Solid-state lighting

Why it will succeed, and why it won't be overtaken

Solid-state lighting is on the verge of replacing every lamp on earth, from the smallest signal lamp to the largest stadium-scale flood lamp. We review the path that solid-state lighting has taken: from its early years; to the pivotal period around 1999 when it began to be taken seriously; to the challenges it faced as it made continued progress; to the present when its success over traditional lighting is practically certain; and finally to the future in which it may face competition from other technologies.

1968–1995: The early years

Since their introduction as commercial products by Hewlett-Packard (HP) and Monsanto in 1968, light emitting diodes (LEDs) have made steady progress. For the first few years, their color was limited to red, the material was GaAsP/GaAs, and the light output was in the 1–5 mlm range, barely visible in the office or laboratory environment but sufficient for indicators and alpha-numeric displays. Over the next twenty years, conversion efficacy from electrical current to visible light flux improved by more than 10× per decade, eventually enabling outdoor applications, even in direct sunlight. At the same time, through use of second-generation GaAsP/GaP:N materials, the color range expanded from 650 nm deep red to 635 nm red to 590 nm yellow and 570 nm yellow-green. Also during this period, third-generation GaAlAs materials enabled 120 ml of luminous flux in the red at a drive current of 20 mA.

In the late 1980's, the first LED applications requiring luminous fluxes well in excess of 1 lm emerged: center high mount stoplight (CHMSL) for cars. The first 1986 design by Stanley for the Nissan 300Z sports car used 76 conventional 5 mm lamps. HP, the leading LED company since the start of the technology in 1968, chose another route borrowed from power transistor technology: increase chip size and drive current and use a lamp package designed for higher power dissipation. This first generation power LED used the HP code name Piranha, and had drive currents first of 50 mA, then 70 mA and eventually 150 mA. In 1989, the 1-lm-per-LED-package threshold was approached for the first time in a commercially available product.

In 1992, two new materials changed the course of LED evolution. The introduction of GaAlInP by HP and Toshiba enabled significant efficacy increases to ~40 lm/A (3 lm at 70 mA) in the orange-red and yellow. In the blue Nichia's GaInN enabled conversion efficiencies of around 5 % – an improvement of at least an order of magnitude.

By 1995, Nichia was using efficient GaInN blue LED chips in conjunction with a broad-spectrum yellow phosphor to generate white light. By today's standards, the white light was quite primitive, with low fluxes (< 100 mlm), a low color rendering index (CRI ~60), a bluish tint, and significant color variations within the angular spread of the light beam and across lamps within a production lot. Nevertheless, it provided a convincing feasibility proof for a semiconductor-based source of white light!

1999: SSL gets serious

By 1999, the output of the second generation of HP power LED products had reached 20 lm in the red and 40 lm in the yellow. Even more important: the wall-plug conversion efficiency for red LEDs had reached 53 % [1]; the quantum efficiency of blue LEDs had reached ~12 % at useful ~30 A/cm2 current densities; and wall-plug efficiencies of LED-like vertical-cavity surface emitting lasers in the infrared had reached > 50 % [2]. Progress was such that the possibility that LED-based white lighting (or solid-state lighting, SSL) might someday compete favorably with traditional white lighting for general illumination began to be taken seriously, along with the possibility of massive savings in the energy consumption for lighting.

In the U.S., a white paper [3] was written which led to a comprehensive tech-

THE AUTHORS

ROLAND HAITZ

Roland Haitz is retired from Agilent / Hewlett-Packard where he led the development of optoelectronic components from 1969–2002. He was co-founder of OIDA (Optoelectronic Industry Development Association) in 1991; and in the mid 1990s was instrumental in forming Lumileds, initially a joint venture between HP and Philips Lighting and now wholly-owned by Philips. He is currently a consultant to the SSL industry.

Roland Haitz
Phone: +1 650 851 7036
E-mail: rhhaitz@aol.com

JEFFREY Y. TSAO

Jeff Tsao is a Distinguished Member of Technical Staff at Sandia National Laboratories, where he studies the integrated science, technology and economics of energy technologies. Jeff has co-authored over 150 publications, is author of the monograph "Materials Fundamentals of Molecular Beam Epitaxy," and is fellow of the APS and the AAAS.

Jeffrey Y. Tsao
Phone: +1 505 844 7092
E-mail: jytsao@sandia.gov
Website: www.sandia.gov/~jytsao

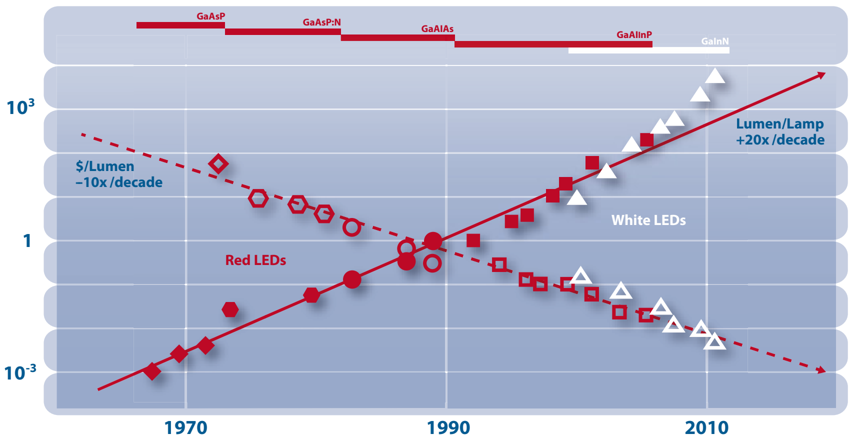

FIG. 1: **This Haitz' Law figure, adapted from Ref. 5, shows the development of highest flux and lowest cost per lumen for red or cool white LEDs commercially available. The two trend lines are based on red data only, different red symbols correspond to the different materials indicated at the top.**

nology roadmap [4] sponsored by the Optoelectronics Industry Development Association and the U.S. Department of Energy. The Japan Research and Development Center of Metals organized a project called "Light for the 21st Century", aimed at developing efficient LED-based lighting. Also in other nations, particularly Taiwan, South Korea and China, significant efforts were initiated.

In arguing for the plausibility of SSL, the white paper constructed a graph showing a 30-year history of red LED technology. An updated version of this graph from a recent retrospective [5] is shown in Figure 1. The graph showed a 20x/decade improvement in the flux of the brightest red LED commercially available, and a 10x/decade decrease in cost per unit of red flux. Because the luminous efficacy of radiation of red is roughly the average of that of green and blue, it was argued that these trends for red LED technology should be a good predictor for white LED technology.

Despite this overall plausibility, however, it was not clear which of the approaches would enable SSL to overtake traditional lighting: the blue-LED-pumped conversion approach; or color mixing in which light from three LEDs, or, even better, four to six LEDs spanning the spectrum from red to blue, are mixed to form white.

In 1999, color-mixing had several perceived advantages:

- No energy loss due to phosphor conversion from the blue to lower-energetic parts of the spectrum.
- Ability to independently vary the drive currents, and hence to tune the chromaticity within the color gamut encompassed by the colored LEDs.

However, perceived disadvantages were:

- The mismatch between the temperature dependences of the efficiencies of the red and yellow GaAlInP material (which drops by 2× between room temperature and 75 °C) and of the green and blue GaInN material (which can be operated at temperatures of 125 °C and above). A lamp made from a combination of these materials would have an unacceptable variation of color with ambient temperature, unless compensated by feedback loops and current drivers for each color.
- The 4–6 loops and drivers would add significantly to the lamp cost.
- The best feedback loops would have to be based on light sensed in the far-field, adding wiring and control-loop cost to the installation.
- The efficiency of green LEDs was inferior to that of red, yellow and blue LEDs.

Considering the above advantages and disadvantages, we thought color mixing would prevail for the following reasons:

- Digital color tuning, larger energy savings and dimming would be desirable.
- Cost of feedback loops would be negligible in the age of ubiquitous silicon.
- The green gap in conversion efficiency would be closed in the next decade.

As discussed in the next section, our forecast was proven wrong, at least as of 2011.

1999–2011: Challenges to Overcome

The most significant questions in 1999 were: Could SSL indeed win against the entrenched lighting technologies? If it did, through which approach would it win?

In the original white paper, five necessary conditions were identified that had to be met to succeed: (a) performance, (b) quality of light, (c) lifetime system cost, (d) availability of investment capital, and (e) constraints on the ability of the existing industry to react. Meeting all five hurdles with clear margins would amount to victory. Missing even one would limit success substantially.

(a) Performance

SSL has to deliver the needed flux for practically all lighting applications at a superior conversion efficiency.

By 1999, yellow LEDs had reached 40 lm/package and were a factor of 25× away from the lighting goal of 1 klm (the amount of light emitted by a 75 W incandescent light bulb). Considering the slope of Haitz' Law, the flux target was one decade away. Given reasonable progress in green LEDs, we expected to reach 50 lm/W by 2010 with the color mixing approach. Further improvements to 150 lm/W were plausible considering the then-recent results [1] on red LEDs. With a 50 lm/W performance for white, SSL could attack the low hanging fruits of incandescent and halogen lamps. But to successfully attack the rest of conventional lighting would require 150 lm/W.

(b) Quality of light

By quality, we mean that SSL has to meet the lighting quality standards set by the entrenched technologies over the last 130 years. They include color rendering, color control, color stability over time and temperature, operating life, flux stability, etc.

In 1999 the quality of white lamps based on a blue LED pump with phosphor conversion was marginal. Early products were called white but scored poorly against any of the light quality specifications used for conventional lamps. Manufacturing yield to a reasonable set of flux and quality specifications was quite marginal.

Our hope to compete in the general lighting market was the color mixing approach. With this, we expected SSL to meet most of the expectations. There were early products using digital color tuning, but these low volume and high-priced products served niche markets and could not meet the expected standards. Nevertheless, we had hopes this could be coerced to succeed.

(c) Lifetime System Cost

By cost, we mean lifetime lighting system ownership cost. This cost includes initial fixture cost and installation, initial lamp cost, cost of replacement lamps, maintenance cost and, most importantly, energy cost.

The easy targets were incandescent and halogen lamps with their low luminous efficacies of around 15 lm/W. At an electricity cost of $ 0.15/kWh, operating a 60 W light bulb for 1000 h (before it burns out) costs $ 10/Mlmh. With an SSL lamp lasting 50 kh, replacement and maintenance practically disappear. Most importantly, assuming an SSL efficacy of 50 lm/W, the 50kh energy cost is reduced from $ 500 to $ 167.

The much more difficult targets were fluorescent and high-intensity-discharge lamps with their higher efficacy and longer operating life. We expected a clear win in the incandescent/halogen market but only a potential win in the rest of the lighting market based on a possible improvement in luminous efficacy to > 150 lm/W.

(d) Availability of Investment Capital

Any company participating in revolutionizing an existing industry must have access to a sufficient amount of capital.

This issue is determined by two factors: cash flow from within the nascent SSL industry and outside investment capital. The self-financing component requires profitable revenue growth. But usual net profit rates of around 5 % of revenue are insufficient to finance the working capital requirements of an exploding market growing at 15–25 %/year. As a rule of thumb, every revenue growth of $ 100 requires new working capital of $ 50–100. The lower end of capital requirements applies to LED packaging companies while the upper end approximates the capital needs of integrated chip/package manufacturers. The external capital infusion could either come from slow growing non-SSL product lines within the same company or from outside investors. For small start-up SSL companies, investor financing is critical.

(e) Constraints on the Ability of the Existing Industry to React

Fortunately for SSL, the conventional lighting industry was unable to make major improvements in the most critical factor: conversion efficacy. These limitations, based on the laws of physics, are quite fundamental.

Incandescent light bulbs are limited because, as black body radiators at a temperature of 2800 K, they radiate only 5 % of their energy in the visible range of the spectrum. The remaining 95 % of its energy consists of infrared radiation not visible to the human eye and some thermal conduction via support leads and the filling gas. Increasing the temperature of the filament would change that ratio but would also shorten the life of the lamp. The technology has stagnated around this 5 % compromise for most of its 130-year history!

Fluorescent light bulbs have a similarly fundamental limitation. One of the most efficient processes to convert electricity into radiation is an electrical discharge in a mercury atmosphere. Decades of improvements have leveled out at a conversion efficiency around 68 % for UV radiation of 254 nm. This energetic radiation has to be converted in a phosphor material to the visible range of 440–670 nm thereby turning ~60 % of its energy into heat due to the Stokes loss. The resulting electricity-to-light conversion then ends up around 28 % for the most efficient geometrical structure, a 4 ft long cylindrical tube.

The 130-year-old conventional lighting industry with a market of around $ 14B in 1999 could easily suppress a nascent power LED industry with less than 3 % of this revenue in a small, non-lighting related subsegment of the market. But the lack of an ability to defend its Achilles heel, energy conversion efficiency, would ultimately be the decisive issue.

Summarizing the situation around 1999, SSL had a good starting position to win a substantial fraction of the general lighting market. SSL had already won the battle for all monochromatic applications and was on its way to wrap up practically every low-performance and low-quality white application such as flash lights, camera flashes, small screen backlights, etc. Substantial hurdles remained for domination of the general lighting market. Performance, quality of light, life time cost and access to capital remained significant question marks.

2011: SSL becomes a certainty

Instead if our favored approach to white light, the market preferred a blue pump phosphor conversion for reasons of simplicity. Significant improvements in blue pump LEDs and conversion phosphors provided a solution that was good enough to meet the first three of the five criteria (performance, quality and cost) outlined above:

a) an efficacy of ~100 lm/W and flux/package well in excess of 1 klm
b) a CRI > 80, color temperatures down to 2800 K, good color and flux stability up to 50 kh, and
c) a cost of $ 5/klm of flux for the highest-volume moderate-power basic lamp element without socket, voltage converter or secondary optics.

By 2011, SSL had met or exceeded all of our 1999 expectations. There is virtually no doubt that further improvements in the manufacturing processes during the next five years will solidify the superiority of SSL. The data in Figure 1, now including information beyond that known in 1999, confirm this prediction. At first, the white triangles, representing white LEDs, lagged the red flux and cost performance by a factor of two. But the flux and cost data crossed the respective trend lines in 2002 and 2007. Flux increases were driven by efficacy improvements and by increases in input power per chip. While efficacy improvements have been slowing down, the increase in input power has accelerated by increasing chip size and by borrowing from the packaging technology of power transistors. Today, several manufacturers are offering products in the range of 5–10 klm, exceeding the flux levels needed for most residential lighting applications.

Regarding the fourth necessary criterion, (d) availability of investment capital, ended up not being a significant problem.

In 1999, SSL was only a dream, and the 30-year old LED industry with global revenues of around $ 2B was small compared to the conventional light bulb industry. For the LED industry to partially succeed in the lighting market, we estimated investment needs for R&D, equipment, working capital and distribution channels, etc, of several billion dollars. To revolutionize the entire industry, we expected to need 5–10× more.

As one important contribution to the needed investment capital, we proposed a US-based 10-year research program in SSL technologies at a level of $ 50M/year. By 2001, the Senate had sponsored a proposal for a Next Generation Lighting Initiative. In 2003, this initiative was approved at the requested level of $ 500M over 10 years.

A second and at least equally important contribution to the investment capital came from non-government private sources. Some significant factors were:

- Rapid growth in non-lighting power LED applications such as traffic lights, automotive exterior signaling, camera flashlights, outdoor displays;
- Emerging low-end lighting applications such as flashlights, landmark and architectural lighting, stair markers, landscape and path lighting and, most recently, backlights for flat panel liquid-crystal displays and televisions;
- Increasing international interest in energy savings and reduced carbon emission, along with government incentives to invest in “green” technologies; and
- The emerging recognition that this disruptive technology might revolutionize the lighting industry and provide opportunities for market entry and growth.

This combination of reasons built up investor confidence and money flowed in spite of two recessions.

Finally, a comment on the fifth necessary criterion, (e) constraints on the ability of the existing industry to react. There was no meaningful efficacy improvement in the conventional lighting sources and incandescent light bulbs are now classified as eco-unfriendly. The three leading manufacturers (Philips, Osram and GE) have chosen to embrace the new SSL technology.

2011 and beyond: Will there be a post-SSL lighting technology?

Humanity graduated from the campfire to the torch for reasons of mobility, to the candle and oil lamp for convenience, to the gas light for better color rendering and higher flux, to the incandescent electric light again for convenience and to halogen, fluorescent, sodium, mercury and metal halide lamps mainly for reasons of electricity cost, lamp life and sufficient flux. SSL meets all the needs listed above and, important for today's economic and environmental concerns, meets most of the requirements significantly better. Moreover, SSL still has headroom for continued improvement.

First, even if one remains within the conversion approach, with its Stokes loss of around 25 %, we could approach an efficacy limit of 300 lm/W if we could create a blue pump with a near-100 % power conversion efficiency. Indeed, a blue pump with an 81.3 % power conversion efficiency was recently demonstrated [6], implying a potential efficacy of 245 lm/W for white light with good color rendering quality.

Second, there is still the possibility for a color-mixed approach. If LEDs at four colors could be developed with such power conversions, luminous efficacy for white light could be as high as 325 lm/W.

Third, because of the easy compatibility of SSL with digital control, there is room for improvement beyond just the production of light by a lamp. "Smart solid-state lighting" promises significant improvements in the efficiency with which light is used.

Fourth, a variant of SSL, organic LEDs or OLEDs, may occupy a segment of the lighting market for large-area sources.

Considering the complexities of converting electricity to electromagnetic radiation at any wavelength and the additional complexity of matching this radiation to the spectral sensitivity of the human eye, it is remarkable that any technology could approach the 50–80 % conversion efficiencies outlined above. We are thus doubtful that any new, post-SSL technology will be able to compete. Considering all the complexities, 75 % may be a practical limit for any new technology. Moreover, even if a new technology could achieve 75 %, the improvement might be "too little too late".

An investment in a competing new technology ("NT") could only be justified in two ways: either on the basis of a lower lighting element cost, or on the basis of energy savings due to a higher electricity-to-light conversion efficiency. Suppose SSL being at 50 % conversion efficiency with room to push it to 55–60 % for high performance applications and the basic SSL lighting element cost at < 50 cents/klm.

The first justification (competing on cost) is unlikely as, at <50 cents/klm, the SSL lighting element cost would be small compared to the remaining cost of building a complete light bulb, a luminaire, installation, etc., and small compared to the electricity cost associated with operating the SSL element. Even if the cost of the NT lighting element approached zero, lighting users would have little incentive to switch.

The second justification (competing on energy savings) is also unlikely, as illustrated by the following dilemma faced by the potential NT investor.

Replacing on average 12 %-efficient conventional lighting with 50 %-efficient SSL saves 76 % of electric energy. Multiplied by the estimated $ 330B/year spent worldwide (in 2005) on energy for lighting, this eventually yields $ 250B/year in reduced energy cost. Most of this energy saving benefits the energy consumer and only a small fraction flows through lamp revenues to the bottom line of the SSL lamp industry. Nevertheless, this profit opportunity, combined with revenue from a series of stepping-stone markets of increasing size, has been sufficient to cover the risks of investing > $ 10B between 1999 and 2010 to reach a 4 % SSL penetration and will be sufficient to cover the investment risk over the next 20 years to reach a 90 % penetration.

Replacing 50 %-efficient SSL with a 75 %-efficient NT results in a quite different risk analysis. First, NT would only save 33 % of a much smaller SSL electricity consumption of $ 80B/year, or $ 26B/year. This is a 10× smaller return in energy savings potential than in the earlier SSL scenario. Second, by the time NT reaches the feasibility proof target in 10 or more years, SSL may be at 55 % or 60 %, potentially further increasing the risk and reducing the return. Third, the first 10-year investment for NT should be comparable to the > $ 10B SSL investment. Fourth, the stepping-stone market opportunities that helped to finance SSL investments in the early years may not be available to NT.

Thus, considering the head start of SSL, the magnitude of the investments required and the risk and uncertainty for NT to even reach 75 % conversion efficiency with competitive quality of light and low costs, we believe this scenario is extremely unlikely. There just is not enough headroom in energy savings potential to justify the risk.

Summary

Today, it is clear that SSL has met or will meet all the five necessary conditions outlined above. The current efficacy level of around 100 lm/W will move up to the 180–200 lm/W range, surpassing all conventional lamps by factors of 1.5–15x. Color rendering quality for SSL will eventually match the current gold standard set by incandescent lamps, dimming will no longer result in loss of efficacy, color control and stability will match fluorescent lamps, and its superior operating life will dwarf the maintenance cost, especially in situations with difficult access or high labor cost.

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