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David L. Andrews



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Edited by

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PREFACE

Since its inception, the term “photonics” has been applied to increasingly wide realms of application, with connotations that distinguish it from the broader-brush terms “optics” or “the science of light.” The briefest glance at the topics covered in these volumes shows that such applications now extend well beyond an obvious usage of the term to signify phenomena or mechanistic descriptions involving photons. Those who first coined the word partly intended it to convey an aspiration that new areas of science and technology, based on microscale optical elements, would one day develop into a comprehensive range of commercial applications as familiar and distinctive as electronics. The fulfilment of that hope is amply showcased in the four present volumes, whose purpose is to capture the range and extent of photonics science and technology.

It is interesting to reflect that in the early 1960s, the very first lasers were usually bench-top devices whose only function was to emit light. In the period of growth that followed, most technical effort was initially devoted to increasing laser stability and output levels, often with scant regard for possibilities that might be presented by truly photon-based processes at lower intensities. The first nonlinear optical processes were observed within a couple of years of the first laser development, while quantum optics at first grew slowly in the background, then began to flourish more spectacularly several years later. A case can be made that the term “photonics” itself first came into real prominence in 1982, when the trade publication that had previously been entitled *Optical Spectra* changed its name to *Photonics Spectra*. At that time the term still had an exotic and somewhat contrived ring to it, but it acquired a new respectability and wider acceptance with the publication of Bahaa Saleh and Malvin Teich’s definitive treatise, *Fundamentals of Photonics*, in 1991. With the passage of time, the increasing pace of development has been characterized by the striking

progress in miniaturization and integration of optical components, paving the way for fulfilment of the early promise. As the laser industry has evolved, parallel growth in the optical fiber industry has helped spur the continued push toward the long-sought goal of total integration in optical devices.

Throughout the commissioning, compiling, and editing that have led to the publication of these new volumes, it has been my delight and privilege to work with many of the world's top scientists. The quality of the product attests to their commitment and willingness to devote precious time to writing chapters that glow with authoritative expertise. I also owe personal thanks to the ever-professional and dependable staff of Wiley, without whose support this project would never have come to fruition. It seems fitting that the culmination of all this work is a sequence of books published at the very dawning of the UNESCO International Year of Light. Photonics is shaping the world in which we live, more day by day, and is now ready to take its place alongside electronics, reshaping modern society as never before.

DAVID L. ANDREWS

Norwich, U.K., July 2014

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SOLID-STATE LIGHTING: TOWARD SMART AND ULTRA-EFFICIENT MATERIALS, DEVICES, LAMPS, AND SYSTEMS

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1.1 A BRIEF HISTORY OF SSL [1]

We start this section with a brief history of solid-state lighting (SSL): key materials and device breakthroughs (illustrated in Fig. 1.1); the current state-of-the-art device and lamp architectures that those breakthroughs have enabled; and the current dominant system applications that those device and lamp architectures have enabled.

1.1.1 Stepping Stones: Red and Blue LEDs

Semiconductor electroluminescence was first reported by H. J. Round in 1907, and the first light-emitting diode (LED) was reported by O. V. Losev in 1927 [3]. Not until the birth of semiconductor physics in the 1940s and 1950s, however, was scientific development of technologies for light emission possible.

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For SSL, the use of semiconductor electroluminescence to produce visible light for illumination, the seminal advances were first, the demonstration of red light emission by N. Holonyak in 1962 [4] and, second, the demonstration of a bright blue LED by S. Nakamura in 1993 [5], along with earlier material advances by I. Akasaki and H. Amano [6, 7]. In Sections 1.1.1.1 and 1.1.1.2, we briefly discuss these two advances and their subsequent evolution.

1.1.1.1 Red LEDs: Ever Increasing Efficiencies and Powers As mentioned earlier, the first seminal advance in visible light emission was in the red, and this is the LED color that dominated the early history of LEDs. The first commercial LED lamps were introduced in 1968: indicator lamps by Monsanto and electronic displays by Hewlett-Packard. The initial performance of these products was poor, around 1 mlm at 20 mA, in part because the only color available was deep red, where the human eye is relatively insensitive. Since then, steady, even spectacular, progress has been made in efficiency, lumens per package, and cost per lumen.

As illustrated in Figure 1.1 (top panel), progress in efficiency was largely an outcome of the exploration and development of new semiconductor materials: first

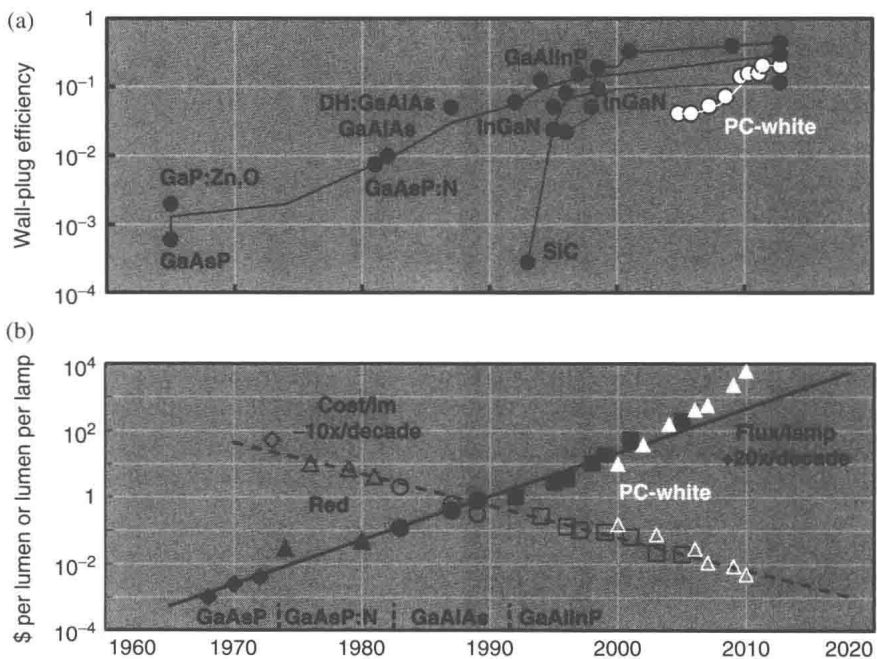


FIGURE 1.1 (a) Historical evolution of the performance (lm W^{-1}) for commercial red, green, blue, and phosphor-converted white LEDs. Data for Part (a) were compiled from Reference 2 and Philips Lumileds datasheets. (b) Historical evolution of the performance (lumen per package) and cost (\$ per lumen) for commercially available red and phosphor-converted (PC) white LEDs. Part (b) was adapted from Reference 1. (For a color version of this figure, see the color plate section.)

GaP and GaAsP, then AlGaAs, then, finally, AlInGaP. Luminous efficacies improved by more than three orders of magnitude: from about 0.02 lm W^{-1} in the 1970s from GaP and GaAsP LEDs to 10 lm W^{-1} in 1990 from AlGaAs LEDs (for the first time exceeding that of equivalent red-filtered incandescent lamps) to the current state-of-the-art of $>150 \text{ lm W}^{-1}$ from AlInGaP LEDs.¹

Also, as illustrated in Figure 1.1 (bottom Haitz' Law panel), progress in efficiency (as well as progress in high-power packaging) then enabled tremendous progress in lumens per package and cost per lumen. In 1968, red LEDs were viewable only if competing with dim indoor lights; by 1985, they were viewable in bright ambient light, even in sunlight. Nevertheless, red LEDs at that time were still limited to small-signal indicators and display applications requiring less than 100 mlm per indicator function or display pixel. Then, around 1985, red LEDs stepped beyond those small-signal applications and entered the medium-flux power signaling market with flux requirements of 1–100 lm, beginning with the newly required center high-mount stop light (CHMSL) in automobiles. At this point in time, red LEDs are well into the $>100 \text{ lm}$ high-flux domain associated with lighting-class applications.

Of course, it was not just that increasingly higher efficiency enabled these increasingly higher flux applications; the needs of these higher flux applications also drove the quest for higher efficiency. In other words, there was a coevolution of higher efficiency (technology push) and power-signaling applications (market pull) that could make use of higher efficiency. Solutions based on large numbers of small-signal lamps were too expensive, thus demanding the development of higher-efficiency, higher-power LEDs. The development of higher-efficiency, higher-power LEDs, in turn, opened up additional stepping-stone markets. The result is the Haitz' law evolution illustrated in the bottom panel of Figure 1.1. In a Moore's-law-like fashion, flux per lamp has been increasing $20\times$ per decade while cost per lumen (the price charged by LED suppliers to original equipment manufacturers, or OEMs) has been decreasing $10\times$ per decade.

1.1.1.2 Blue LEDs: Enabling White Light As mentioned earlier, the second seminal advance in visible LEDs was the blue LED, and this is the color that came to dominate the subsequent history of LEDs. The initial breakthroughs came in the late 1980s and early 1990s, with the discoveries by I. Akasaki and H. Amano that a previously recalcitrant wide-bandgap semiconductor, GaN, could be p-type doped [7] and grown with reasonable quality on lattice-mismatched sapphire [6]. Building on these discoveries, in 1993 S. Nakamura at Nichia Chemical Corporation demonstrated a bright blue LED [5]. As illustrated in the top panel of Figure 1.1,

¹Osram Opto Semiconductors GmbH of Regensburg, Germany, recently announced research results with a record efficiency of 61% for a red high-power LED. The 1 mm^2 chip, housed in a laboratory package, emits at a dominant wavelength of 609 nm with a luminous efficiency of 201 lm W^{-1} at an operating current of 40 mA. At a typical operating current of 350 mA its luminous efficacy is still 168 lm W^{-1} , so even at this high wattage more than half of the electrical energy is converted into light.

efficiency improvements followed quickly, to the point where today’s state-of-the-art blue LEDs, at least at low-power densities, have power-conversion efficiencies exceeding 80% [8].

Most importantly, because blue is at the short-wavelength (high-energy) end of the visible spectrum, it proved possible to “downconvert” blue light into green, yellow, and even red light using passive phosphorescent and fluorescent materials [9]. The visible spectrum could thus be filled out, white light could be produced, and general illumination applications became a possibility. Indeed, as illustrated in the bottom panel of Figure 1.1, Haitz’ Law, developed originally for red LEDs, is continuing for white LEDs. There is now virtually no question that SSL will eventually displace all conventional technologies in general illumination applications, and indeed in virtually every application in which visible light is needed [10].

1.1.2 State-of-the-Art SSL Device Architecture: InGaN Blue LED + Green/Red Phosphors

At this point in time, the state-of-the-art SSL architecture is based on blue LEDs combined with green, yellow, and/or red phosphors, the so-called PC-LED (phosphor-converted LED) architecture illustrated in Figure 1.2. As indicated, the

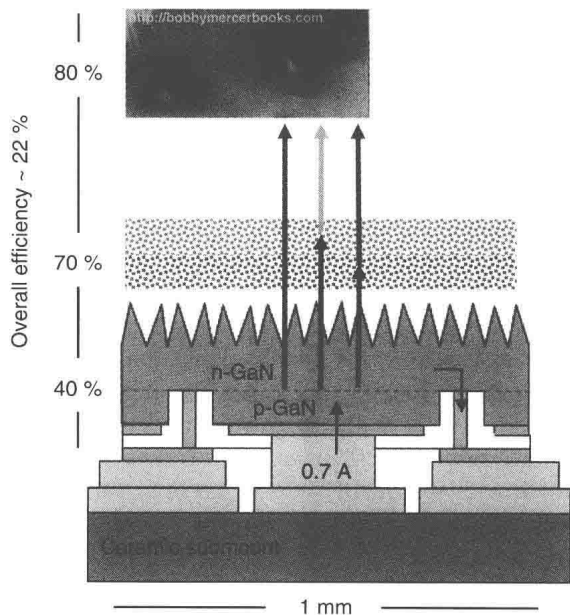


FIGURE 1.2 State-of-the-art PC-LED (phosphor-converted white LED). The blue LED is a thin-film flip-chip (TFFC) design, on top of which red and green phosphors have been coated. The TFFC schematic is courtesy of Jon Wierer (Sandia National Laboratories); the photo at the top is courtesy of Bobby Mercer. (For a color version of this figure, see the color plate section.)