ANOTHER SEMICONDUCTOR REVOLUTION: THIS TIME IT'S LIGHTING![1]

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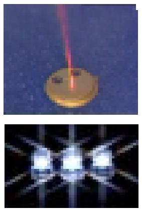
1 INTRODUCTION

Fire

Candles and Lamps

Bulbs and Tubes



Semiconductors

Energy is the lifeblood of our economy, and a critical building block for global peace and security. Its generation incurs huge economic and environmental costs (i.e., smog and particulate emissions, acid rain, global warming, waste disposal). And, the economic costs will only increase as concern heightens over how to reduce the environmental costs. 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 electrical equipment are constantly being examined for energy saving opportunities.

Among the most widespread, important, and *growing* uses of energy is electricity used for lighting. In the U.S., about 20% of all electricity, and about 7.2% of all energy, is consumed by lighting. Worldwide, the percentages are similar. As a consequence, improvements in lighting efficiency would have major consequences on U.S. and worldwide energy consumption.

Until recently, significant improvements would have been considered impossible. As illustrated in Figure 1, none of the conventional "tube" technologies -- incandescent, halogen, and fluorescent -- has improved significantly during the last 30 years. Recently, however, a semiconductor technology, light emitting diodes (LEDs), has emerged. Red LEDs are now efficient and bright enough to be able to replace incandescent and halogen lamps in traditional monochrome lighting applications such as traffic lights and automotive tail lights. And, recent developments in green and blue LEDs are enabling the first applications in white lighting.

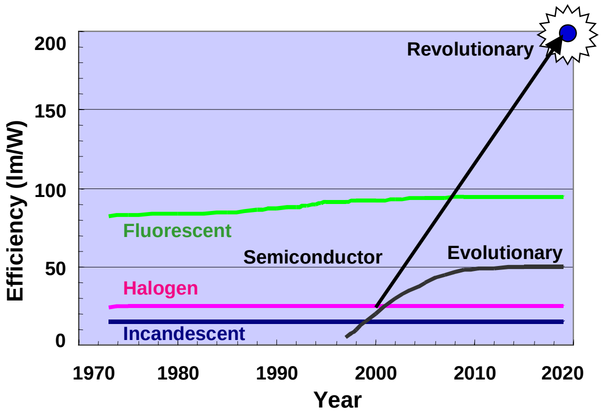


Figure 1. History and projection of efficiencies (in lm/W) of conventional "tube" (incandescent, halogen and fluorescent) and semiconductor (LED) white lighting technologies.

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 target the technology we believe has the highest potential to be the lighting source for the new millennium, and the highest

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[1] This is a preprint of a paper published in the March, 2002 issue of Compound Semiconductor Magazine A long version of this paper was first presented publicly at the 1999 Optoelectronics Industry Development Association (OIDA) forum in Washington DC on October 6, 1999, and is available by request from bjkazmi@sandia.gov.

potential, in our assessment, of reaching the lighting holy grail of an efficiency of 200*lm/W (lumens/Watt)*.

2 SEMICONDUCTOR LIGHTING

The use of semiconductors to produce light is not particularly new. The first LED was demonstrated as far back as 1962 by General Electric, and the first LED products were introduced in 1968 by Monsanto (indicator lamps) and Hewlett-Packard (LED displays that replaced Nixie tubes). However, throughout the 1970's and 1980's, their output flux and electrical-to-optical conversion efficiencies were low, and their uses were limited to small-signal (10-100*mlm*) applications such as indicator-lamps and displays in the red to yellow-green part of the spectrum.

During the last decade, however, the technology of LEDs has improved remarkably in two ways: (1) higher output flux and conversion efficiency and (2) coverage of the entire color spectrum including green and blue. Today, monochrome LED efficiencies substantially exceed the efficiencies of filtered incandescent lamps, and white light LED efficiencies are slightly better than the efficiencies of unfiltered white incandescent lamps. These improvements have opened up new applications in power-signaling and specialty white lighting, which in turn will drive continued evolutionary improvements in LED technology. Our best projections are that white LED efficiencies will increase from 20*lm/W* today to 30 *lm/W* in 2002, 40 *lm/W* in 2005, and 50 *lm/W* in 2010.

Indeed, with these projected evolutionary improvements, we also anticipate some penetration of general lighting (see Figure 2). The main impediment is the substantially higher cost of LEDs compared with conventional lamps, a cost differential which must be recovered within a "reasonable" time through energy savings. For that part of the general lighting market served by incandescent lamps, we expect the cross-over point to be the year 2002, when the cost of the LED lamp can be recovered within 3-6-years through lower operating cost. From then on, LED-based lamps will gradually replace incandescent lamps. Assuming, conservatively, a 25-30% replacement of incandescent and halogen lamps by the year 2025, we estimate the global energy savings to be 400*TWh/yr*, corresponding to a cost savings of about $40B/yr, and a decrease in required generating capacity of nearly 50*GW*.

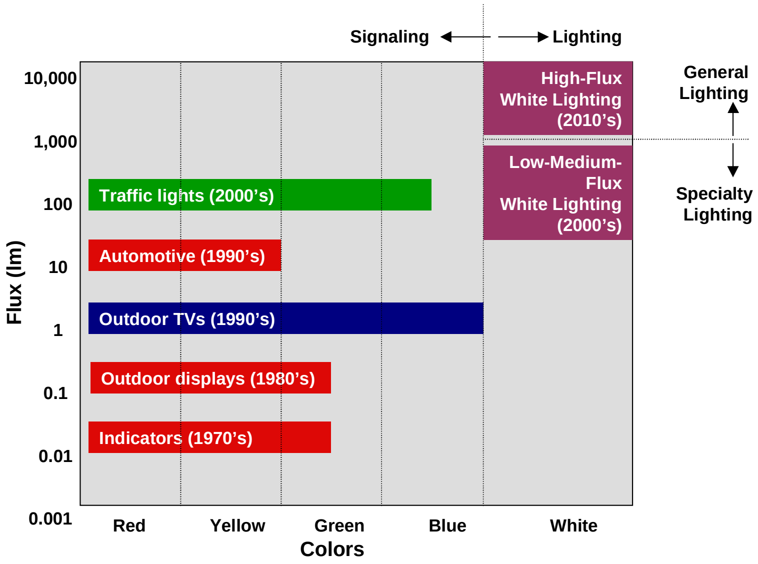

Figure 2: The stepping stones in output flux and color for semiconductor lighting applications from low-flux indicator lamps (lower left) to medium-flux power-signaling lamps and specialty white lighting (middle), to high-flux general lighting (upper right).

But, at an efficiency of 50*lm/W* a white LED lamp converts only 12% of its input energy into light. *We do not believe that this level represents the ultimate limit of the semiconductor lighting technology.* And we have good reasons to be hopeful. In 1997 Sandia National Laboratories demonstrated an energy conversion efficiency of over 50% for a novel device, a so-called vertical cavity surface emitting laser (VCSEL). This demonstration was done at a wavelength range where it is fairly easy to design and build VCSELs: 850-980 nm (infrared). Another important milestone was a 1999 experiment by Agilent Technologies demonstrating a 45% conversion efficiency with a specially shaped red LED.

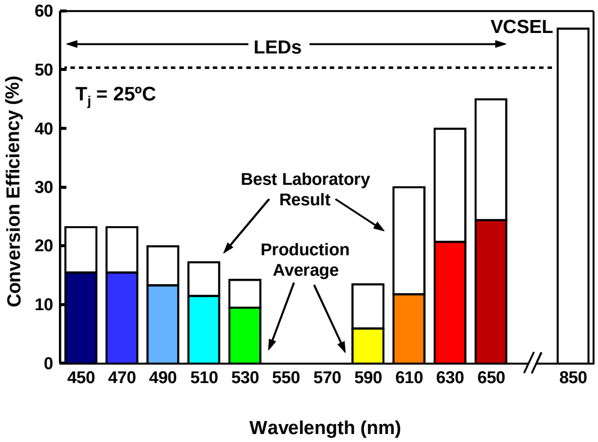

Figure 3: Best laboratory results and production averages for LED electrical-to-optical power conversion efficiencies. The two grand challenges are (1) to close the wavelength gap in the green/yellow, and (2) to raise the efficiencies at all wavelengths to 50.

What keeps us from replicating these VCSEL and/or LED results in the rest of the visible spectrum between red and blue? Not the laws of physics, but the not so precisely definable law of "Conservation of Trouble." So far, no one has succeeded in making a VCSEL at a wavelength shorter than red. And we need arrays of several hundred VCSELs in small chips, that for cost reasons, should not exceed $1 mm^2$. The shaped LED chips are a similar headache. They do not scale to larger chip size without giving up most of the efficiency we gained by chip shaping. And last, but not least, we have a color gap in the 530-590*nm* range (see Figure 3). For an experienced III-V technologist, this set of circumstances looks like a "Mission Impossible."

Why then do we propose a project of such extraordinarily high risk? One reason is our boundless optimism that is fueled by the steady and, at some times, surprising progress of semiconductor technology generally and LED/VCSEL technology in particular. The other reason is the pot of gold at the end of the rainbow. If the LED/VCSEL technology succeeds in building 200*lm*/*W* lamps, then we can attack even fluorescent lamps, revolutionize the lighting industry, reduce the consumer's electricity bill and, at the same time, make a significant dent in the steadily increasing global consumption of electricity. No other major electricity application (motors, heating, refrigeration) represents such a large energy savings potential. And no other energy savings potential presents such an attractive return to investment ratio. To be specific, if the LED/VCSEL breakthrough attempt is successful, we should be able to achieve a 50% market penetration (measured in fraction of light flux generated by LED/VCSEL technology) by 2025. Globally, this penetration should translate into electricity savings of 1000*TWh*/*yr*, cost savings of $100B/yr, power generation capacity reductions of 120*GW*, and carbon emission reductions of approximately 350*Mtons*/*yr* (assuming that all the savings come from coal-fired plants).

3 BREAKTHROUGH ATTEMPT

In the previous section, we briefly touched on the degree of difficulty to achieve a breakthrough from the evolutionary LED projection of 50*lm*/*W* to the revolutionary LED/VCSEL goal of 200*lm*/*W*. To the authors of this paper, who have a combined III-V experience of 60 years, this task looks formidable. At one time, we compared it to the Manhattan Project. From this comparison arose the concept of a national program on semiconductor lighting research with the goal of attempting a performance breakthrough to the 200*lm*/*W* level. But, this performance alone is not sufficient to revolutionize the lighting industry. In addition, we have to bring the lamp cost close to a level such that we have a "reasonable payback time" even when replacing the most efficient fluorescent lamps. And, finally, we have to meet a level of "lighting quality" that the user expects. This latter issue is not well defined at this time, because we don't know yet what lighting quality problems we will encounter.

It is because of this large risk, coupled to the enormous potential benefit, that we propose a concerted, coordinated *national* effort, and a major government investment: We recommend $500M over a ten year period.

Moreover, the U.S. also benefits as a nation in one additional indirect but important way. The compound semiconductors on which this new lighting technology would be based are the foundation for the next-generation high-performance optoelectronics and microelectronics critical to national security. In terms of sheer volume, general lighting will be the "killer app" for compound semiconductors, and will drive the development of its tool and process infrastructure. The nation that is at the forefront of this killer app will be in the best position ultimately to exploit its spin-off applications for national security.

And, finally, vision is arguably our most basic sensory input. The quality of our living experience depends critically on the quality of the lighting that enables us to see. This new light source promises to change completely the quality of our lighting experience. LEDs and their semiconductor variants have the potential to be programmable in intensity and color, so that virtually any desired flux and color may be produced, at any time and at any place. And their compactness and cool operation have the potential to revolutionize the way in which lighting sources are integrated into our living environment.

We believe a major government R&D investment in semiconductor lighting, large in absolute terms but modest in relation to its energy impact, can trigger a paradigm shift benefiting every consumer in the country and, through its environmental impact, every human being on earth!