Solid-State Lighting: Lamp Targets and Implications for the Semiconductor Chip

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ABSTRACT

A quiet revolution is underway. Over the next 5-10 years inorganic-semiconductor-based solid-state lighting technology is expected to outperform first incandescent, and then fluorescent and high-intensity-discharge, lighting. Along the way, many decision points and technical challenges will be faced. To help understand these challenges, the U.S. Department of Energy, the Optoelectronics Industry Development Association and the National Electrical Manufacturers Association recently updated the U.S. Solid-State Lighting Roadmap.

In the first half of this paper, we present an overview of the high-level targets of the inorganic-semiconductor part of that update. In the second half of this paper, we discuss some implications of those high-level targets on the GaN-based semiconductor chips that will be the "engine" for solid-state lighting.

KEY WORDS

Solid-State Lighting; GaN; White Light; LEDs; Illumination; III-Nitrides

INTRODUCTION

Solid-State Lighting through Light-Emitting Diodes (SSL-LEDs) is the use of solid-state, inorganic semiconductor light-emitting diodes to produce white light for illumination. Like semiconductor transistors, which displaced vacuum tubes for computation, SSL-LED is a disruptive technology: it has the potential to displace vacuum or gas tubes (like those used in traditional incandescent or fluorescent lamps) for general white lighting.

SSL-LEDs' enhanced efficiency will enable substantial reductions in electrical energy consumption and carbon-related greenhouse-gas pollution. SSL-LEDs' enhanced color flexibility and programmability will enable substantial improvement in the overall human visual experience. And SSL-LEDs' reliance on versatile new GaN semiconductor materials will enable substantial spin-off benefit for national security.

Nevertheless, tremendous challenges must be met for SSL-LEDs to achieve its potential for general white lighting. These challenges have been outlined in a recent comprehensive update [1], co-sponsored by the U.S. Department of Energy, the Optoelectronics Industry Development Association, and the National Electrical Manufacturers Association, of the U.S. SSL-LED Roadmap.

In the first half of this paper, we present an overview of the high-level targets of that update. In the second half of this paper, we discuss the implications of those high-level targets on the GaN-based semiconductor chips that will be the "engine" for solid-state lighting.

SSL-LED LAMP TARGETS

The high-level Roadmap targets are listed in Table 1. The various categories of targets are: luminous efficacy, in lm/W; lifetime, in hours; flux per lamp, in lm/lamp; input power to the lamp, in W/lamp; cost to purchase a lamp, in $/klm and $/lamp; and finally color rendering index, or CRI, which is a measure of the quality of the white light.

The leftmost column is where solid-state lighting was last year; the next three columns are the 5, 10 and 18 year targets; and the last three columns are where the competition -- incandescence, fluorescence and high-intensity discharges -- is now.

LAMP TARGETS	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	Incan-descent	Fluore-scent	HID
Luminous Efficacy (lm/W)	25	75	150	200	16	85	90
Lifetime (hr)	20,000	20,000	100,000	100,000	1,000	10,000	20,000
Flux (lm/lamp)	25	200	1,000	1,500	1,200	3,400	36,000
Input Power (W/lamp)	1.0	2.7	6.7	7.5	75.0	40.0	400.0
Lumens Cost ($/klm)	200.0	20.0	5.0	2.0	0.4	1.5	1.0
Lamp Cost ($/lamp)	5.0	4.0	5.0	3.0	0.5	5.0	35.0
Color Rendering Index (CRI)	75	80	80	80	95	75	90

Table 1: High-level targets for the U.S. SSL-LED Roadmap Update 2002..

Except for one – the color rendering index -- these targets were chosen based on "hard" economic competitiveness (rather than on "soft" features, such as color flexibility and programmability). The idea is to beat incandescence in 5 years, and to beat fluorescence and high-intensity discharges in 10 years, purely through brute force economics.

To see that, Figure 1 shows graphically the two major costs associated with lighting. The bottom axis of the plot is the operating cost – how much it costs to run a light bulb, day after day. The left axis of the plot is the capital cost – how much it costs to buy a light bulb or lamp, amortized over its lifetime (up to a maximum of 20,000 hours that typical applications are likely to need). The units for both are $/(Mlm-hr).

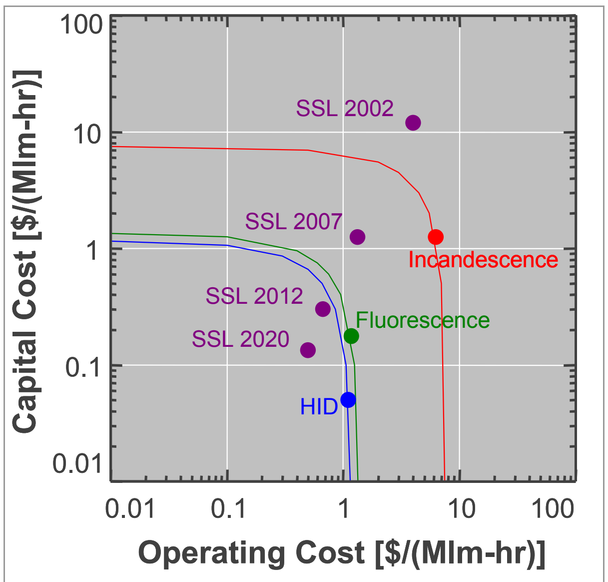

Figure 1: Graphical comparison of costs (ownership = capital + operating) associated with various white lighting technologies.

Incancdescence. First, consider incandescence. Its luminous efficacy is low (16lm/W), so its operating cost is relatively high. Light bulbs are relatively inexpensive (about 0.4$/klm), but because their lifetimes are so short (1,000hrs), their capital cost amortized over the life of the lamp isn't as low as one might expect. From the incandescence data point in Figure 1, one can see that the capital and operating costs are actually pretty similar.

To enable comparison between incandescence and other technologies, a constant life-ownership-cost curve has been drawn through the incandescence data point. Points along the upper left portion of that curve have very high capital cost but very low operating cost. Points along the lower right portion of that curve have very high operating cost but very low capital cost. But all points along the curve have the same life ownership cost as incandescence.

Fluorescence. Second, consider fluorescence. Its luminous efficacy is higher (85lm/W), so it's further to the left in operating cost than incandescence. Also because of its long lifetime (10,000 hours), it is farther down in capital cost, again amortized over the life of the lamp, than incandescence.

HID. Third, consider high-intensity discharges. Its luminous efficacy is slightly higher (90lm/W) than fluorescence, so it is slightly to the left in operating cost. And, both because of its even longer lifetime (20,000 hours) and lower lamp cost, it is significantly lower in capital cost than

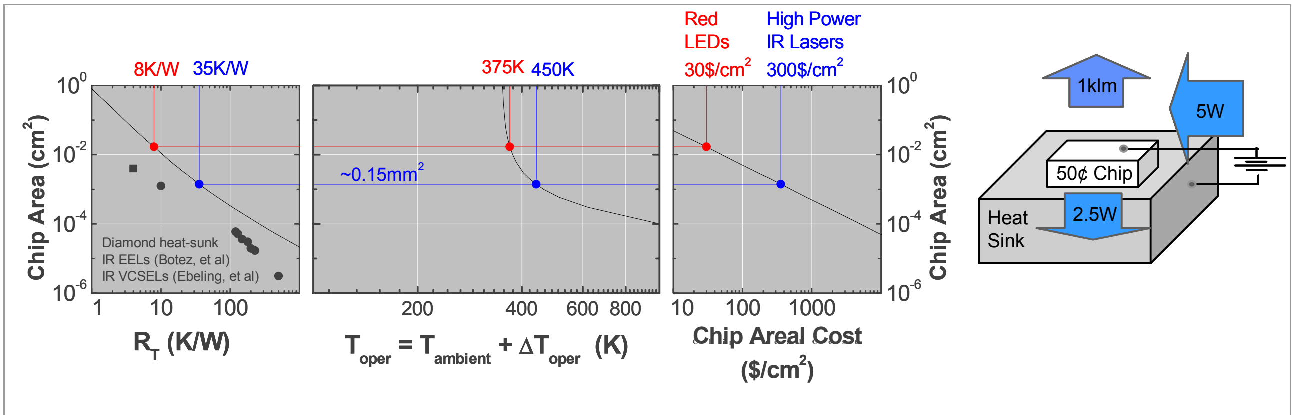

Figure 2: How chip areal cost and operating temperatures must scale with chip area in order to meet Roadmap targets.

fluorescence. However, because, for both fluorescence and high-intensity discharges, life-ownership cost is dominated by operating cost, their life-ownership costs are very similar.

SSL. Finally, consider solid-state lighting. Currently, it is more efficient than incandescence, but it is also much more expensive, so its life-ownership cost is much higher. If the targets are achieved, however, by 2007 its life-ownership cost will be much lower than incandescence, and by 2012 and 2020 will be much lower than fluorescence.

IMPLICATIONS FOR SEMICONDUCTOR CHIP

The high-level Roadmap targets have "trickle-down" implications on the semiconductor light-engine chips that are at the core of solid-state lighting. The highest-level implications are illustrated on the right side of Figure 2.

First, the lamp must have an output of roughly 1klm of white light – slightly more than the output of a 60W light bulb.

Second, the lamp must have a roughly 50% conversion efficiency, or 200lm/W. 1klm of light divided by 200lm/W implies about 5W of input power. Half of that 5W goes into white light generation; the other half, or 2.5W, is lost and must be sunk by the heat sink.

Third, the capital cost of the light must be roughly 2$/klm to the consumer. Assuming a factor of 2x mark-up, and a factor 2x due to packaging cost, that means we're looking for a chip that costs 2$ divided by four, or 50 cents, to manufacture.

So, all together, we have a 50 cent chip, driven by 5W, producing 2.5W of white light and sinking 2.5W of waste heat.

CHIP AREA TRADE-OFFS

At one more level of detail, one can ask how large the chip will be – or at least what some of the cost and performance trade-offs are that will determine it. These trade-offs are indicated in the left three panels of Figure 2, all having chip area as their y-axis.

Chip Areal Cost. The first trade-off is the areal cost of the chip (in $/cm2). For a fixed chip cost, the chip areal cost scales inversely as chip area. Two extremes can be imagined.

On the one hand, there is the low-cost extreme, which one might call the red LED scenario, because GaAs-based high-brightness red LEDs, which cost about $30/cm^2 to manufacture, are one of the least expensive compound semiconductor technologies. In fact, if GaN-based blue or white LEDs become as inexpensive, the size of the chip can be pretty large: about 1.5mm^2.

On the other hand, there is the high-cost extreme, which one might call the high-power laser scenario, because GaAs-based high-power IR lasers, which cost about $200-300/cm^2 to manufacture, are one of the more expensive compound semiconductor technologies. If GaN-based LEDs or lasers end up being this expensive, the size of the chip will need to be much smaller: about 0.15mm^2.

Chip Operating Temperature. The second trade-off is the operating temperature of the chip. As shown in the leftmost panel, thermal resistances

(R_T) generally scale inversely as the square root of chip area. The data points shown are research results [2,3] for high-power lasers with state-of-the-art diamond-heat-sinking. The drawn curve assumes that solid-state lighting chips will be within a factor 3x of these research results.

As shown in the center panel, this means that, for a fixed power wasted into the heat sink, the chip operating temperature (plus ambient room temperature, which is assumed here to be as high as 350K) decreases as chip area increases. If the chip is large, its operating temperature can be low; if the chip is small, its operating temperature is going to be high.

At the inexpensive, red LED extreme with large, 1.5mm^2 chip areas, the operating temperature can be as low as 375K, only 75K above normal room temperature. But at the expensive, high-power laser extreme with 0.15mm^2 chip areas, the operating temperature may need to be as high as 450K, 150K above normal room temperature.

CONCLUSIONS

In summary, we have presented an overview of the high-level targets of the recent update to the U.S. SSL-LED Roadmap. These targets targets were chosen based on raw economic performance; if achieved, SSL-LEDs will "beat" incandescence in 5 years, and beat fluorescence in 10 years, purely through brute force economics.

We also discussed some implications of those high-level targets on the GaN-based semiconductor chips that will be the "engine" for solid-state lighting. The trade-offs between chip area, chip areal cost and operating temperature were quantified through physical scaling laws and comparisons to existing similar (but more-mature) chip technologies.

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ACRONYMS

SSL: Solid-State Lighting.

LED: Light-Emitting Diode