Light-Emitting Diodes – Looking back 100 years and looking forward to the next 10 years

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Abstract

Light-emitting diodes were first demonstrated 100 years ago. We take this opportunity to look back 100 years as to how the technology evolved from its accidental discovery to the most precious light source available to humankind. We also look forward 10 years to exciting new developments and functionalities afforded by light-emitting diodes.

Henry Joseph Round, a British born radio engineer, shown in Figure 1(a), first discovered the phenomenon of electroluminescence, that is, the emission of light from a solid-state material subjected to an electrical current. Round, a prolific inventor, who at the end of his career had more than 100 patents, made the accidental observation that light emanates from a SiC crystal rectifier when stimulated by electricity. The "curious phenomenon" of electroluminescence was reported in a remarkably short publication consisting of only two paragraphs, as shown in Figure 1(b)

The phenomenon of electroluminescence became forgotten until rediscovered in 1923 by a highly talented Russian scientist, Oleg Vladimirovich Lossev, at the age of only 20 years (Lossev, 1923). He took the first photograph of electroluminescent light, which, in his case, was emitted by a SiC metal-semiconductor diode, as shown in Figure 2.

Lossev performed detailed measurements of the current-voltage characteristic, shown in Figure 3, and found that light is being emitted when the diode is biased in the forward as well as the reverse direction. This indicates that both, impact ionization and minority carrier injection, can be the physical origin of light emission. Lacking this understanding, Lossev was puzzled about the origin of the luminescence. He investigated whether light was generated by heat glow (incandescence) and tested the evaporation rate of a droplet of liquid benzene that he had put on the luminous sample surface. He found, however, that the benzene evaporated very slowly and thus correctly concluded that the luminescence was not caused by incandescence. Lossev's studies are the first detailed studies of electroluminescence originating from a semiconductor

The first modern and correct interpretation of light-emission from p-n junctions was offered by Lehovec et al. in 1951 (Lehovec et al., 1951), who postulated that the luminescence is due to minority carrier injection across the boundary of a p-n junction under forward bias. An explanatory band diagram of such a p-n junction is shown in Figure 4.

(a)

Henry Joseph Round
(1881 – 1966)

(b) A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—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. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole. a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y. H. J. ROUND.

Figure 1: (a) Photograph of Henry Joseph Round. (b) 1907 publication of electroluminescence published in the journal Electrical World (after Round, 1907).

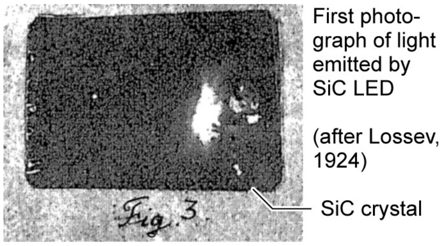

Figure 2: First photograph of electroluminescence emanating from a SiC light-emitting diode (after Lossev, 1924).

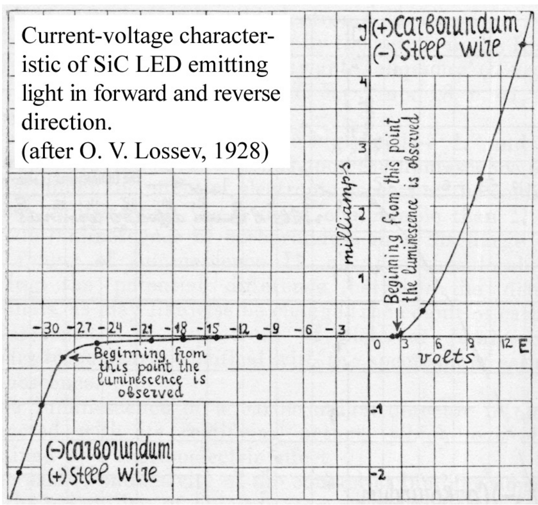

Figure 3: Current–voltage characteristic of SiC LED. Lossev's labeling indicates that electroluminescence is found in the forward- and reverse-bias direction (Lossev, 1928).

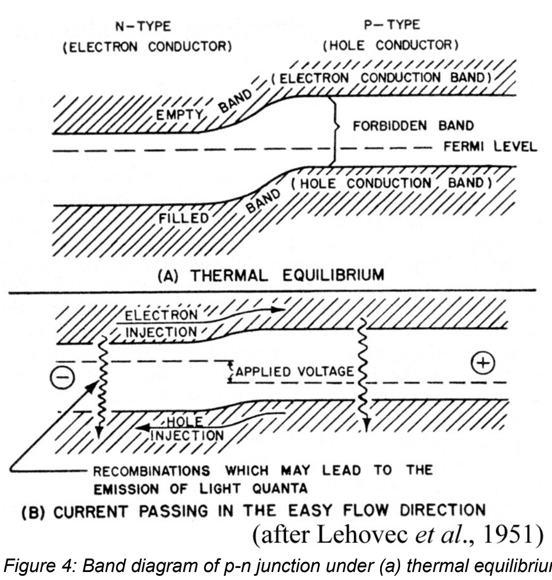

Figure 4: Band diagram of p-n junction under (a) thermal equilibrium conditions and (b) forward bias, called "easy-flow direction" by the authors (after Lehovec et al., 1951).

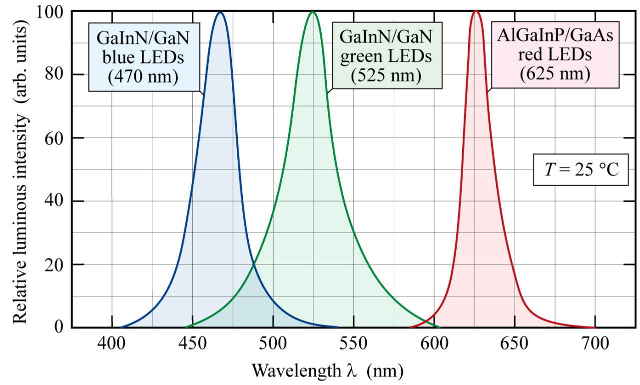

Figure 5: Typical emission spectrum of GaInN/GaN blue, GaInN/GaN green, and AlGaInP/GaAs red LED at room temperature manufactured by Toyoda Gosei Corporation.

LED technology developed more rapidly in the 1950s and following decades. Milestones (that will not be discussed in detail here) include the growth of single crystal GaAs, the development of GaAs LEDs and injection lasers, and visible-spectrum LEDs made from GaPAs, GaP doped with N, GaPAs doped with N, and GaP doped with Zn and O. All of these materials are now considered to be of low-efficiency and unsuitable for modern high-power applications.

To date, three types of material families are capable of high-efficiency visible-spectrum emission: $Al_xGa_{1-x}As$, $(Al_xGa_{1-x})_{0.50}In_{0.50}P$, and GaInN. At the given alloy compositions, AlGaAs and AlGaInP are lattice matched to GaAs. GaInN is grown mostly on sapphire substrates. The three materials cover the entire visible spectrum with exemplary emission spectra shown in Figure 5.

However, the interest for white LEDs is much greater than for single-color LEDs. The mixing of colors, as schematically shown in Figure 6, is a viable way to attain white light with a high color rendering index.

The dominant commercial implementation of white light with LEDs is based on the use of a phosphor that is photo-excited by a blue LED chip as shown in Figure 7(a). The mixing of the two complementary colors, e.g. blue and yellow as shown in Figure 7(b), results in white light, which can have, for a sufficient spectral breadth of the yellow emission, a high color rendering index. LED manufacturers have announced luminous efficacies of 100 – 150 lm/W during 2006 and 2007. This compares very favorable to the luminous efficacy of 15 and 70 lm/W of incandescent and compact fluorescent lamps, respectively.

Bergh et al. (2001) pointed out that very substantial benefits would result when energy wasting conventional light sources would be replaced by highly efficient solid-state sources. These benefits include the savings of tremendous amounts of primary and electrical energy, reductions in the emission of gases causing acid rain (SO_2) and global warming (CO_2), emission of mercury, reduction of waste heat afflicting our rivers and streams, and financial savings. Furthermore, 280 major electrical power plants could literally be switched off when transitioning from conventional to solid-state sources (Schubert et al., 2006). In addition to the lighting market, there is another huge emerging market for LEDs: liquid-crystal displays (LCDs) for televisions and computers, where LEDs promise mercury-free backlighting with a greater color gamut than attainable with fluorescent lamps, a reduction of motion artifacts, and other benefits.

Yet, there is one other aspect that fundamentally distinguishes solid-state sources from conventional light sources, namely controllability (Schubert and Kim, 2005). Scientists and engineers, who strive to control and tune all properties of an LED, have the unprecedented challenge of constructing light sources that can be controlled in terms of spectrum, polarization, color temperature, temporal modulation, and spatial emission pattern, as illustrated in Figure 8. Some of the properties can be controlled fairly well, e.g. the optical spectrum. However for other properties, such as polarization, only primitive or no control at all exists to date, so that novel concepts are needed.

With LEDs becoming the most versatile light source available, the control of emission will become increasingly important, particularly when considering the fact that conventional light sources are essentially inaccessible for such control. New classes of benefits based on the enhanced functionality will emerge. The following examples illustrate this point: (i) LCDs ideally would be backlit by linearly polarized sources, because one of the first optical components of an LCD panel is a polarizer, which discards (i.e. reflects) the unwanted polarization. Thus, polarized light sources are highly desirable for LCD applications. (ii) Over evolutionary periods of time, humans have adapted to our natural light source – the sun. During the course of a day, the color temperature and intensity of sunlight change by orders of magnitude. Since our wake-sleep rhythm is directly coupled to light, the control of brightness and color temperature would be highly desirable. (iii) In transportation applications, light sources carry mostly visual signals. However solid-state light sources can also carry encoded information without affecting the visual appearance. Thus a red traffic light, that carries the visual order “stop”, could also carry an encoded signal communicating to an intelligent car to stop.

Although 100 years have passed since Henry Joseph Round stumbled across the SiC rectifier crystal that, unexpectedly, emitted light, and although this field has seen breathtaking progress, it is clear that the potential of LED technology goes far beyond its current use. We thus realize that we are just the beginning of the LED revolution.

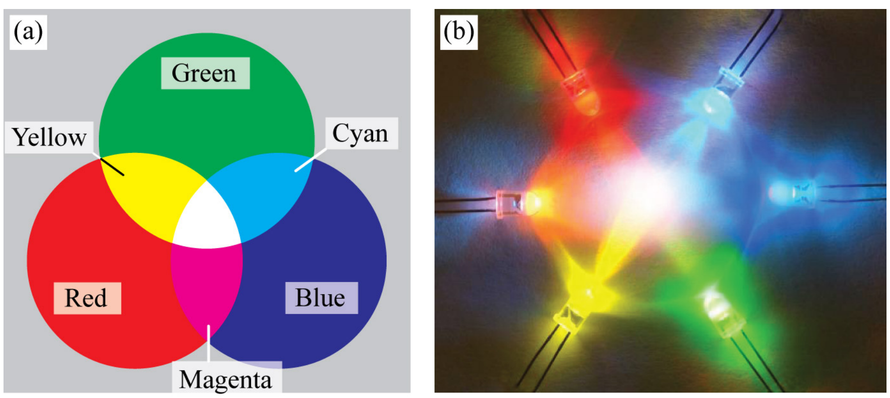

Figure 6: (a) Schematic of additive color mixing of three primary colors. (b) Additive color mixing using LEDs.

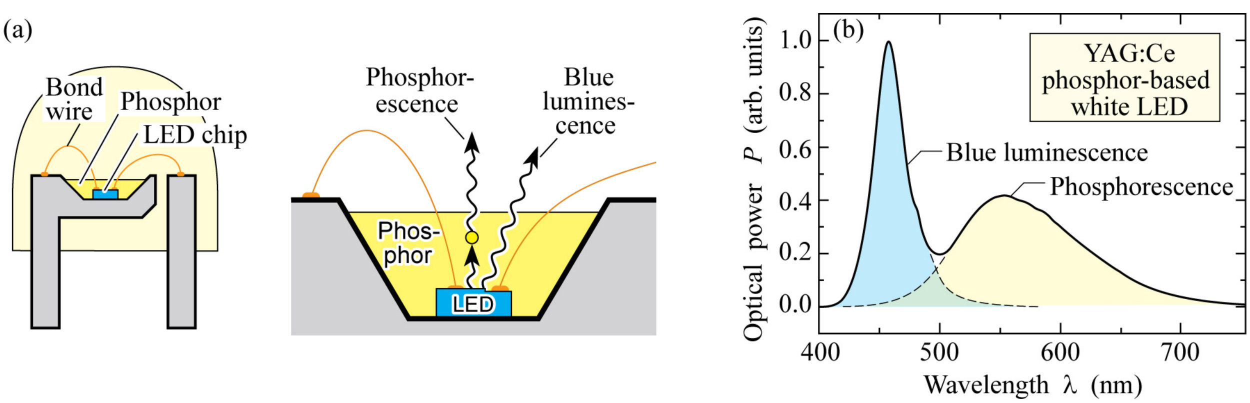

Figure 7: (a) Structure of white LED lamp consisting of a GaInN blue LED chip and a wavelength-converting phosphor introduced by Nichia Corporation (Anan, Tokushima City, Shikoku Island, Japan).

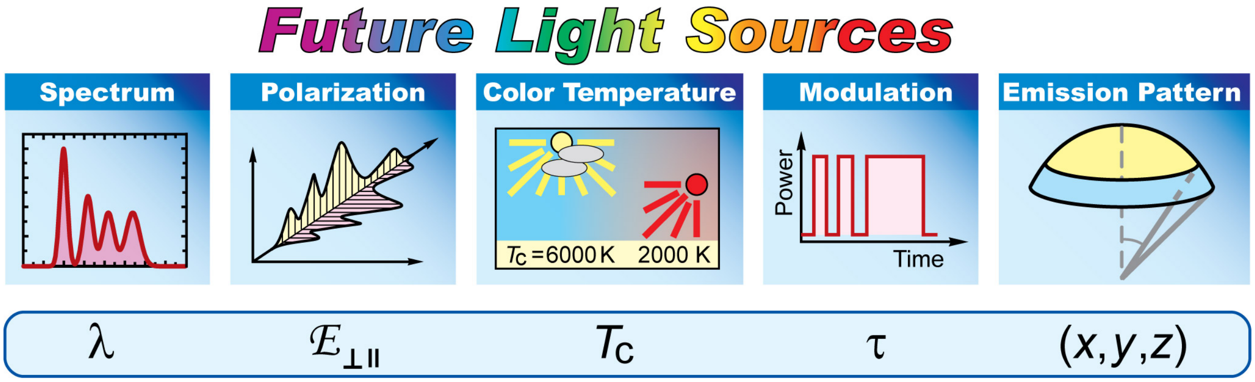

Figure 8: Controllable parameters of solid-state sources include the emission spectrum, polarization, color temperature, modulation, and far-field emission pattern.

Note: Parts of this publication are scheduled to appear in the October 2007 issue of *Compound Semiconductor Magazine* (IOP Publishing, Bristol, UK, 2007).

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