LEDs for Lighting Applications

Edited by
Patrick Mottier
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How could we possibly underestimate the achievement of Thomas Edison when he manufactured the first incandescent lamp in October 1879? Humanity had finally succeeded in producing light without combustion, without smell, without smoke. From then on, such light was to be available anywhere and everywhere that a source of electricity existed. 130 years later, this technology is still widespread, though the use of arc lamps has been increasing since the 1950s.

However, a more recently developed technology for the production of light could well consign incandescent lighting to oblivion. Though quite expensive at the moment (but prices are going down every day), it seems to offer a much higher level of performance in all respects: lifespan, compactness, output, color adjustment and ease of dimming. The technology in question is the Light-Emitting Diode (LED).

As a pure product of optoelectronics, the LED came along at just the right time. It was in 2008 that governments round the world made a decision to speed up reductions in energy use and the associated CO₂ emissions. They also decided, more generally, to cut down on the use of resources.

Lighting accounts for 19% of electrical consumption worldwide, which means that it presents a considerable potential for reductions over the next decade. Moreover, LEDs offer a way forward: they can already compete with incandescent lights, and in due course they will rival arc lights.
This opportunity, which is historical in its importance, is closely related to environmental issues. It goes hand in hand with a growing demand for lighting systems that can better satisfy consumer needs and can also entail lifestyle spinoffs. LEDs seem especially adaptable to maintenance devices using sensors, wireless control and power supplied by photovoltaic panels and batteries.

LED technology should benefit from the impressive developments currently taking place in optoelectronics generally, particularly in the fields of mobile phones, computers and TV screens, automobile equipment and advertising panels.

Still, the question remains: “Do we really need such flexible, versatile light sources?”

The almost unlimited possibilities of optoelectronic technologies, with respect to flux dimming and color control, will undoubtedly have repercussions for photobiology and psychology, as regards exposure to light (or other forms of radiation). Technical specifications should no longer involve light that imparts visibility alone, but also light that promotes comprehension, predictability, safety, beauty and emotion. In short, what is now required is light for life.

It would be a mistake to underestimate the possible benefits of a light source such as the LED. The prospects of increased luminous efficacy at 120-200 lm/W (i.e. the ratio between light flux and electrical power) make it a front-runner with regard to the production of white light (incandescent, halogen, arc lamps). This would provide a further incentive to develop it in such a way as to take optimal account of environmental considerations.

The present book constitutes a major contribution to the issues involved, given the outstanding quality of the information it provides, and the date of its publication. 2009 is, in effect, the year when LED-based products are finally starting to enter the market on a large scale. A new lighting revolution is underway.

Patrick Mottier has brought together the leading French experts to produce this work, which should provide LED manufacturers and lighting specialists with essential strategic information. It should also prove
indispensable to all of those who, for whatever reason, wish to broaden their knowledge of the field.

I’m sure you’ll take pleasure in reading it.

Dr Marc Fontoynont

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Introduction

Is the revolution running in lighting? Indeed, the lighting domain is facing a unique technology breakthrough with the emergence of new kinds of devices and luminaries based on semiconductor chips, so-called Light-Emitting Diodes or LEDs. In the beginning, the low power and fluxes of LEDs impeded them from being used for lighting and kept them confined to indicator applications. However, the invention of the blue LED in the middle of the 1980s gave access to white light combining red, green and blue LEDs or by means of partial photoconversion of blue light to yellow light using phosphors. White LEDs in their turn have made electronic lighting accessible, opening new business opportunities to companies. Consequently, labs and companies have focused their efforts on increasing LED efficiencies and fluxes. All these efforts have already led to significant results.

LED-based lighting is a recent phenomenon, but LED deployment in this field of application now seems inevitable. The LEDs have become a credible alternative to incandescent lamps, soon to be banned because of their energy inefficiency. The multiple benefits of LEDs and the continuous increase in their performance allied to the decrease of their manufacturing costs are likely to make them competitive when compared to fluorescent lamps and tubes. Will 2009 mark the true take-off of LED lighting? We do not know yet, but in any case High Brightness white LEDs have become a reality and it is the objective of this book to give to its readers a wide scientific and technological overview of what they are, including all LED manufacturing steps, aspects related to their photoelectric characterization up to characteristics of the light they produce. It also opens up opportunities in organic LEDs.
Chapter 1 starts with a quick history of LEDs, then positions them within the lighting problematic, before setting out issues and challenges still facing High Brightness LEDs. We can consider this chapter to constitute the actual introduction to this book.

The next four chapters describe the successive LED manufacturing steps.

First, Chapter 2 presents the gallium nitride (GaN) material, the semiconductor on which any blue LED is achieved and the problems bound to its epitaxy on so-called “hetero-substrates”. Basic techniques of metallo-organic vapor phase epitaxy are presented and finally some results on bulk GaN crystal growth are given.

Chapter 3 is devoted to the junction itself. After a short history of the discovery of blue LEDs, the authors focus on the achievement of the p-n junction in the GaN semiconductor and then on quantum wells inserted into the p-n junction as a way to increase the LED efficiency. Next, they discuss diode optical properties and radiation efficiency before commenting on possible future developments.

Chapter 4 focuses on processing of diode heterostructure wafers to achieve a high efficiency LED. Different LED structures are described and the evolutions of LED design are presented with their advantages and drawbacks. Then, the successive technological processing steps are discussed.

Chapter 5 deals with LED chip packaging. It presents a quick historical review from the first LED devices to today’s products. Then, problems specifically bound to High Brightness LEDs and related to thermal management are discussed. It then addresses primary optics issues with light extraction and related materials. Finally, the different characteristics given in the LED technical data sheet are discussed.

Chapter 6 is devoted to LED characterization. It begins by focusing on its photometric aspects, i.e. on their luminous behavior, and then looks at their electrical and thermal characterization.

Lighting by LEDs, however, requires the LEDs to reach a certain level of light quality: this is the subject of Chapter 7. It outlines the fundamentals of white light, before addressing the various ways to produce white light from
LEDs. Finally, the author presents and discusses some recent works on the estimation of the quality of light coming from LED-based sources from a lighting point of view.

Finally, if the very concept of LED is the result of the invention of blue LED on gallium nitride, which now holds pride of place, the emergence of OLEDs, or Organic Light-Emitting Diodes, must be taken into account now. Chapter 8 discusses the technology originally developed for display, considering here its application to lighting. We hope that, by presenting this comprehensive overview, this book will meet the expectations of engineers, teachers and students concerned with the technology that aids breakthroughs and opens up possible sources of innovation in an area, lighting, which until a few years ago we imagined would have technical relative stability.

I would like to express my extreme thanks to the authors for their great contributions to this book.

Patrick MOTTIER
Chapter 1

Light-Emitting Diodes:
Principles and Challenges

1.1. History of a revolution in the world of the light sources

“During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 Volts between two points on a crystal of carborundum, the crystal gave out a yellowish light […]”.

Henry Joseph Round (Marconi Co, UK) reported a century ago, in 1907, the first known report of the effect of the light emission from a semiconductor material [ROU 07]. Figure 1.1 shows a reconstitution of Captain Round’s experiment. The first LED patent was filled in 1929 by a Russian radio technician Oleg Vladimirovich Losev [LOS 29].

Without clear explanation, this discovery was quickly forgotten. It was not until 1962 that Nick Holonyak¹ and S.F. Bevacqua, consultants at General Electric, signed “the official birth certificate” of the first red light-emitting diode [HOL 62] (Figure 1.2).

Chapter written by Georges Zissis.
1. In 2002 N. Holonyak received the National Medal of Technology from the President of the USA for his invention. In 1995 he also received the “Japan prize” awarded to honor the achievements of people who have contributed to the progress of science and technology and the advancement of world peace and prosperity.
2. **LEDs for Lighting Applications**

![Figure 1.1](image1.jpg)

**Figure 1.1.** Silicon carbide crystal emitting yellow light under electrical excitation; this picture reproduces the original 1907 experiment of captain H.J. Round (right picture), accidental illustration of light emission from semiconductors.

![Figure 1.2](image2.jpg)

**Figure 1.2.** Professor N. Holonyak (left), inventor of visible light LEDs, shows his demonstrator to his mentor, Professor J. Bardeen, inventor of the transistor (picture taken in 1972, credits IPPO).

Since then, things have rapidly gained pace. In 1968, the first commercialized LED (Light-Emitting Diode) produced barely 0.001 lm of red light. Nowadays High Brightness\(^2\) white LEDs, generating more than 100 lm, are commercially available\(^3\). Recently, a record value of 1,100 lm was achieved with devices combining several LED junctions on a chip\(^4\). This is a true revolution compared to the general trend: in the last 30 years, the

---

2. High Brightness corresponds to a luminous flux between 50 and 250 lumens. Ultra High Brightness to more than 250 lumens.

3. Luxeon has presented an experimental white LED generating 500 lm.

luminous flux generated by a single device doubles each 18 to 24 months (a 20-fold increase per decade). In the meantime the price per device also rapidly decreases (a tenfold decrease per decade). This trend, shown in Figure 1.3, was first observed by Roland Haitz and hence is known as “Haitz’s Law” [HAI 02].

Figure 1.3. “Haitz’s Law” predicts that the luminous flux generated by LEDs increases 20 times per decade whereas the cost decreases 10 times within the same time period (inserted picture: R. Haitz)

An obvious question can legitimately be asked following these revolutionary results: can LEDs replace the traditional illumination devices (light bulbs and electrical discharge systems)?

The question is worth asking but the answer is not as obvious. Of course, many technological and scientific aspects have to be taken into account, but the most important issue is to evaluate this innovative light source in the light of today’s economic and energy saving considerations.

1.2. LEDs and lighting

Electrical lighting has drastically changed everyone’s everyday life to a point that one could not live without it. It is estimated that 30 billion light bulbs are in use on the planet, consuming each year a total of
2,650 TWh, that is about 19% of the total electricity produced worldwide\(^5\). Today, two main technologies dominate the market, incandescence and electrical discharge.

Although these technologies are now mature, the luminous efficiency of the light sources together with their quality of light have not quite reached their limits: there is still room for innovation. The design, optimization and mass production of new and more efficient light sources for lighting are scientific, technical, economic and environmental challenges, but seem to be a sustainable solution. However, despite many scientific and technical progresses in the field of the electrical discharge light sources, the maximum efficiency of these systems has been growing since the 1970s to reach about 100-110 lm/W\(^6\). LEDs on the other hand, with a steady growth of their luminous efficiencies (Figure 1.4), establish themselves as breakthrough solutions.

If white LEDs could reach 200 lm/W by 2025, they could replace the existing fluorescent lights\(^7\). The estimated energy saving would be of the order of 1 billion barrels of oil per year (which corresponds to an electricity production capacity reduction of the order of 250 large nuclear plants\(^8\)).

This energy saving would also imply a significant reduction in CO\(_2\) emission, more than 270 millions tons per year. On top of this, the use of white LEDs in lighting systems will also significantly transform this domain because of its numerous advantages compared to traditional lights:

- higher energetic efficiency of the illumination systems;
- longer lifetime and therefore less maintenance;
- size reduction of the equipments;
- higher flexibility and control of the level of light and color variation;

---

5. As of today, electricity represents approximately 16% of the total energy produced worldwide (20% for industrialized countries); lighting therefore consumes 3% of the energetic resources per year.
6. Only good quality white light sources are considered here.
7. The luminous efficiency is the only criterion considered here, but other technological aspects also have to taken into account.
8. Each “plant” represents 2 TWh/year.
– low power consumption (battery driven autonomous systems, consumer applications where security is important);
– lack of ultraviolet and infrared emission (of the utmost importance for the conservation of fragile items, in museums for example).

Figure 1.4. Luminous efficiency of the main technologies for light sources versus time. HPS: High Pressure Sodium (yellow - pink light); MHL: Metal HaLogens; FL: Fluorescent Lights; LED: white LED; GLS: General Lighting System lamps; Hal: Halogens; Hal+IR: Halogens with infrared reflector; DOE Roadmap: goals of the American “white LED” program

Beyond the energetic issue there also is an economic one. At the moment the lighting market is dominated by three major companies: OSRAM, Philips and General Electric. Within this oligopoly context Europe holds a dominating position today. The technological breakthrough proposed by the uprising of LEDs will probably shake this European domination and reshape the lighting market on a worldwide level.

LEDs are nowadays mainly fabricated in Asia, for standard LEDs, and in Japan and the USA for high brightness LEDs. The chart in Figure 1.5

9. These three major companies have a €12 billion accumulated annual income (2005), whereas the total lighting world market reaches €15 billion.
10. Luminous flux less than 50 lm.
compares the needs and production capacities in various regions of the world [EDE 06].

This market is now becoming a commodity market where very few European companies are active. On the other hand, Europe can capitalize its know-how on semiconductors in order to play a leading role on the optimized performance LEDs market. With an annual growth rate of 30%\textsuperscript{11}, the Chinese LED industry will soon be part of the world leaders (Figure 1.6) [WUL 07].

\begin{figure}
\centering
\includegraphics[width=\textwidth]{production_consumption.png}
\caption{Production capacities and consumption of High Brightness LEDs in the different parts of the world}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{china_production.png}
\caption{LED production in China (in hundred million units).
For comparison, the total number of LEDs produced in 2000 was estimated to be 100 billion units, of which Chinese production corresponded to less than 10%}
\end{figure}

\textsuperscript{11} Annual growth rate based on production volumes for the period 1997-2006.
Today, the overall LED market is worth $8.5 billion. According to Robert Steele [STE 07], director of optoelectronics programs at Strategies Unlimited, High Brightness and Ultra High Brightness LEDs which have a huge market potential estimated at more than $6 billion with an annual growth rate of 8%. If this trend is confirmed and maintained for the next 5 years, this market segment would be worth close to $9 billion in 2009 and more than $10 billion in the following decade (Figure 1.7).

If this growth is confirmed, LEDs will become one of the key sector in the microelectronic market before 2020 (Figure 1.8). The development of LEDs therefore becomes vital, not only to save energy, but also to re-boost the semiconductor industry, whose growth rate has been slowed down by the telecommunications sector in the last couple of years.

However, as shown on Figure 1.9 [STE 07], the main applications of High Brightness LEDs are mobile devices, displays and automobiles. Today the market share of LEDs in general lighting is around 6%, likely to reach 10% in 2010. Will this share increase in the coming years? Despite the overall optimism due to the spectacular scientific breakthrough obtained and
brought forward by some\textsuperscript{12}, this question today remains unclear because some technological issues are yet to be solved.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.8.png}
\caption{Market predictions for electronics, semiconductors (without LEDs), and LEDs for the next three decades [SZE 02]. If the growth rate of LEDs is confirmed, they will be one of the key sectors of the market before 2020.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.9.png}
\caption{Applications of High and Ultra High Brightness LEDs. General lighting remains behind.}
\end{figure}

\textsuperscript{12} Some predictions reach 50\% market share of the standard light bulbs in the next couple of years, and even 100\% by 2020.
Even if today LEDs are yet to confirm their efficiency in the general lighting systems, they have established themselves in signaling and have begun to penetrate the specialized lighting market. Figure 1.10 summarizes the LED applications as a function of color and luminous flux.

Signaling applications usually require small luminous flux and monochromatic light. In the 1970s, a sole LED was used as an “indicator” (on/off, fault, levels, etc.) on electric and electronic equipments, whereas a few dozen LEDs are nowadays used for a single function on more complex signaling systems (traffic lights for example). Displays require several LEDs of different colors and relatively important flux. Finally, lighting requires white light and powerful luminous flux. Availability of high intensity diodes will no doubt lead to lighting orientated systems, which will function with a limited number of diodes. Knowing this, it is now easier to understand the graph in Figure 1.11 which indicates, according to Steele [STE 07], that LEDs have for a few years reached their “power” zone and now target illumination systems, automotive, back-lighting of large screens and finally lighting.
LEDs for Lighting Applications

Figure 1.11. LEDs have now become mature enough to enter into their power zone [STE 07]

Besides lighting, several original new applications have emerged, such as the illuminations of skyscrapers in Hong Kong or dynamic lighting of the ancient stone “Pont Neuf” bridge in Toulouse (France) as shown in Figure 1.12. LEDs are increasingly entering this promising sector of the “architectural illumination”, where they not only enable viewing but also emphasize the artistic features of major buildings.

Figure 1.12. Left: LED illumination of the Canon tower in Kowloon (Hong Kong) 14 lines with 30 LEDs per line. Each chip consumes 6 W and includes six junctions (2 red, 2 green and 2 blue), for a total power of 12.5 kWh per night [LED 07]; right: arches of the Pont Neuf bridge in Toulouse have been illuminated since November 2007 with a dynamic LED lighting (total power 1 kW)(see color plate section)