cost, i.e., street and tunnel lights, and swimming pool lights. To shut down a tunnel or to partially drain a swimming pool is both a nuisance and expensive.

<u>Long Life</u>: Lamps with an extended life rating of 3000-6000 hours or lamps that are designed for a shock and vibration environment have a reduced efficiency in the range of 8-12*lm/W* increasing the energy consumption by 25-100% over a regular incandescent lamp. The breakeven time is reduced correspondingly.

<u>Dimmability</u>: Most dimmable lamp applications use incandescent lamps. Dimming an incandescent lamp reduces its filament temperature slightly and dramatically kills the efficiency. The result is a much reduced flux at nearly the same energy consumption. In contrast, an LED based lamp can be dimmed with practically no loss in efficiency. Also, a dimmed incandescent lamp changes its color temperature and subsequently its color rendering properties while an LED lamp maintains its color temperature.

Year	LED Efficiency *(lm/W)*	Cost *($/klm)*	Breakeven time at Equal flux *(Years)*	Breakeven time at Half flux *(Years)*
2002	30	100	6.1	2.1
2005	40	75	3.8	1.5
2010	50	47	2.2	0.9

Table 3. Summary of breakeven times at which LED lamps operated 12 hrs/day become economical over standard 100W incandescent lamps with 15lm/W efficiencies. The equal-flux and half-flux breakeven times assume LED flux equal to, and half, that of the incandescent lamp flux., respectively.

Beyond this critical threshold (100$/*klm* and 30*lm/W*), penetration will increase as LED technology continues to improve. As indicated in Table 1, we expect the 85°C efficiencies to increase to 40*lm/W* in 2005 and to 50*lm/W* in 2010. In parallel, we expect white LED cost to drop by at least 10% per year, reaching $75/*klm* in 2005 and less than $50/*klm* in 2010. With these improvements, the breakeven times will be substantially reduced, as shown in Table 3. A strong replacement of incandescent lamps in commercial and industrial applications should start in 2005, and should reach residential applications well before 2010.

Note that we do not expect that, at efficiencies of 50*lm/W* or less, LEDs will penetrate that part of the general lighting market currently served by fluorescent lamps, either compact or large tubes. Only in applications where fluorescent lamps lead to large, undesired light spillage or to significant losses within the luminaire could LED-based lamps "break-even" over fluorescent lamps by the Year 2010. Therefore, for the analysis described in the next Section, we do not count on any LED penetration into the fluorescent lamp market.

4 IMPACT ON ENERGY CONSUMPTION

As discussed in the previous Section, in the Year 2002 we expect LED-based white lamps with an efficiency of 30*lm/W* to start to replace incandescent lamps with an efficiency of 12*lm/W*. What will be the global economic and energy impact of the penetration of LED lamps into these general lighting applications? To answer this question requires creating an economic model for the evolution of lighting usage and LED penetration. We discuss a simple such economic model in Appendix C. The model depends on a multitude of assumptions, some of which characterize lighting and electricity usage generally, and others of which characterize LED cost, performance and market penetration. The assumptions we have made are described in detail in Appendix C. They are somewhat conservative, but because lighting is such a large market, they nonetheless imply very significant global economic and energy savings. The total worldwide electricity used for lighting in the Year 2000, e.g., is expected to be over 2,000*TWh*, at a cost of approximately US$200B!

Table 4 summarizes the projected savings. The key assumption is that LED penetration begins, as expected from the above breakeven analysis, in the Year 2002, gradually increases through the Year 2020, where it saturates at roughly 10%. The saturation occurs when LEDs reach an efficiency plateau of 50*lm/W*, which is sufficient for significant penetration into that part of the general lighting market currently served by incandescent lamps, but not sufficient for penetration into that part of the general lighting market currently served by fluorescent lamps.

	Year	2005	2010	2015	2020	2025
LED Penetration	%	0.05	0.5	4	9	10
Energy Savings per year	TWh/yr	1	18	150	370	440
Energy Cost Savings per year	M$/yr	100	1,800	15,000	37,000	44,000
Energy Generating Capacity Savings	GW	0.1	2	17	42	50

Table 4. Projected global savings in energy, energy cost, and energy generating capacity due to LED penetration into specialty lighting markets, assuming LED efficiencies level off at 50lm/W in 2010.

The projected savings are obviously very significant. The $44B savings in 2025 corresponds to 15% of the $300B conventional lighting would have cost. According to this model we have replaced 10% of the least efficient installed flux base and saved 18% of the electricity used in lighting, or 440*TWh*. That also represents a 15% reduction in the carbon emissions associated with electricity, or 88 million tons. These are of course ongoing savings in electricity usage every year. There is also a savings in the electricity generation capacity that would be freed for other uses or that would not need to be created. That savings is 50*GW*, the equivalent of 37 large 1.35*GW* power plants, which would require more than $20B to construct.[12]

5 EFFICIENCY BREAKTHROUGH!

The above analysis is based on evolutionary improvements in the efficiency of white LED based light sources. Based on our 30 years of LED leadership and on the experimental data that we have seen so far we are quite confident that the 50*lm/W* goal for 2010 can be achieved without counting on any breakthrough. But 50*lm/W* corresponds to an energy conversion from electricity to light of only 12%. Is this the end? How far can we push the technology? In this section we will develop the arguments for a very bold scenario that could revolutionize the entire lighting industry.

In 1997, Sandia reported a conversion efficiency exceeding 50% for a vertical cavity surface emitting laser (VCSEL) at a wavelength of 980*nm*. This VCSEL generated 2*mW* of light at a drive current of 2*mA* and a drive voltage of 2*V*. Such a VCSEL takes up only a 10μm diameter circle. Replicating these VCSELs with a 40μm spacing yields 500 VCSELs in a 1mm^2 chip. Each VCSEL has a reasonable large series resistance allowing a massive parallel operation from a single current source. Driving the array with 1*A* at 2*V* should result in a 1*W* optical source with a 50% conversion efficiency. Nobody has built such a 1*W* source yet, but 300*mW* prototype arrays have demonstrated the feasibility of this concept.

[12] The cost per GW is approximately $400M for combined-cycle natural gas plants, and is higher for other types of power plants (coal, oil, nuclear).

Now comes a leap of faith: Let us assume that a major national R&D program involving National Labs, universities and industry can replicate the projected infrared result at any wavelength in the visible spectrum: 1W of optical flux with a conversion efficiency of 50% in a 1mm² chip anywhere from blue to red. As a next step, imagine that we could build a white lamp consisting of six chips with a 30*nm* wavelength spacing between 470*nm* and 620*nm*. This 12*W* lamp would generate an optical flux of 6*W* or 2,400*lm* and have a superior color rendering index approaching 100. With an efficiency of 200*lm/W*[13], it would beat incandescent lamps by more than an order of magnitude and the most efficient fluorescent lamps by more than 2x. But that is not all. The VCSELs have well-defined beams – the photons are trained while they are young! - and light distribution is quite straight forward. A large fraction of "light pollution" and internal losses can be avoided. This feature is worth another factor of 2x in many lighting applications. Such a lamp would truly revolutionize the industry!

Back to reality! The best reported efficiency of red VCSELs is in the 12% range and no one has yet succeeded making any yellow, green or blue VCSELs. The problem is enormous! There are many arguments suggesting a "Mission Impossible". But since the concept does not violate any laws of physics and since the infrared results are so compelling, a large national research project for the "Wonder Bulb" can be justified (see below).

There are two other approaches worth exploring. Can we develop blue or UV power lasers with 50% conversion efficiency? Those lasers could pump a phosphor. The conversion process results in a down-conversion related energy loss, and 200*lm/W* would not be possible, but we still could beat all other light sources, including the LED.

The second approach is LED based. Why should LEDs be limited to a 12% conversion efficiency (50*lm/W*)? In the red GaAlInP system, Hewlett-Packard recently reported a quantum efficiency of 53% corresponding to an energy conversion efficiency of 45%. How far can we push the GaInN system? Is the 30-50% range a realistic target and worth a major research project?

Suppose we are successful in creating such a light source. What will be the global economic and energy impact of the penetration of semiconductor lamps into not only that part of the lighting market served by incandescent lamps, but into that part of the lighting market served by fluorescent lamps ? To answer this question requires creating an economic model for the evolution of lighting usage similar to that described previously. The model is described in detail in Appendix C. The overall projected savings are summarized in Table 5. The key modified assumptions from the previous model are:

- Semiconductor lamp penetration is accelerated from 2005 on, reaching 2% in 2010. And, instead of flattening out at 10%, the penetration continues to rise and reaches 55% in 2025 (see Table C2 in Appendix C).
- The cost per *klm* of flux is assumed to be the same as in the previous model, because the cost forecast is already quite aggressive.
- Since this more efficient lamp can attack the fluorescent lamp installations, the efficiency of the replaced lamps keeps rising to 65*lm/W* in 2025. Similarly the average efficiency of the new lamps keeps rising and reaches 150*lm/W* in 2025. This value is less than the 200*lm/W* mentioned above. The difference is due to the fact that we need a broad family of lamps and not all lamps will be at 200*lm/W*.

[13] 200*lm/W* would be the efficiency of a white light source made up of six LEDs spaced evenly by 30*nm* from 470*nm* to 620*nm* and which convert electrical to optical power with 50% efficiency at each wavelength.

	Year	2005	2010	2015	2020	2025
LED Penetration	%	0.05	2	12	30	55
Energy Savings per year	TWh/yr	2	67	330	720	1100
Energy Cost Savings per year	M$/yr	200	6,700	33,000	72,000	110,000
Energy Generating Capacity Savings	GW	0.2	8	38	82	125

Table 5. Projected global savings in energy, energy cost, and energy generating capacity due to semiconductor lighting penetration into specialty and general lighting markets, assuming semiconductor lighting efficiencies increase to 150lm/W and beyond.

To put the above into perspective: The $110B saving in 2025 corresponds to 37% of the $300B conventional lighting would have cost. That also represents a 37% reduction in the carbon emissions associated with electricity, or 220 million tons. These are ongoing savings in electricity usage every year. The savings in the electricity generation capacity that would be freed for other uses or that would not need to be created is 125*GW*, the equivalent of 93 large 1.35*GW* power plants, which would require approximately $50B to construct.

6 Magnitude and Nature of a National Lighting Research Program

The benefits of the efficiency breakthrough discussed in the previous section and summarized in Table 5 are very large indeed, both for the U.S. and for the world. However, a set of enormous technical problems has to be tackled, and the breakthroughs that are required are not likely to be achieved without a concerted, coordinated national effort. In this section, we discuss the nature, size and possible structure of such an effort.

A Technical Areas

As mentioned in the preceding section, a set of enormous technical problems has to be tackled. To increase the probability of success and to accelerate the LED penetration in the early years the following three technical areas have to be addressed:

1 Cost Reduction of the LED Lamp. III-V materials and processes are a far cry from the processes used in the silicon industry. The wafers are small and fragile, processes are complex and have practically no margin for error (narrow process windows). Yields are variable and the device parameters vary all over the map. The development of robust manufacturing equipment and processes with substantially improved controls is one of the most important elements of this program.

The manufacturing infrastructure technologies developed would also have substantial spin-off benefit to a wide range of compound semiconductor device types. These include optoelectronic (LEDs, diode lasers, VCSELs, modulators, and photodetectors), electronic (both discrete transistors as well as analog and digital integrated circuits), sensor, and solar cell devices. The market for these devices and chips is expected to grow from approximately $6B in 1997 to over $10B in 2002. It is composed of chips and applications ranging from high-speed lasers and integrated circuits for optical fiber and RF/microwave wireless communications to high-efficiency photovoltaic cells for satellites to short-wavelength lasers for digital videodisk (DVD) players/recorders.

2 Breakthrough in LED Efficiency. As mentioned earlier, the best reported LED efficiencies are around 45% for red. How far can we push yellow GaAlInP, and the blue and green GaInN, materials? We must reduce the resistive losses in the wide bandgap GaInN material. Can we reduce the temperature sensitivity of GaAlInP such that operation at 85°C does not cut the efficiency by 2x relative to room temperature? Can we avoid the efficiency drop in GaInN with increasing current

density? Will a reduction in dislocation density improve the efficiency of GaInN? All of these questions are critical to improving LED efficiency.

It is also not just sufficient to have high quality material. Even after light has been created within an LED structure, its extraction presents considerable difficulty, as there are numerous parasitic channels by which light can be trapped and absorbed within the structure. Clever and innovative design and chip design integrated with materials advances may be key here. The development of advanced and comprehensive electrical transport and optical models for testing new ideas will also be important.

<u>3 Lasers.</u> This technical area would be aimed at creating efficient lasers at all colors. Ideally, these would be vertical-cavity surface-emitting lasers (VCSELs), as these appear to be the most amenable to batch manufacturing. However, VCSELs are perhaps the toughest solution. Innovative, breakthrough thinking and a large number of potential options would have to be explored. A dozen universities with some of our most brilliant scientists should participate. An especially important breakthrough would be efficient blue or UV lasers. This approach could be based on Fabry-Perot lasers or VCSELs. Fabry-Perot lasers with reasonable product life have been reported at 410*nm*. The efficiency is still low and improvements are expected. However, this technology must achieve a 50% conversion efficiency in the blue or UV to be attractive. The subsequent conversion to longer wavelength light includes a down-conversion shift and, therefore, an additional conversion loss. Resonant-cavity LEDs may also play a role here.

We note that these technical areas complement and build upon ongoing fundamental research in semiconductor materials and devices at universities. As illustrated in Figure 7, these research programs have a much longer time horizon of 8-16 years, and are much more broadly targeted at fundamental III-V semiconductor materials and device research. Likewise, these technical areas complement and build upon ongoing evolutionary development activities at industrial laboratories. These development activities have a much shorter time horizon of 0-8 years, and are very narrowly targeted at improving current devices. *The program we envision would fill this gap, with an intermediate time horizon of 4-12 years. It would be aimed directly at semiconductor lighting, but would not be confined to evolutionary, low-risk improvements of current devices.*

We also note that these technical areas would complement separate efforts aimed at developing building and lighting architectures that could, at a system level, exploit best the unique characteristics of semiconductor lighting while still appealing at a consumer level to human ergonomics. Many of these efforts are already ongoing (e.g., the RPI lighting institute, Lawrence Berkeley's lighting research center, and other efforts connected to the U.S. Department of Energy's Office of Building Technology, State and Community Programs), and could be expanded to include a forward-looking component on semiconductor lighting.

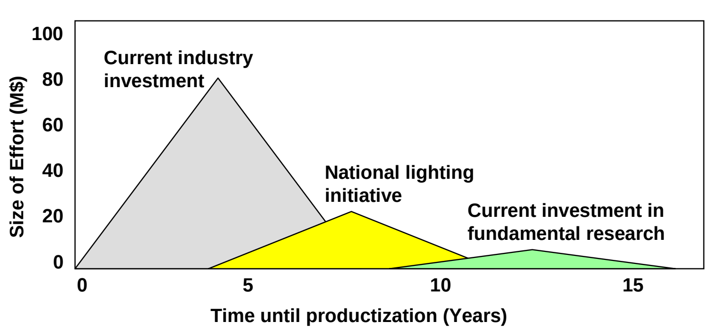


Figure 7. Current and proposed R&D investments in the area of semiconductor lighting.

B Organization

Of the above technical areas, the manufacturing technologies addressed in area 1 have to be tackled by industry with important help from national laboratories. Universities can participate in exploring some subtasks. In the remaining technical areas 2 and 3, universities can and must play an important role. We envision that clusters of universities, similar to the existing DARPA centers, jointly attack a series of well defined research tasks followed by a technology transfer to the industrial partners.

We further envision that one or more of the national laboratories could coordinate the overall project, along with the university programs. These non-profit national laboratories can be the recipient of proprietary information from various companies, and hence can help facilitate work that would require access to such information and that would also benefit the larger consortium.

In principle, there may be more than one consortium. In the major consortium that we envision, industry participation should include and be limited to the 2-3 major players in this area: HP/Philips, Emcore/WiTech/GE and, possibly, Cree/Osram/Sylvania. The 2-3 groups mentioned above are all established lighting suppliers and are all partnering with the leading North American and European technology companies in compound semiconductors. A consortium with these nearly equal partners should ensure a fairly effective cooperation since all partners have comparable opportunities to exploit the technology. With smaller competitors in the consortium, we fear that the openness of the cooperation would suffer -- the smaller partners would demand an equal share in the technology for a very small contribution to the overall program. If smaller companies would like to participate in some way, then we suggest that they do so through separate consortia.

C Size

How much DOE support is required to achieve critical mass and to assure a credible opportunity to succeed with a significant breakthrough? Let us start with an estimate of what the lighting industry (the 3 above partnerships) will spend on short-term development of monochrome and white power LEDs, not including the development of small signal LED indicators and displays: $60-80M in 2000, $100-120M in 2005 and $120-150M in 2010. This spending chain will sum to $1B over 11 years.

This total frames the magnitude of the investment, but is dwarfed by the magnitude of the potential cost savings indicated in Table 4. It is an upper bound to the DOE support required for the initiative we propose, but should not be far off the mark. An enormous set of technical problems has to be tackled, and the breakthroughs that are required are not likely to be achieved without a similar critical mass. Hence, we believe a DOE supported program should be of a comparable magnitude, i.e., $500M for the period from 2000 to 2010. We would propose to start with $30M in 2000, $40M in 2001 and $50M for 2002 and thereafter. This program represents a smaller investment, appropriate for a higher-risk program with longer-term impact, but the pay-off is even more profound, as indicated in Table 5.

How should these funds be distributed? Our initial proposal is in the range of 30/30/40% to 25/25/50% for universities/national laboratory/industry. There should be an additional condition on the funds going to industry: 3:1 matching. The industry should not receive more than 1$ for every $3 of its own R&D spending in semiconductor-based lighting. This degree of industry cost-sharing for a program this forward-looking and of this magnitude is unprecedented, and is an indication of our seriousness.

D Risk Exposure

Some people will quickly raise the question: If this is such a great deal, why doesn't the industry pay for it out of their profits? The answer is quite simple: The profits aren't there, at least not in the next six years.

Between now and the middle of the next decade, the power signaling and lighting segments of the LED industry will be losing money. The calculation behind this statement is quite simple. In 1999, Strategies Unlimited estimates that the power signaling market represents $400M of the $2,100M LED market. At a growth rate of 20%, it will grow to $1,200M in 2005. In 1999, and, most likely, also in 2005, approximately half of this market will be controlled by Asian companies. The illumination market will grow from nothing today to $200M in 2005 bringing the combined power signaling and lighting markets to $1,400M or $700M for the non-Asian participants.

Because of the potential size of the illumination market beyond 2005, we estimate the R&D spending of the U.S. and European power LED industry will be very large: $60-80M in 2000 and $100-120M in 2005. In 2000, this R&D spending represents 30-40% of revenue dropping to 14-17% by 2005. With cost of goods sold typically in the 60-70% range, and selling and administrative expenses of 10-15%, simple arithmetic shows that in 2000, the industry will be in the red to the tune of 10-20% of revenue and, with some luck, might break even in 2005. The only way out of this dilemma is a drastic reduction in R&D spending. If the industry chooses this option, then the critical threshold of 30*lm*/*W* and $100/*klm* for penetration of white lighting moves out, well beyond 2005. The energy savings discussed in Appendix C and Table 4 will shift correspondingly to later years.

The only way to achieve the energy savings of Table 4 and, subsequently, of Table 5, is through a government-industry partnership, where the industry commits to the LED program (and its financial losses in the early years), and the government commits to an LED or laser based breakthrough attempt of comparable magnitude.

There are benefits for both sides that justify this risk exposure. We create a new segment of the lighting industry that is LED based. The value of this segment is substantially enhanced by the government's funding of the breakthrough attempt. If the attempt is successful, the industry's return off-sets the losses in the early years and the taxpayer obtains a substantial reduction in electricity bills, year after year for a long time to come.

E Intellectual Property

Intellectual property and how to deal with it are issues that always arise with technology research and development partnerships. Among the issues that would have to be resolved: Licensing terms for university-generated IP, sharing of national-laboratory-generated IP, ownership and licensing terms for industry-generated IP supported by DOE funds.

Resolving these issues will require some discussions between the parties involved, but we do not believe they are a deal killer. Sematech, the consortium of semiconductor manufacturing equipment suppliers, had to solve a similar problem several years ago. The Department of Commerce's Advanced Technology Program also has a great deal of experience with this. Indeed, we would expect to borrow ideas from other successful government-industry-university partnerships in intermediate time-horizon technologies. These technologies are forward-looking enough that sharing the risk and the rewards is reasonable even for the largest companies, while important enough that the nation cannot afford not to invest.

7 CONCLUSIONS

In summary, we have presented a case for a national research program on semiconductor lighting. Enough progress has been made since the first products in the 1960's to know that this technology is real and that it has the potential to alter significantly the economics of energy usage.

We have also identified an investment gap that, if closed, could revolutionize the development and ultimate application of this technology. We believe this gap represents a unique opportunity to engage our nation's best scientists and engineers in a university/national lab/industry research program whose success would truly change the way we live.

Appendix A: Examples of Power Signaling and Low-Flux White Lighting Applications

In this Appendix, we describe some examples of specialty lighting applications for which LEDs, with current and projected performance and cost, can compete effectively with incandescent solutions. Note that, as with any relatively immature technology, in the early years LED solutions will be more expensive than incandescent solutions. To justify their selection, the higher initial cost has to be compensated by a combination of benefits such as energy savings over the product life, switching speed, ruggedness, operating life, etc.

Monochrome Applications

Traffic Lights: A 12 inch traffic light in the US usually uses a 135*W* long-life light bulb in combination with a red, yellow or green filter. The most advanced red LED solution uses 12-18 lamps per traffic light and consumes a total of 14*W* including power-supply losses. A single LED traffic light sells for $110 compared with a $30 cost of an incandescent solution. The operating cost for electricity is approximately $10 per year for the LED compared with $90 for the incandescent model. The long operating life of the LED further reduces maintenance and emergency repair costs. The payback period for the higher LED investment is significantly less than one year. There are 10M red/yellow/green traffic lights in the USA consuming approximately 400*MW* of power. Red lights are lit on an average 65% of the time, 90% in the case of red arrows. Just converting all red lights to LEDs would reduce the US electricity consumption by approximately 250*MW*.

Safety/Emergency Lights: All large buildings with public access must have lighted emergency signs assisting the evacuation during a power failure. These "Exit" signs are designed with two incandescent or compact fluorescent lamps consuming 15-30*W*. A solution using approximately 100 cheap LEDs is comparable in cost to the conventional solution but uses only 5*W*. An LED solution not only saves $10 to $25 in annual electricity cost per sign, it also reduces the size and cost of the stand-by battery.

Decorative Lighting: For many years the trademark of the Ford Thunderbird was a taillight that covered the entire width of the car. When the car designers lowered the trunk lid all the way to the bumper for easier access, the wide tail light had to go. Slamming the lid when the tail light switched on would have broken the filaments of any incandescent lamp. So, for a few years in the late 80's the T-bird was built without its trade-mark tail light. For the 1992 model year, HP designed an LED based taillight that could survive repeated slamming of the trunk lid at night.

Another decorative lighting application emerged recently. The Australian branch of the McDonald's restaurant chain started to outline the roof lines of its buildings with a chain of red LED's. LED's are significantly more energy efficient than the competing neon technology. Red LED's are already at cost parity with neon and we expect similar cost parity for yellow, green and blue in 2-3 years. There are three major groups of commercial enterprises that are interested in decorative lighting: fast food chains, gas stations and hotels. All three groups wish to be noticed by people driving at night.

Automobile Tail Lights: As mentioned earlier, LEDs started on the tail end of cars shortly after the CHMSL was made a mandatory feature in the USA in 1982. As of 1999, LED's have reached a penetration of 30-40% of those cars equipped with a CHMSL. In the model Year 2000, the first rear combination lights (tail light, brake light and turn indicator) will emerge on high-end models in the US and Europe. Other functions such as side markers and front turn indicators will follow in the early years of the next decade. The reasons for choosing LED's are: shallow design that does not protrude into the trunk, styling freedom, reduced warranty cost, reduced power consumption (smaller alternator), etc. The red tail lights will convert from incandescent to LEDs quite rapidly, while the yellow front beam indicators will start converting in a few years and eventually the white back-up and license plate lights will follow. In total, the average car will contain 1000*lm* of LED flux: 300 red, 300 yellow and 400 white. Operating these LED chips at $100 A/cm^2$ will require about $20 mm^2$ of LED material per car. The conversion of the passenger car market is quite sensitive to the cost differential between LEDs and incandescent solutions. The rapid decline of the cost per unit of flux for LEDs will lead to an LED penetration of > 50% by the end of the decade. The truck and bus market is less cost sensitive and failed tail lights require an immediate repair. As a result, the US truck market made a quick and nearly complete conversion to LEDs several years ago.

Outdoor Displays: Outdoor large video screens and changeable displays for advertising are target applications for LEDs. For instance, a $600 m^2$ video screen uses 3M 5*mm* LEDs. The LEDs are arranged in end-stackable tiles. The LED density is 1 lamp per $2 cm^2$ of board space. The 5*mm* lamp itself has a cross section of $0.2 cm^2$, thus leaving 90% of the space empty. The LED flux is sufficient to fill the $2 cm^2$ space and achieve an average brightness of several hundred nits, good enough for outdoor viewing. As a matter of fact, the LED is the technology of choice for large video screens: it is the technology with the lowest cost of the empty space between the pixels, the cost of a two-sided printed circuit board. This is far cheaper than any glass based display technology! And since the LEDs are directly viewed and unfiltered, the power consumption is far lower than for any other competing display technology.

Low Flux White Light Applications

There are many lighting applications that are served by low power incandescent or halogen lamps. For instance, a 15*W* incandescent bulb generates 120*lm,* while a 50*W* compact halogen lamp generates 600*lm*. In this low-flux range from 100-600*lm* incandescent and halogen lamps are relatively inefficient and the energy savings from LED's can be significant, especially for applications with 12-24 hours of operation per day.

Shelf Lighting: In many retail outlets the merchandise is illuminated by lamps mounted on the underside of shelves. Incandescent and halogen lamps are quite hot and protective surfaces make the lamp fixture quite bulky. Fluorescent lamps require protection against the high operating voltage. LED based solutions are nearly ideal: cold, compact, efficient, dimmable, long operating life, low voltage, etc.

Theater/Stair Lighting: Low power lights are often used to illuminate stair steps in darkened theaters or to illuminate flights of stairs or gangways. The lights can either be mounted into the stair steps or they can be wall mounted. Very often, wall mounted units require a very directional beams wasting a large fraction of the light from an incandescent light bulb. The superior directionality of an LED based design should lead to significant energy savings.

Accent Lights: Accent lights are used in retail shops to highlight merchandise. In the residential market the main application is decorative ceiling lighting or highlighting artwork. The majority of the applications use incandescent or compact halogen lamps. LED based solutions will contribute to energy savings, lower maintenance cost and reduced fire hazards. Since most accent lights require a highly directional beam, LEDs should have a substantial power advantage over incandescent lamps.

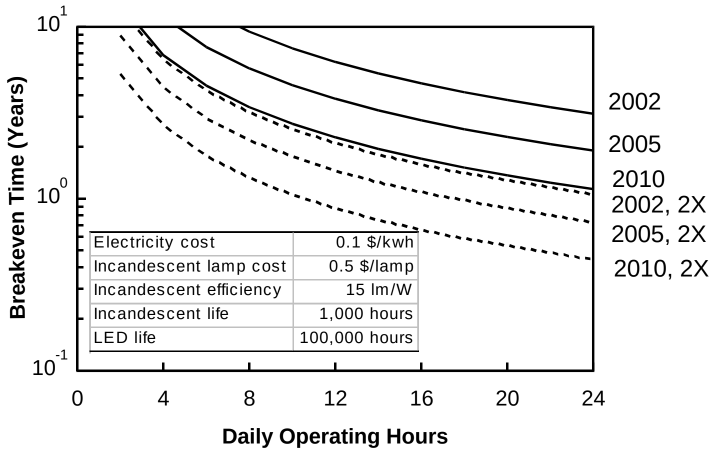
Landscape Path Lights: These lights are used to provide orientation in public places such as parks, gardens, office grounds, etc. Most lights use low voltage, inefficient incandescent lamps and LEDs could make a contribution to energy savings. Also, low voltage operation should reduce installation cost.

Flashlights: Incandescent lamps in flashlights have chronically poor shock resistance. Many flashlights are thrown away when the incandescent filament breaks during a drop. The 40-60*lm* that are needed can easily be provided by an LED source. At $0.05/*lm* the LED adds $2.50 to the cost which is quickly made up by extended battery life.

APPENDIX B: BREAK-EVEN ANALYSIS FOR LED REPLACEMENT OF INCANDESCENT LAMPS

In this Appendix, we give a simple calculation of the breakeven time over which the energy savings due to LED replacement of an incandescent lamp equals the difference in initial lamp costs. The results are shown in Figure B1 for a standard 100*W* incandescent lamp and an LED lamp of equivalent flux. The assumptions we have made for incandescent lamp and LED cost, lifetime and efficiency are listed in Table 1 and in the inset to Figure B1. We do not expect significant improvements over time for the incandescent lamp technology, but do expect significant improvements for LED technology. In particular, we anticipate that the 85°C LED efficiency will start at 30*lm*/*W* in 2002, increase to 40*lm*/*W* in 2005 and level off at 50*lm*/*W* in 2010.

Note that the breakeven time is a strong function of the duty cycle, i.e., the fraction of time the light is on during a day. The longer the average daily burn time, the shorter the interval between incandescent lamp replacement, while with 100,000-hour lifetimes LEDs never need to be replaced on the time scale of this calculation. Therefore, the longer the average daily burn time, the higher the relative cost of the incandescent lamp solution, and the shorter the breakeven time. If the LED lamp has a useful service life significantly exceeding the breakeven time, then the additional energy savings are a bonus.



Electricity cost	0.1 $/kwh
Incandescent lamp cost	0.5 $/lamp
Incandescent efficiency	15 lm/W
Incandescent life	1,000 hours
LED life	100,000 hours

Figure B1. Breakeven time for LED lamps as a function of daily operating hours, for the projected efficiencies in the Years 2002, 2005 and 1010. The solid upper curves are based on LED fluxes equal to incandescent lamp fluxes. The dashed lower curves represent applications where the LED solution substantially reduces light spillage and thus requires only 50% of the flux of an incandescent lamp.

The solid lines refer to LED lamps with the indicated projected efficiencies for the Years 2002, 2005 and 2010. For instance, in 2002, for a lamp with an average operating time of 12 hours, a retail price of 100$/*klm* and an efficiency of 30*lm*/*W*, the breakeven time is 6.1 years. This is a marginal payback situation and penetration would be quite limited. Moreover, although such long average daily operating times are not that uncommon in industrial or commercial applications, they are rare in residential applications.[14] By 2010, however, improvements in efficiency and reductions in cost should reduce the daily operating time for a 5-year breakeven time to 5 hours. Now LED lamps make economic sense in many residential applications.

In addition, in many applications conventional lamps waste a significant fraction of the light. Inexpensive luminaires trap light or send it into unwanted directions ("light pollution"). 50% waste or losses are quite common. LED lamps are far superior in this respect and our studies have shown that a 750*lm* LED lamp can substitute for a 1500*lm* incandescent lamp in many applications. Since the initial LED cost is proportional to the flux rating of the lamp, this effect cuts the purchase cost and the energy consumption in half.

[14] It should be noted that this analysis does not include any maintenance labor to exchange the burnt-out incandescent lamps. The break-even picture improves in favor of the LED when maintenance labor costs are significant.

With these assumptions, the breakeven time is substantially reduced, as shown in the dashed lines of Figure B1. For a daily operation of 8 hours the breakeven time is less than 3 years in 2002 and less than eighteen months in 2010. Now the cost of an LED lamp is practically equivalent to the electricity cost during the life of 3-4 incandescent lamps. This argument should be compelling to budget-conscious households.

Appendix C: Economic Model of LED Penetration into White Lighting

In this Appendix, we describe a simple economic model for the impact of LED penetration into specialty and general lighting markets. The model depends on a number of assumptions, some of which characterize lighting and electricity usage generally, and others of which characterize LED cost, performance and market penetration.

The assumptions that characterize lighting and electricity usage generally are listed in Table C1. According to DOE report DOE/EIA-0219(93), global electricity consumption in 1993 was 10,800*TWh*. With an estimated growth rate of 2% per year, the consumption in the Year 2000 will grow to 12,400*TWh*. Assuming that 20% is used for lighting and dividing by the number of hours per year, we compute an electricity consumption of 280*GW*. Further assuming that some of the energy is used to remove the lighting related heat, and in ballasts and drive electronics, we estimate that 200*GW* are used in the light generating process itself.

To estimate the amount of light that is actually generated, we must estimate the efficiency of the average light source. The spectrum of lamp efficiencies ranges from a few *lm/W* for low end incandescent lamps to 120*lm/W* for low pressure sodium lamps. The bulk is fluorescent at 80*lm/W* and incandescent/halogen at 15*lm/W*. Mercury lamps at 50*lm/W* are in between. If we assume that 50*lm/W* is the average efficiency for all lamp types, then the 200*GW* of electricity generates 10*Tlm* of flux at every instant in the Year 2000. Not every lamp is lit at any moment. We estimate an average lamp use of 30%. Then the installed lamp capacity is 10*Tlm*/30% = 33*Tlm*. For subsequent years, we assume a 2% growth rate.

Global electricity consumption in 2000:	10,000 TW-hours	Average lamp efficiency	50 lm/W
Growth rate:	2 %/year	Average light flux from lamps	10 Tlm
Electricity for lighting:	2,000 TW-hours	Average lamp duty cycle	30%
Cost of electricity per unit:	0.1 $/kW-hour	Installed flux capacity	33 Tlm
Cost of electricity for lighting:	200 G$/year	Growth rate of light flux	2 %/year
		Lamp mark-up in retail channel from OEM price	100%

Table C1. Assumptions on lighting and electricity usage used in the economic models shown in Tables C2 and C3.

The assumptions that characterize LED cost, performance and market penetration are entered directly into the spread-sheets shown in Tables C2 and C3. In terms of cost, we assume the retail price of LED lamps will start at 100$/*klm* in 2002 and decrease 10% per year between 2002 and 2015, reaching $75/*klm* in 2005 and less than $50/*klm* in 2010. Then, beyond 2015, we assume that it will drop 5%/year.

In terms of performance, we use two different sets of assumptions for the spreadsheets in Tables C2 and C3. For Table C2, we assume that LED efficiency saturates at 50*lm/W* in 2010, limiting penetration to specialty lighting applications dominated by incandescent lamps. For Table C3, we assume that LED efficiency continues to improve to 200*lm/W*, enabling penetration of general lighting applications dominated by fluorescent lamps.

LED penetration into incandescent white lighting market (low-investment model)

Let us start first with Table C2, which assumes an LED efficiency saturating at 50*lm/W*. Based on the break-even analysis of Section 3, we concluded that LEDs start to make economic sense in the Year 2002. The break-even point over 5 years is at a daily operation of 16 hours, even without considering maintenance cost or reduced light losses/spillage in LED lamps relative to incandescent lamps. So, we set the 2002 LED penetration flux as a percentage of the total flux at an arbitrarily low level of 0.001%. By 2005, both LED performance improves and costs are reduced. By 2010, LEDs can compete effectively against halogen lamps and the penetration reaches 0.5%. Over the next decade, the penetration keeps increasing and levels off in 2021 at 10%. This is not very scientific, but we have to make some assumptions.

Semiconductor Lighting: Low Investment Model

Assumptions:	Cost/kWh ($)	**0.1**	Price Decline/Year	**10%**	**Investment 2000-2010**		File:roland\ssl1b.xls
	Avge. Duty Cycle	**30%**	Hours/Year	8760	**Industry**	**1000M$**	
	SSL Lamp Life (Y)	**10**	Retail Mark-up	**100%**	**DOE**		

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Act. Flux Usage	TLm	**10.0**	**10.2**	**10.4**	**10.6**	**10.8**	**11.0**	**11.2**	**11.4**	**11.6**	**11.8**	**12.0**	**12.2**	**12.4**
Installed Capacity	TLm	33	34	35	35	36	37	37	38	39	39	40	41	41
SSL Penetration	%			**0.001**	**0.01**	**0.02**	**0.03**	**0.05**	**0.10**	**0.15**	**0.30**	**0.50**	**1.00**	**1.50**
SSL Installed Capacity	TLm			0.0003	0.004	0.01	0.01	0.02	0.04	0.06	0.12	0.20	0.41	0.62
Ann.Conversion Rate	TLm			0.0003	0.003	0.00	0.00	0.01	0.02	0.02	0.06	0.08	0.21	0.21
Ann.Replacem't Rate	TLm													
Ann. Convers. + Replacem't	TLm			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2
Retail Price	$/kLm			**100**	91	83	75	68	62	56	51	47	42	39
Retail Value	G$			0.0	0.3	0.3	0.3	0.5	1.2	1.1	3.1	3.8	8.8	8.2
OEM Value White	G$			0.0	0.1	0.2	0.1	0.3	0.6	0.6	1.5	1.9	4.4	4.1
Efficiency Old Lamp	Lm/W	**12**	**12**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**18**	**18**	**18**	**18**
Efficiency SSL Lamp	Lm/W	**20**	**25**	**30**	**32**	**35**	**38**	**40**	**41**	**42**	**43**	**44**	**45**	**45**
Energy Saving New Inst.	G$			0.00	0.04	0.04	0.04	0.08	0.17	0.17	0.51	0.71	1.81	1.87
Energy Sav. Prev. Inst.	G$				0.00	0.04	0.08	0.12	0.20	0.37	0.54	1.05	1.76	3.57
Total Energy Savings	G$			0.00	0.04	0.08	0.12	0.20	0.37	0.54	1.05	1.76	3.57	5.44

		2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Act. Flux Usage	TLm	**12.6**	**12.8**	**13.0**	**13.2**	**13.4**	**13.6**	**13.8**	**14.0**	**14.2**	**14.4**	**14.6**	**14.8**	**15**
Installed Capacity	TLm	42	43	43	44	45	45	46	47	47	48	49	49	50
SSL Penetration	%	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**10**	**10**	**10**	**10**
SSL Installed Capacity	TLm	0.84	1.28	1.73	2.20	2.68	3.17	3.68	4.20	4.73	4.80	4.87	4.93	5.00
Ann.Conversion Rate	TLm	0.22	0.44	0.45	0.47	0.48	0.49	0.51	0.52	0.53	0.07	0.07	0.07	0.07
Ann.Replacem't Rate	TLm		0.00	0.00	0.01	0.02	0.02	0.06	0.08	0.21	0.21	0.22	0.44	0.45
Ann. Convers. + Replacem't	TLm	0.2	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.7	0.3	0.3	0.5	0.5
Retail Price	$/kLm	35	32	29	28	26	25	24	23	22	21	20	19	18
Retail Value	G$	7.7	14.1	13.2	13.1	13.1	12.8	13.5	13.7	16.0	5.8	5.6	9.5	9.2
OEM Value White	G$	3.9	7.1	6.6	6.5	6.6	6.4	6.8	6.8	8.0	2.9	2.8	4.7	4.6
Efficiency Old Lamp	Lm/W	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
Efficiency SSL Lamp	Lm/W	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**	**45**
Energy Saving New Inst.	G$	1.93	3.85	3.97	4.09	4.20	4.32	4.44	4.56	4.67	0.58	0.58	0.58	0.58
Energy Sav. Prev. Inst.	G$	5.44	7.36	11.22	15.19	19.28	23.48	27.80	32.24	36.80	41.47	42.05	42.64	43.22
Total Energy Savings	G$	7.36	11.22	15.19	19.28	23.48	27.80	32.24	36.80	41.47	42.05	42.64	43.22	43.81

Table C2. Economic model of LED penetration into global power signaling and incandescent white lighting markets, assuming best production LED efficiencies at 85°C of 30lm/W in 2002 and 50lm/W in 2010.

With these assumptions on LED performance and penetration, we can proceed to calculate the energy savings associated with increased efficiencies of LEDs as compared to incandescent lamps. These savings depend, of course, on the difference between the efficiencies of the lamp replaced and the new LED lamp, and so we must make some assumptions on the efficiency of the lamp being replaced. We assume that these lamps are at first low/medium flux incandescent lamps, with efficiencies of 12*lm/W* in 2002. With time this average will shift up to 18*lm/W* as more efficient and lower cost LEDs start to replace halogen lamps. Since for Table C2, LEDs will not replace fluorescent lamps the replaced lamp average will level off at 18*lm/W*.

Let us discuss the key assumption of 10% penetration around 2020. With an average LED efficiency of around 45*lm/W* from 2010-2020, LEDs will be more efficient than incandescent and halogen lamps by 3x and 2x, respectively, so there will be a strong incentive for replacement. An upper bound on the penetration would then be the percentage of lighting that is either incandescent or halogen -- approximately 20-30%. That upper bound could be approached if LED lamp costs could be reduced even further than the 20-25$/*klm* assumed in this analysis, and if the industry can design a family of LED lamps that can be screwed into existing incandescent sockets. However, if LED lamps require new light fixtures then the conversion could be significantly slower. So, we believe our 10% penetration assumption to be reasonable, neither overly optimistic nor overly pessimistic.

Another cross-check of the model is a comparison of LED industry revenue with energy savings. Since to the consumer the trade-off is the price of the lamp versus the cost of operating the lamp, these two should at first be roughly comparable. The line labeled "OEM Value White" represents the revenue of the LED lamp industry -- it reaches $100M in 2005, $1,900M in 2010, and $6,800M in 2020. The line labeled "Total Energy Savings" represents the energy savings associated with the accumulated conversions of less-efficient incandescent lamps with more-efficient LED lamps. In 2005, LED lamp revenue and energy savings are balanced and in the range of $100M. There is a similar balance in 2010 at $1.8-1.9G. In the 2010-2015 period, the pace of installations is picking up to a lamp revenue level of $7G, but savings from the installed base exceed $15G. By 2020, conversion is saturating, but energy savings have reached $37G/year and continue at this level indefinitely.

We have chosen the scenario of Table C2 because we believe that the industry is likely to make these investments, especially if governments provide some financial or tax incentives. Another argument is based on the magnitude of the market that is created by this new lighting technology. Table C2 in Appendix C shows a $6-8B market from 2014 to 2021 compared with today's total light bulb market of around $20B. And the biggest incentive for the industry to make these investments over the next 5-7 years is the opportunity that it creates: Go for a real breakthrough in semiconductor lighting efficiency and revolutionize the entire lighting industry!

LED penetration into incandescent and fluorescent white lighting market (high investment model)

Let us now discuss Table C3, which assumes a semiconductor lamp efficiency that continues to increase beyond 50*lm/W*, to the 200*lm/W* level. In other words, we assume here that there will be a research breakthrough that will keep the efficiency of semiconductor light sources rising after 2010 to a top performance of 200*lm/W* by 2015. There is also a corresponding rise in the performance of the replaced lamps by attacking compact fluorescent and, eventually, regular fluorescent, lamps.

The results of these assumptions are shown in the spreadsheet of Table C3. The semiconductor penetration rate by 2025 is somewhat speculative. If the SSL technology is really superior (2x against fluorescent and 10x against incandescent/halogen), then we should have a lighting revolution at hand. The rate of penetration, however, depends on a number of factors that are difficult to predict today. Can we build a cost-effective lamp that screws into an incandescent lamp socket? Such a lamp could result in a rapid penetration. But, it is unlikely that semiconductor lamps would go into the sockets of fluorescent tubes. For this market segment, the conversion would be slow. On the other hand, building code changes for new construction or remodeling could have an accelerating effect.

Also note that the caveats of Table C2 regarding our assumptions apply here in spades. A significant breakthrough in efficiency is anything but certain. A 50% penetration between 2015 and 2025 against the well entrenched and fairly efficient fluorescent technology is also quite uncertain. But if the industry can deliver the efficiency, then the energy savings are huge and real and conservation arguments will amplify the economic arguments. A 40% reduction of electricity used in lighting translates into an 8% reduction of total electricity consumption. Such large savings in the second largest energy sector will be difficult to find elsewhere, especially at the fairly modest level of the proposed government incentives.

Semiconductor Lighting: High Investment Model

Assumptions:							
	Cost/kWh ($)	**0.1**	Price Decline/Year	**10%**	**Investment 2000-2010**		File:roland\ssl1a.xls
	Avge. Duty Cycle	**30%**	Hours/Year	8760	**Industry**	**1000M$**	
	SSL Lamp Life (Y)	**10**	Retail Mark-up	**100%**	**DOE**	**500 M$**	

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Act. Flux Usage	TLm	**10.0**	**10.2**	**10.4**	**10.6**	**10.8**	**11.0**	**11.2**	**11.4**	**11.6**	**11.8**	**12.0**	**12.2**	**12.4**
Installed Capacity	TLm	33	34	35	35	36	37	37	38	39	39	40	41	41
SSL Penetration	%			**0.001**	**0.01**	**0.02**	**0.05**	**0.10**	**0.20**	**0.50**	**1.00**	**2.00**	**4**	**6**
SSL Installed Capacity	TLm			0.0003	0.004	0.01	0.02	0.04	0.08	0.19	0.39	0.80	1.63	2.48
Ann.Conversion Rate	TLm			0.0003	0.003	0.00	0.01	0.02	0.04	0.12	0.20	0.41	0.83	0.85
Ann.Replacem't Rate	TLm													
Ann. Convers. + Replacem't	TLm			0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.4	0.8	0.9
Retail Price	$/kLm			**100**	91	83	75	68	62	56	51	47	42	39
Retail Value	G$			0.0	0.3	0.3	0.8	1.3	2.4	6.6	10.3	19.0	35.1	32.9
OEM Value White	G$			0.0	0.1	0.2	0.4	0.6	1.2	3.3	5.1	9.5	17.5	16.4
Efficiency Old Lamp	Lm/W	**12**	**12**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**22**	**24**
Efficiency SSL Lamp	Lm/W	**20**	**25**	**30**	**33**	**36**	**40**	**42**	**44**	**46**	**48**	**50**	**55**	**60**
Energy Saving New Inst.	G$			0.00	0.04	0.04	0.12	0.19	0.37	1.04	1.67	3.21	5.92	5.61
Energy Sav. Prev. Inst.	G$				0.00	0.04	0.09	0.21	0.40	0.77	1.81	3.48	6.69	12.61
Total Energy Savings	G$			0.00	0.04	0.09	0.21	0.40	0.77	1.81	3.48	6.69	12.61	18.22

		2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Act. Flux Usage	TLm	**12.6**	**12.8**	**13.0**	**13.2**	**13.4**	**13.6**	**13.8**	**14.0**	**14.2**	**14.4**	**14.6**	**14.8**	**15**
Installed Capacity	TLm	42	43	43	44	45	45	46	47	47	48	49	49	50
SSL Penetration	%	**8**	**10**	**12**	**15**	**18**	**22**	**26**	**30**	**35**	**40**	**45**	**50**	**55**
SSL Installed Capacity	TLm	3.36	4.27	5.20	6.60	8.04	9.97	11.96	14.00	16.57	19.20	21.90	24.67	27.50
Ann.Conversion Rate	TLm	0.88	0.91	0.93	1.40	1.44	1.93	1.99	2.04	2.57	2.63	2.70	2.77	2.83
Ann.Replacem't Rate	TLm		0.00	0.01	0.02	0.04	0.12	0.20	0.41	0.83	0.85	0.88	0.91	0.93
Ann. Convers. + Replacem't	TLm	0.9	0.9	0.9	1.4	1.5	2.1	2.2	2.4	3.4	3.5	3.6	3.7	3.8
Retail Price	$/kLm	35	32	29	28	26	25	24	23	22	21	20	19	18
Retail Value	G$	30.8	29.0	27.4	39.1	38.8	51.3	52.1	55.5	73.3	71.8	70.2	68.6	67.0
OEM Value White	G$	15.4	14.5	13.7	19.6	19.4	25.7	26.1	27.8	36.7	35.9	35.1	34.3	33.5
Efficiency Old Lamp	Lm/W	**26**	**28**	**30**	**32**	**34**	**36**	**38**	**40**	**45**	**50**	**55**	**60**	**65**
Efficiency SSL Lamp	Lm/W	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**	**110**	**120**	**130**	**140**	**150**
Energy Saving New Inst.	G$	5.34	5.11	4.91	6.90	6.68	8.47	8.24	8.04	8.86	8.07	7.44	6.92	6.49
Energy Sav. Prev. Inst.	G$	18.22	23.56	28.66	33.57	40.47	47.14	55.61	63.86	71.90	80.75	88.83	96.27	103.20
Total Energy Savings	G$	23.56	28.66	33.57	40.47	47.14	55.61	63.86	71.90	80.75	88.83	96.27	103.20	109.69

Table C3. Economic model of semiconductor light source penetration into power signaling and incandescent/fluorescent white lighting markets, assuming substantially improved best production efficiencies of 150-200lm/W in 2015.