Another Semiconductor Revolution: This Time It's Lighting!

Roland Haitz

Retired from Agilent Technologies

Abstract. A 40 year old semiconductor technology, Light Emitting Diodes (LEDs) has steadily improved performance and cost to a point where it will move from its home turf, signaling applications to the much larger market, general lighting. The white LEDs are building momentum at such a rapid rate that we predict a revolution in lighting comparable to blowing out the gaslights by Edison's incandescent lamp 100 years ago. One technology will compete for all applications from the smallest indicator lamp to the lighting system for sports stadiums. LEDs will provide superior performance and lower cost of ownership, at any point in this dynamic range of 11 orders of magnitude. A complete conversion to LED based lamps could reduce electricity consumption for lighting by up to 75% and reduce global coal production by approximately 600 Mtons/year. There is no single technology investment on the horizon with a better environmental benefits to cost ratio.

1 Introduction

This paper is about revolution, a revolution that is expected to change the way we are lighting our homes, shops, offices, streets and even sports stadiums. This revolutionary lighting technology is based on a 40 year evolution of tiny semiconductor based lights (Light Emitting Diodes or LEDs) that could not even be seen in direct sunlight before 1975. Today, the technology is at a transition point from signaling a message to illuminating a small area. Over the next 20 years, LEDs will improve performance and cost to a point where they will practically compete for every light-based signaling and lighting application on the surface of the earth! There will be some of exceptions:

- LEDs will not match the low weight and un-tethered mobility of the firefly,
- LEDs will not compete with the spectacular display of a thunderstorm, and
- LEDs will not match the high flux and the low energy cost of the sun.

Every other application between those extremes will be fair game!
LEDs will bring some unique advantages to the "lighting table". LEDs are very efficient and are beating incandescent lamps today. The efficiency of compact fluorescent lamps (CFL) will be matched in a couple of years. A decade from today, LEDs will surpass the efficiency of the most efficient white lamps such as fluorescent lamps (FL) and high intensity discharge lamps (HID).

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Efficiency – and its tie to energy cost – is only one of the critical parameters in lighting. Other issues are: initial lamp cost, color control, color-rendering index (CRI) and life-time systems cost including maintenance. Today LEDs excel on maintenance cost (lamp life, ruggedness, etc.) but lag on color control (CRI over temperature, time, drive current, etc.). The existing lighting technologies have spoiled users with superb color control. LEDs will face an up-hill battle on CRI against the entrenched technologies. But an active color control system could turn this handicap into an advantage: Unlimited color and dimming control without a loss of efficiency.

At this point of the revolution, initial lamp cost is the decisive parameter for market conversion. Today, LEDs have a cost structure to dominate all monochrome signaling applications within a few years. The situation for white LED lighting looks much worse: LED lamps are at least two orders of magnitude more expensive than equivalent conventional lamps. But this disadvantage shrinks significantly when life-time energy costs are included. Expected cost improvements for LEDs will bring the initial lamp cost to the range of today's CFL lamps within 5–10 years. At that price level, energy costs will become the dominant cost factor and favor LED lamps.

This paper will start with a brief description of the physics behind the light generating process in LEDs. Next comes a description of the important milestones in the evolution of signaling LEDs. The meat of the paper will concentrate on today's challenges in the transition from signaling to lighting and on the vision of revolutionizing today's lighting technology. A non-trivial side benefit will be energy savings for the consumer and a significant reduction in the emission of green house gases.

2 The LED Light-Generation Process

The essential element of an LED is a p-n junction, the most basic element of the semiconductor industry. A p-n junction (Fig. 1) is the transition layer between two classes of semiconductor materials: The electron carrying n-layer and the hole carrying p-layer. When a forward voltage is applied to the structure (positive to p-layer and negative to n-layer), then electrons are injected from the n-layer into the p-layer and holes from the p-layer into the n-layer. These injected carriers are called minority carriers: a relatively small number of electrons surrounded by a large number of holes on the p-side and vice versa on the n-side. These electron and holes can be in the same physical space, but they are separated in energy and momentum space. The separation in energy is called the energy gap E_g (see Fig. 1). A positively charged hole is nothing else but a missing electron in the crystal lattice. Both electrons and holes can move freely through the crystal lattice. By applying a positive voltage V_F to the p-side electrode (Fig. 2), electrons will diffuse from the n-side to the p-side of the conduction band. Similarly holes will diffuse to the n-side of the valence band. A positively charged hole can attract a negatively

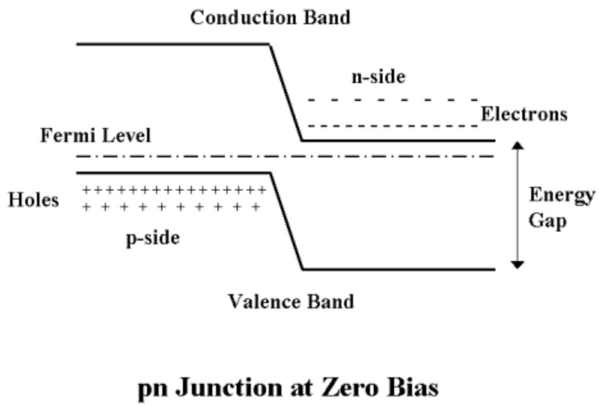

Fig. 1. Schematic representation of an un-biased pn junction

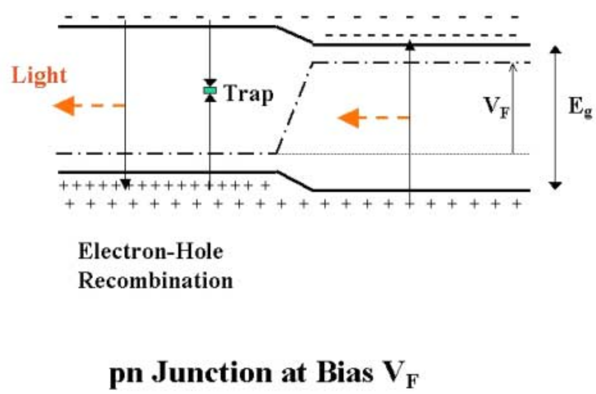

Fig. 2. Junction biased with a forward voltage V_F resulting in minority carrier injection into both conduction and valence bands

charged electron and the electron can recombine with the hole. However, this process has to obey two fundamental laws of physics: energy and momentum conversation.

The energy conservation law is readily met by emitting a photon with a quantum energy $h\nu = E_g$. This process results in the conversion of an injected electron or hole into a *visible* photon as long as the energy gap is in the range of E_g=1.9eV (red) to E_g = 3.0eV (violet).

The momentum conservation law is more difficult to meet. Without going into all possible variations, let us consider the most important case. In practically all semiconductors, the holes occupy states near zero momentum. In Si and Ge, the electrons occupy the lowest energy states – which happen to be far away from zero momentum – and recombination accompanied by the emission of a photon is practically impossible. In other semiconductor materials, like the alloys between elements of Group III and Group V of the periodic system, very often – but not always – the electrons also occupy states near zero momentum. In these so-called direct bandgap materials, such as GaAs, GaAlAs, GaInN, GaAlInP, etc., injected electrons recombine readily with holes by emitting infrared or visible light with a wavelength depending on the gap energy E_g.

But, electrons also have a chance to recombine without emitting light. To recombine radiatively, the electron (hole) must find a hole (electron) with exactly opposite momentum to meet the law of momentum conservation. This process will take some time. During this time delay, the electron (hole) has a finite probability to drop into an electron (hole) trap such as a crystal defect. While being trapped, the electron (hole) will eventually recombine with a hole (electron), but instead of generating a photon, the recombination process will meet the energy conservation law by emitting multiple phonons or lattice vibrations (heat). Considering these two recombination paths, radiative and non-radiative, the efficiency of the recombination process can be described by a simple equation

$$\eta_{int} = \tau_n/(\tau_n + \tau_r) \tag{1}$$

Here, η_{int} denotes the internal quantum efficiency, τ_r the mean time to recombine radiatively and τ_n the mean time to recombine non-radiatively. The ideal case is $\tau_r << \tau_n$, then $\eta_{int} \approx 1$. In this case, the electrons recombine radiatively long before they have a chance to get trapped. In some III-V materials, like GaAlAs (850nm) and GaAlInP (650nm), we approach the condition of $\eta_{int} \sim 100\%$. In Si and Ge, we have the opposite condition: $\tau_r >> \tau_n$ and the radiative recombination is essentially zero.

Most practical LED materials have an internal quantum efficiency in the range of 10–50%. The losses are dominated by crystal defects, inter-valley electron scattering, and lack of perfect confinement. The latter two loss mechanisms go beyond the scope of this paper, and are discussed in great detail in the relevant LED literature.

Generating photons inside the LED chip is only half the story of making efficient LEDs. The chip itself is a formidable photon trap. The light emitted by the p-n junction is directed equally into all directions (isotropic emitter). The LED material has an index of refraction in the range of $n_0 = 2.9$–3.6. When the photons emitted towards the top surface reach the chip-air interface, total internal reflection sends most of them back into the chip and only 1.5–2.0% of the internally generated photons escape through the top surface (Fig. 3). If the bulk of the chip is transparent to the generated light (Fig. 4), then we have essentially 5 transmission surfaces and 7.5–10% of the photons can escape directly into air. The remaining 90–92.5% will be absorbed within the chip. If the chip is embedded in a material with an index of refraction of $n_1 = 1.5$ (epoxy), then the escape probability increases by approximately ${n_1}^2$ and the extraction efficiency for a transparent substrate chip is in the 20–

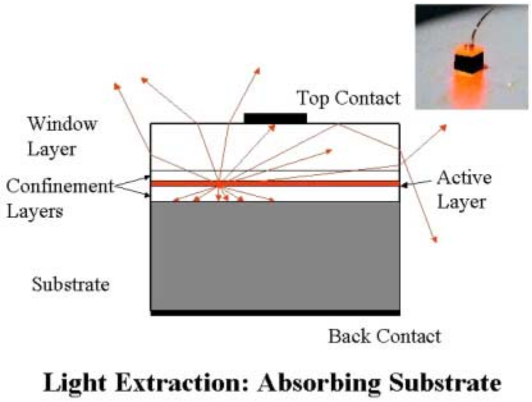

Fig. 3. LED chip based on an absorbing substrate and a thick window layer allowing for top emission and some emission through the side walls

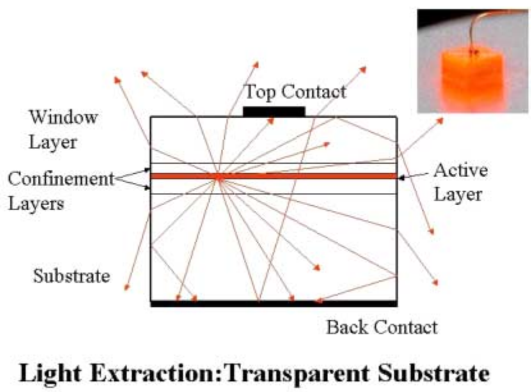

Fig. 4. LED chip based on a transparent substrate with top emission and substantial emission through the side walls. A partly reflecting back contact further improves extraction efficiency

25% range. We can express this situation by defining an extraction efficiency $\eta_{\text{extraction}}$. The external quantum efficiency of an LED, η_{ext} is given by

$$\eta_{\text{ext}} = \eta_{\text{int}} \cdot \eta_{\text{extraction}} \tag{2}$$

The extraction efficiency cannot be easily quantified in mathematical terms. The usually low extraction efficiency is caused by several factors that contribute to the internal absorption of light. In a cubic chip with walls that are perpendicular to each other, only low order modes that fill a 17° cone perpendicular to each surface can escape the chip. For higher order modes, the chip behaves like a corner reflector: it preserves the modal structure and all photons outside of an escape cone will eventually be absorbed. For the case of $n_1 = 1.5$ (epoxy encapsulation), the escape cone expands to 26° and 20–25% of the flux can escape. The higher order modes keep bouncing around the chip until they are absorbed at low reflectance surfaces, such as electrical contacts, by the active layer itself, by free-carrier absorption in the bulk substrate or by crystal defects.

One way to enhance extraction efficiency is by means of rapid mode conversion. So far, the most effective chip design is a chip that looks like an inverted truncated pyramid. Non-perpendicular surfaces do not conserve modes, and after a couple of bounces, even the light in high order modes can be converted into low order escape modes. Embedding these chips into epoxy [1] has resulted in an external quantum efficiency record for LEDs of 53%. With an internal quantum efficiency in the 90–100% range, the extraction efficiency must be between 53% and 59%. This experiment has been an important step in raising our hopes for further improvements.

3 Brief History of LED Evolution

The first recorded history of light emission from a "semiconductor" material occurred in 1907 by H. J. Round [2]. Passing current through wire point contacts on SiC produced yellow light. There are no recorded consequences to this observation.

The second recorded light emission from SiC was described by O.V. Losev in 1928–30. His detailed experiments clearly show a pn junction structure, at a time long before pn junctions were discovered and understood. Losev's observations are described in a historical reference by E. E. Loebner [3]. The potential invention fell into the cracks of the political instability during the Stalin years and the up-coming war.

In the late 1950's, Welker's proposal [4] that compound semiconductors from the III and V columns of the periodic system should have properties comparable to Ge and Si led to the detection of infrared (IR) emission from GaAs crystals with quantum efficiencies in the range of 0.01–0.1%.

The observation of IR emission and understanding band structures of semiconductor materials (momentum conservation) was soon followed by a quest for visible emission. Bandgap widening in the ternary GaAsP compound led to the first engineered structure for visible emission: N. Holonyak [5] in 1962. The LED chip was placed in a conventional diode package of the time. The device lit up, but the device was useless as a product since only a very small fraction of the light was exiting the LED package and its distribution was uncontrolled.

By the mid 1960's, Hewlett-Packard (HP) was the largest user of the only digital display of the time, the Nixie tube. This device had its share of disadvantages from angular reading problems to expensive, high-voltage drive electronics. HP was determined to find another solution. It teamed up with Monsanto Co. and in 1968 both introduced the first usable LED products: digital displays by HP and indicator lamps by Monsanto. Around the same time, Bell Labs introduced LED products and used them to replace incandescent lamps in multi-line telephone sets. 1968 constitutes the first year in which LED products were designed into end-user equipment.

In 1972/74, HP had a phenomenal success with its HP 35 calculator. In the early years, calculator sales were limited by the availability of LED displays. Other display applications for character sizes from 5–15 mm emerged. The early years of LED technology were dominated by numerical display applications. Indicator lamps played a minor role.

By 1975, a new display technology, Liquid Crystal Displays (LCD) killed the battery powered part of the LED display products for reasons of lower power consumption. By 1980, the indicator market for LEDs overtook display products and started to influence performance requirements.

The government-forced introduction of the center high-mount stop light (CHMSL) for automobiles in 1986 generated the first LED signaling application with a multi-lumen flux requirement. Its first solution using 72 conventional 5mm LEDs looked like an unnatural act. The need for power packaging became apparent. In the late 1980's, HP introduced the first LED lamps that were rated beyond the conventional 20-mA limit: 50-mA, 70-mA and then 150-mA. The lamp count for a CHMSL was reduced to 20 in the early 1990's and to 12 by 1998. Better optical light distribution might bring the lamp count down to 1–2. The first automobiles with complete LED lighting on the rear end (except back-up light) have been introduced in 2000.

What about white light for illumination? 1992–93 saw the first introduction of GaAlAsP and GaInN based LEDs, both with surprising performance. Combining these technologies, LEDs could now cover the entire visible spectrum with unprecedented efficiency for monochromatic sources and with competitive performance against incandescent white lamps. With this improved capability, will LEDs be able to compete with white light sources that are used for lighting? The answer is complex and affirmative. The answer covers a convoluted analysis based on efficiency, cost, color performance, time and available industry investment.

4 LED Performance

The first GaAsP based LED products in the 1968–72 period were characterized by their ability to be recognized in a well-lit office environment. The target was a brightness of 30 ftLambert $\approx$ 100ṅits for a signal to be recognized in ambient light. This target translates to a flux of approximately 0.1mlm for a segment in the HP35 calculator display. Such a segment is not visible in direct sun light or in any bright environment.

In 1972–74, LEDs had a major breakthrough in efficiency, nearly an order of magnitude. Figure 5 describes this development in the *line* labeled "Flux/Package". To understand this breakthrough we have to look at Eq. (3) for luminous efficacy

$$\eta_{\mathrm{lum}} = 683 \cdot R_{\mathrm{eye}} \cdot \eta_{\mathrm{int}} \cdot \eta_{\mathrm{extraction}} \tag{3}$$

The two new factors are: (1) Peak eye response of 683 lm/W at 555nm and (2) eye response relative to 555nm.

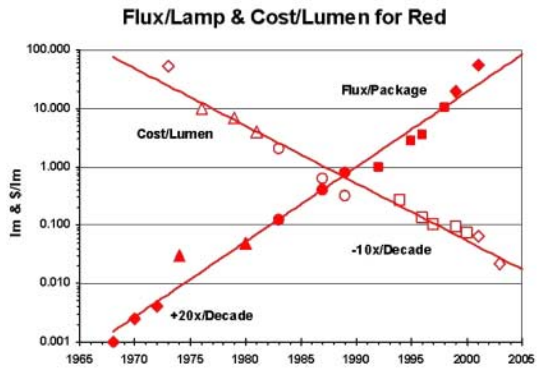

Fig. 5. Evolution of red LEDs over more than three decades. The line labeled "Flux/Package" represents the most powerful commercially available LED in a given year. The *line* labeled "Cost/Lumen" describes the price decline per unit of flux for the highest volume LED customers in that year

In our analysis of the progress of red LEDs over the last three decades (Fig. 5) we have to recognize contributions from the last three factors of Eq. (3). The LED performance started around 1ml in 1968. In 1973-74 we had a nearly 10× improvement roughly divided by three nearly equal contributions from R_{eye}, η_{int} and $\eta_{extraction}$. The first factor resulted from a wavelength shift from 655 nm to 635 nm with improved eye sensitivity. The second factor was caused by a shift in direct to exciton recombination (not explained in this paper). The third factor was due to a shift from absorbing to transparent substrate (Figs. 3–4).

The next step in LED development was limited to long wavelength red LEDs and was based on the GaAlAs system. This system is very efficient in the IR but drops off very rapidly in the red. From 1985 to 1992 this was the most efficient material for red LEDs. It lost out to GaAlInP in the mid 1990's because of its sensitivity to Al oxidation in a high temperature, high humidity environment that is typical for traffic lights in southern parts of the USA.

In 1992, Toshiba and HP introduced the GaAlInP material system. This system is today – and will be for the near to distant future – the dominant system for red and yellow LEDs. During the mid 1990's, the new GaAlInP technology fell behind the trend line. The cooperation between HP and Philips Lighting led to the first serious recognition that LED technology will play a major role in lighting. This recognition accelerated the interest in power LEDs. The introduction of lamps based on truncated pyramid chips set new efficiency and power records [1] and moved the performance ahead of the now 30 year old trend line with a slope of 20×/decade.

The second trend line in Fig. 5 describes the continued reduction in cost/lumen for the same red LED technologies of the flux line. It is based on historical data from my HP files. In the early years, the cost/lamp was more important than the cost/lumen. With the start of power signaling devices such as CHMSL, the cost/lumen emerged as an important issue. For higher flux applications such as traffic lights, the cost/lumen becomes a competitive issue. Figure 5 represents a 25 year old trend line with a downward slope of 10×/decade.

How will this trend continue into the future? To answer this question we are segmenting the flux trend line into its two most important contributions for red LEDs: external quantum efficiency and drive power. The data in Fig. 6 is only approximate. It ignores wavelength shifts (eye response) between materials. The important issues are: (1) start in 1968–75 and (2) near term performance in 2000–05. In the early years all performance improvements were due to increases in efficiency. The drive current for indicator lamps was flat at a rated current of 20mA. As efficiencies increased during the next decades, the slope of the efficiency curve started to saturate. At the same time the need for increased flux accelerated drive power.

Between 1995 and 2005, the efficiency curve will increase by approximately 2.5× while drive power will increase by 30×. 1 W lamps were introduced in 2000, 5W in 2003 and practically every major LED supplier has a 10W LED lamp on its roadmap for 2004–2005. From here on out, efficiency improvements will be relatively slow but still extremely important in achieving energy savings. Increased drive power will open up new applications but without any impact on energy savings. Power increases will be most important for a continued reduction of the cost/lumen. As LED technology matures, packaging cost will dominate and higher power LEDs will translate into lower cost/lumen.

5 White LEDs and Their Impact on Illumination

The addition of the GaInN material system by Nichia and Toyoda Gossei in 1993 added another dimension to the LED ball game. Now, LEDs could cover the entire visible spectrum from red to blue and generate white light by either mixing red, green and blue LEDs or by using a blue LED to pump a phosphor. Both approaches will coexist in the generation of white LED

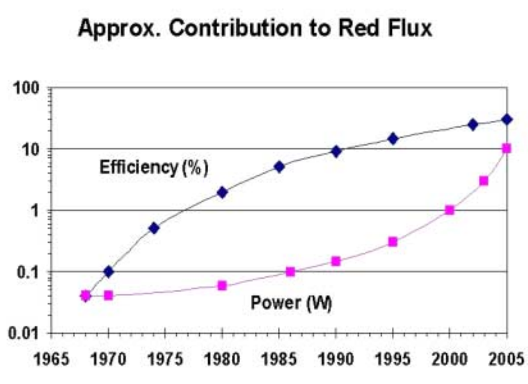

Fig. 6. The two main drivers of the flux trend line in Fig. 5 are efficiency and drive power. In the early years, practically all improvements are due to efficiency. In the later years, efficiency saturates and drive power becomes the dominant factor

light sources. At this point in the technology cycle, we face two fundamental questions:

- Where is white relative to red, both in flux and cost/lumen?
- Will white continue on a trend line comparable to red or will its flux and cost level off over time?

It has been our speculation for several years that the flux performance of white should track red quite closely. At 620 nm, the eye response is around 0.35, green at 535 nm is at 0.85 and blue at 470 nm is at 0.09. The red eye sensitivity lies in between the arithmetic and geometric means of the green and blue sensitivities. Therefore, white is expected to be close to the performance of red LEDs.

In Fig. 7 we have added recent flux and cost data to Fig. 5. Indeed, white is close to red. White starts below the red flux trend line in 2001 and above the cost trend line. By 2003, white exceeds the red flux trend line. Cost for white is still above the red trend line but is expected to drop close to the trend line by 2005.

How will this trend for white continue? Figure 8 combines our forecast for white flux/lamp and its underlying drivers, efficacy and drive power. This time we chose luminous efficacy rather than quantum efficiency. For efficacy we use the current data for 2002–03 and the projected data from the OIDA roadmap [6]. Since the OIDA roadmap may be hyped for reasons of generating government support and because implementation is usually late, we slowed down its progress by 2–5 years. Drive power for the 2001–05 time frame is based on current products or published plans by the leading LED manufacturers. From 2005–10, we expect a slowing trend in drive power for a couple of reasons. During this period cost will still lag market expectations and prevent wide-spread adoption. With an expected performance of 100W and 70 lm/W in 2010, LEDs will exceed the flux of practically all incandescent or fluorescent lamps used in home or office applications. Market penetration to a level beyond 3000 lm LED lamps will be limited by high lamp costs and

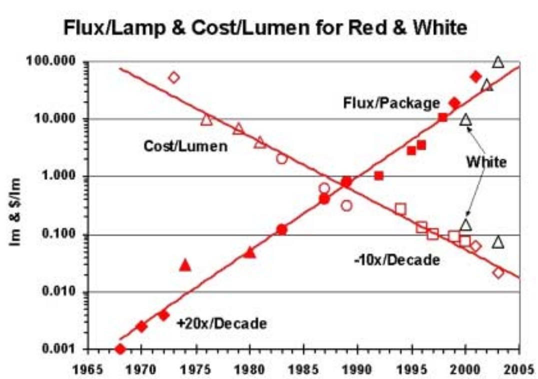

Fig. 7. Superposition of early white flux and cost data on the red trend lines of Fig. 5. White flux is crossing the red trend line in 2002 while cost remains a factor of 2× above the trend line

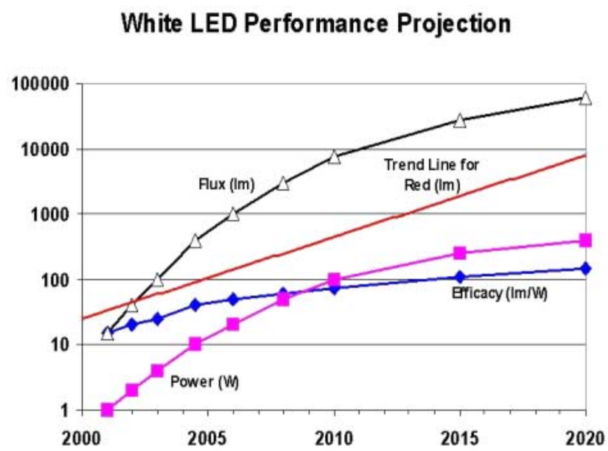

Fig. 8. Near term flux performance of white LEDs and extrapolation to 2020. Efficacy is expected to increase by 10× to 150 lm/W while drive power will increase by 500× to 500W in 2020. By 2010, white flux will be ahead of the red trend line by 20×

lack of energy savings in competition with FL and HID lamps. Continued increases in efficacy from 70–150 lm/W will be absolutely crucial during the 2010–20 period to penetrate the medium power market (300–3000 lm) and to establish a beach-head in high lumen applications such as street lights and sports stadiums.

Comparing white flux data with the red trend line, we see a crossover around 2002 and a performance advantage of more than an order of magnitude by 2010. In other words, the white lamps will stay ahead of the red trend line with its 30 years of history. This is an extremely important finding because of its impact on cost predictions for the 2005–20 time frame. If flux performance is ahead of the red trend line by >20x in 2010, we should be able to meet or beat the red cost trend line during the 2010–20 period.

The future battle between LED lamps and conventional lamps is illustrated in Fig. 9. White flux performance from Fig. 8 and trend lines for red flux and cost are extrapolated to 2020. LED lamps will enter the sweet spot for conventional lighting – defined by a flux range from 300 lm for a 25W incandescent light bulb to 3500lm for a 4 ft fluorescent tube – during the period of 2005–08. Initially, their penetration will be limited by lamp cost, standards and the general unfamiliarity of a new technology. As LED lamp start to penetrate the sweet spot on cost towards the end of the decade and into the 2010–20 period, we will see a steady conversion towards LED lighting.

So far we have compared LEDs with conventional light sources on a lumen for lumen basis. LEDs bring another advantage to the table. LEDs are cold point sources and reflective or refractive optical surfaces can be placed in close proximity. The result is a superior control of light distribution expressed by the distribution efficiency in Eq. (4)

$$\eta_{\text{lighting}} = \eta_{\text{lum}} \cdot \eta_{\text{distribution}} \tag{4}$$

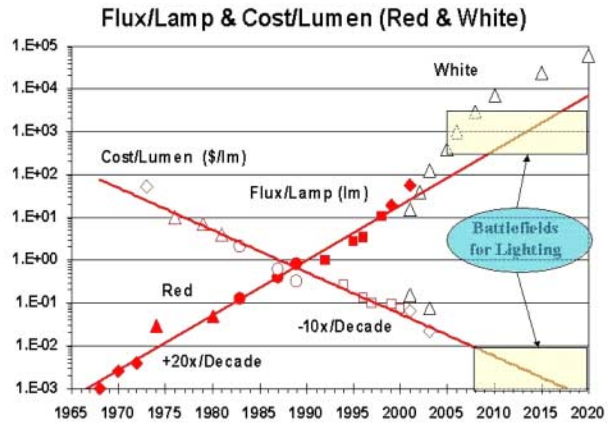

Fig. 9. A superposition of the flux projection of Fig. 8 onto the trend line of Fig. 5. Since white LEDs will be far ahead of the red trend line, we expect that LED costs will meat or beat the red cost trend line. Later in this decade, LEDs will enter the sweet spot for lighting: flux packages of 300–3000 lm and costs of < 10\$/klm

Our current data with experimental LED sources indicate a 20–50% improvement in distribution efficiency over conventional light sources. This result should not surprise any designers of luminaires. Hot sources require remote and large surfaces to shape the light distribution. High quality surfaces are expensive and low quality surfaces quickly dominate the light distribution efficiency. The same argument holds for 4ft FL lamps. The surface of the lamp is cold, but very large.

The arguments of the above paragraphs bring us to an important prediction: During the 2015–20 period, LED technology will drive lighting. Its value proposition of energy savings, lamp life even in extreme environments, maintenance, safety and a host of other beneficial features will make LED lighting a disruptive technology. In addition, LED lighting will bring a few other features to the table:

- Practically unlimited dimming range without sacrificing efficiency.
- Color control, not only along the Planckian white point line but over the entire color gamut of the primary light sources.
- Instant turn-on after a power failure (streetlights, sports stadiums).
- Longer stand-by operation for a given battery size (emergency lights including dimming options).

This list could be extended by including the needs of a variety of lighting applications. It only serves to demonstrate the unmatched and nearly universal lighting contributions that LED lamps will be able to offer.

Unfortunately, the transition to LED lighting will hit a few bumps. The conventional lighting technologies have had decades to hone their lighting quality and to spoil their customers' expectations. Color rendering, white point control, flux maintenance, variations over temperature, etc. are issues that LED lamps have not addressed at all or are only starting to address. We expect that LEDs will be able to successfully resolve these issues, but it will take 1-2 decades before LEDs can deliver a comparable lighting quality.

6 Energy Savings

The enormous energy savings potential from LED lighting was first outlined in a White Paper by Haitz, Kish, Tsao and Nelson at the OIDA Forum in 1999 [7]. LED lamps will have a significant impact on the amount of electricity that is consumed by lighting. The savings will first come from replacing incandescent and halogen lamps with an average efficacy of 15 lm/W by LEDs with 50 lm/W by 2005. During the 2005-15 period, LEDs will reach 150 lm/W and attack FL and HID lamps with an average efficacy around 75 lm/W.

Today's electricity consumption for lighting in the USA is approximately 60GW averaged over 24 hours: 24GW for incandescent/halogen lamps and 36GW for FL/HID lamps.

Let us estimate the maximum energy conservation in a single-minded model that replaces all existing lamps with LED lamps having an efficacy of 150 lm/W by 2020 (or earlier/later depending on the availability of R&D funds for economic or political reasons). In this model we can save 90% of the electricity used in incandescent/halogen lamps and 50% used in FL/HID lamps. For the USA, this energy savings amounts to 40GW, or approximately $40B/year at an electricity cost of $0.11/kWh. By adding a modest improvement in light distribution efficiency of 25%, the projected savings increase to 48GW. In other words, the maximum energy savings potential in lighting could be as high as 80%. This estimate for the USA is based on today's lighting use and does not include a 2% increase per year. Since the USA lighting amounts to roughly 33% of global use, we estimate the global energy savings at >140GW, or $140B.

Should the global society choose to shut down – or not to build new – nuclear reactors, we could reduce the nuclear reactor count by > 100 of the largest 1.4 GW reactors!

7 Lighting Revolution

The above described energy savings potential is not going to be implemented over night. LED lamps will have to systematically improve performance and cost. But the light at the end of the tunnel is very bright!

Today's lighting technology is divided between more than 10 branches of different lamp technologies: Incandescent, halogen, neon, CFL, FL, low pressure sodium, high pressure sodium, high pressure mercury and variations of the HID family. Each technology requires different lamp manufacturing processes, electrical drive circuits, luminaire design, and other technology specific features.

With LED lamps, we need only one technology to cover all signaling/lighting applications from the dimmest indicators (0.1mlm) to the most demanding sports stadiums (10Mlm). *By 2020, no other electricity-based signaling/lighting technology can cover such a dynamic range of 11 orders of magnitude and/or match the efficacy and cost of LEDs at any point within this range!*

Today, LED lamps represent the only lighting technology with a significant annual slope in performance and cost improvements. Incandescent lamps have practically not improved in efficiency since Edison's lamp more than 100 years ago. Halogen, FL, CFL, and HID lamps have been similarly stagnant for the past 2–5 decades. The conventional technologies are stuck with the fundamental laws of physics and significant improvements in efficiency are unlikely, if not impossible. LED lamps, and their potential Laser variant, provide the only hope for substantial energy savings in lighting. *For this simple reason, LEDs will win the battle for lighting in the 21st century!*

8 Government Support and Incentives

As long as this LED story looks so good and so convincing, why is the LED industry requesting substantial government support instead of making the required investment on their own Nickel? The answer to this question is complex and has many facets pointed out by the following arguments:

- The global power LED industry is fairly small, maybe $600–800M in 2002 revenue and burdened with current R&D expenses around $150M. Profits for most "clean-play" companies are negative and the industry over-all is at break-even, at best.
- The established light bulb companies with annual revenues of $13B consider LEDs to be an intruding technology and therefore the established management is antagonistic and fighting a turf battle.
- Most benefits of LED lighting will flow to other segments of the economy and not to the LED industry. By far the biggest beneficiary will be the electricity consumer through energy savings (approx. 60–70% of the potent benefits). Next come the general economy with a reduction in demand for new power plants and the environment with substantial reductions in the emission of green house gases. And last in this ranking is the LED industry: modestly increased revenues, but no profits in the early, investment dominated years. The LED industry is stuck with the hope on future benefits while the rest of the economy enjoys the energy cost reduction of the LED investments! Would you invest in such an industry, yet alone recommend it to your pension fund?
- At the same time, the LED industry shoulders all the investment and market risk. Based on my 33 years of LED experience, I estimate that the

USA based industry will have to invest at least $1B in R&D before the 150 lm/W efficacy goal is reached in 2010–20. The investment sunk to date in these new technologies is in the $150–250M range. That amounts to $750–850M to go. In addition, the LED industry has to carry the market risk: Lighting is a standards-based industry. Such industries innovate only slowly because of the established building codes, union rules, buyer hesitation, fear of exposure to new unproven lights, ect.
- Consumers like to see broad-based trials for new technologies such as the effects on health, cost, and reliability. The consumers ask questions like "Does a government agency really agree with the hyped cost reductions or other advertised benefits?" Who pays to build this customer confidence?

Considering the huge energy savings potential for consumers, the impact on the general economy and the risk exposure for the LED industry, we have no choice but to propose a risk-sharing arrangement:

- Government investments to accelerate research toward the 150 lm/W goal by supporting University, National Labs, and industry investments.
- Government support to reduce the high-risk industry investments in performance improvement, manufacturing cost reduction, standards, and market acceptance.
- Government support to remove or modify acceptance inhibitors such as building codes, union/trade rules, safety/health regulations, ect.

9 Impact on the Environment

Today in the USA, 56% of electricity is generated by the most polluting technology: coal-fired power plants. It is a fair question to ask "What reduction in carbon emissions can we achieve, if all the energy savings from lighting is applied to reduce the use of coal-fired power plants by 2020 at today's rate of lighting consumption?" The answer is quite amazing.

Again we use a simple-minded analysis of complete conversion to LED lamps that have an efficacy of 150 lm/W. The US savings discussed above are estimated at 48GW per year. At a coal burn rate of 4Mtons/GWyear, we are looking at a potential saving of 192Mtons of coal in 2020. This US saving represents nearly 25% of annual US coal production in 2000 and its implementation would amount to a significant contribution to the Kyoto agreement on green house gas emission.

10 Summary

We have a lighting revolution on our hands! This revolution is not an evolution from existing lighting technologies. It is a disruptive revolution based on an emerging light emitting technology that will sweep from indicator lamps to lighting applications within a couple of decades. Over the last three decades, LEDs have conquered practically all small signal indicator and large area emissive display applications. Within a decade, LEDs will dominate power signaling applications from traffic lights to the brake lights on automobiles.

The large lighting market is the next target. Today, LED lamps can beat incandescent lamps on efficacy, but not on initial purchase cost. Given a decade or two with the current performance and cost slope, LED's will dominate all lighting applications because of their superior value proposition offered to the consumer, the economic infrastructure and the environment.

The governments around the globe carry the responsibility to accelerate this revolution through substantial financial support and a speed-up of the regulatory process!

References

1. M. R. Krames et al., "High-power truncated-inverted-pyramid AlGaInP/GaP light-emitting diodes exhibiting >50% external quantum efficiency," Appl. Phys. Let., vol. 75, p. 2365, 1999. 40, 42
2. H. J. Round, "A note on carborundum," Elec. World, vol. 49, p.308,1907. 40
3. E. E. Loebner, "Subhistories of the Light Emitting Diode," IEEE Trans. Electron Devices, vol. ED-23, p. 675, 1976. 40
4. H. J. Welker, "Discovery and Development of III-V Compounds," IEEE Trans. Electron Devices, vol. ED-23, p. 664, 1976. 40
5. N. Holonyak and S. F. Bevacqua, "Coherent (visible) light emission fromGaAsP junctions," Appl. Phys. Let., vol 1, p. 82, 1962. 40
6. J. Y. Tsao, "Light Emitting Diodes for General Illumination," OIDA technology roadmap update 2002, available from Optoelectronic Industry Development Association (www.oida.org). 44
7. R. H. Haitz et al., "The Case for a National Research Program on Semiconductor Lighting," White Paper presented at the 1999 OIDA Forum and available from OIDA, (www.oida.org). 47