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# Light-Emitting Diode Technology for Solid-State Lighting

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Light-emitting diode (LED) technology has advanced tremendously since the first demonstration of a practical visible-spectrum LED almost 50 years ago (Holonyak and Bevacqua, 1962). Subsequent LEDs initially used in simple displays (e.g., calculators, watches) and indicator lamps (e.g., clock radios, compact disc players) have been replaced by more powerful, and more sophisticated, devices that produce not only red and green emissions, but also blue and, most important, white. The latter were enabled by the development of the indium-gallium-nitride (InGaN) material system, which was made possible after key breakthroughs in materials technology were made in Japan in the late 1980s (Amano et al., 1986, 1989).

In the early 1990s, efficient blue LEDs based on this material system were demonstrated (Nakamura et al., 1993, 1995), and in combination with a well known yellow-emitting phosphor for scintillators and cathode-ray-tubes,  $Y_3Al_5O_{12}:Ce^{3+}$  ("YAG"), these devices demonstrated emission of solid-state white light for the first time (Nakamura and Fasol, 1997). In the late 1990s, Watt-class, high-power LEDs (Höfler et al., 1998) that delivered meaningful levels of light output (from an illumination perspective) were made commercially for the first time.

Since then, InGaN-based LEDs have become more efficient and even more powerful, and the availability of suitable phosphors has increased; today the variety, light output, and quality of LED-based white light has reached the point that it is beginning to unseat conventional lighting technologies in general illumination

applications. Indeed, with their high energy efficiency and strong environmental attributes (no lead, no mercury, long operating lifetime), LEDs are certain to be dominant in the future of lighting.

## BASICS

In principle LEDs are similar to the simple silicon-based p-n junction diode. Layers of semiconductor material are deposited by an epitaxial method (usually metal-organic chemical vapor deposition [MOCVD]) (Manasevit and Simpson, 1969) on a suitable substrate wafer. The layers are treated (i.e., doped) with extrinsic impurities to form negatively charged (n-type) and positively charged (p-type) regions. The charges induce a built-in electric field at the interface between these regions (the p-n junction).

When sufficient positive external voltage is applied across Ohmic contacts to the p- and n-type regions, the built-in electric field across the p-n junction is reduced, thereby initiating current flow. The current flow is sustained by the recombination of negative charge-carriers (electrons) with positive charge-carriers (holes) in the vicinity of the p-n junction. Each recombination event produces energy approximately equal to the electronic energy band-gap of the semiconductor material at the p-n junction. Since silicon is an *indirect* band-gap semiconductor (Bardeen et al., 1956), electron and hole recombination in silicon requires interaction with the crystal lattice (i.e., the recombination current generates mostly heat).

In other semiconductor materials, especially many III-V compound semiconductor materials, such as gallium arsenide (GaAs), indium phosphide (InP), and gallium nitride (GaN), the transition for an excited electron to the valence band does not require momentum (i.e., lattice interaction), so the released energy is in the form of light. Even in these *direct* band-gap materials, which are used for LEDs, a radiative transition must always compete with crystal lattice imperfections and impurities that produce non-radiative transition pathways. Nevertheless, in very pure material, such as GaAs and InP, the radiative efficiency (internal quantum efficiency) can approach 100 percent. In addition, the external applied voltage is approximately the same as that of the emitted photon. We can thus see that the LED has the potential to generate light with almost 100 percent efficiency, providing a basis for what has been called the “ultimate lamp” (Holonyak, 2000).

Typically, a layer(s) of specific composition is inserted at the p-n junction to allow control over the energy band-gap, and thus over the photon energy (or wavelength), of emission. Today the InGaN-GaN system is used for wavelengths of ~ 365 (ultraviolet, UV-A) to 550 (yellow-green) nanometers (nm). For amber (~ 590 nm) to deep red (~ 650 nm) emission, the most efficient LEDs are based on the (Al,Ga)InP system.

Efficient generation of light alone does not make for an efficient diode. The

light must escape the semiconductor crystal into air to be useful. Accomplishing this is less straightforward than one might expect, because the optical refractive indices of most III-V semiconductors is quite high (GaN:  $n \sim 2.4$ , InGaP:  $n \sim 3.5$ ). The high refractive index means that light generated inside the semiconductor must impinge near-normal incidence at the semiconductor/ambient interface in order to escape. Light incident at higher angles is totally internally reflected back into the semiconductor, increasing the chance of absorption (e.g., at metal electrodes, etc.). Various means are used to increase the probability of light extraction, such as chip shaping, texturing, and photonic crystal structures. In the highest performing LEDs today, light extraction efficiency is  $\sim 80$  percent for InGaN and  $\sim 60$  percent for AlGaInP (Krames et al., 2007).

For ease of use and to encourage wide adoption in applications, the LED interface for users must be similar to interfaces with other electronic components. Thus means of accessing and contacting (e.g., reflow solderability) the electrodes and, especially for high-power LEDs, removal of heat, are critical factors. The latter is usually accomplished by including a heat-sink element (usually copper) into the primary LED package. Indeed, today's high-power LED packages (Figure 1) have very little resemblance to their "5mm lamp" ancestors, which had small chips

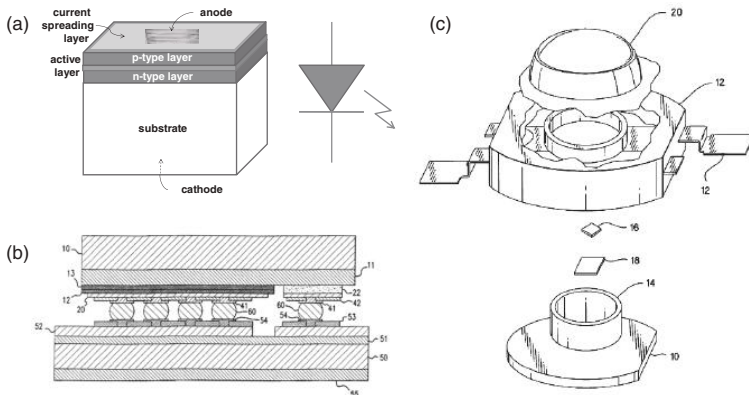


FIGURE 1 (a) Simple LED chip construction (conductive substrate). Typically, the n-type layers are epitaxially deposited, followed by the active layer(s), and then the p-type layers. Ohmic contact electrodes are formed for injecting current into the device. In many cases, current spreading means are employed to provide uniform electrical injection within the thin epitaxial layers. (b) Cross section of a high-power flip-chip LED, showing a considerably more complex structure that is the present requisite for state-of-the-art LEDs for illumination (Krames et al., 2003). (c) Exploded view of a high-power LED package (Carey et al., 2001). High-power chips require sophisticated packaging with good optical efficiency and means for thermal management.

that dissipated less than 100 milliWatts (mW) and produced very little heat. LEDs used today for automotive forward lighting are capable of dissipating up to 10 Watts of power (Dupuis and Krames, 2008).

**PERFORMANCE**

Sustained improvements in the material quality, diode-layer structure, and overall chip architecture have improved the performance of LEDs dramatically over the last decade or so. Figure 2 shows the best-reported external quantum efficiencies (i.e., the ratio of photons out per electrons injected) for power LEDs for both InGaN and AlGaInP. The best InGaN devices are in the blue-emitting region and have external quantum efficiencies of ~66 percent, meaning that two out of every three electrons injected into the electrical contacts emit a useful photon. Figure 2 also shows the photopic luminosity function,  $V(\lambda)$ , which is a measure of the response of the human eye as determined by the Commission Internationale de l'Éclairage (CIE).

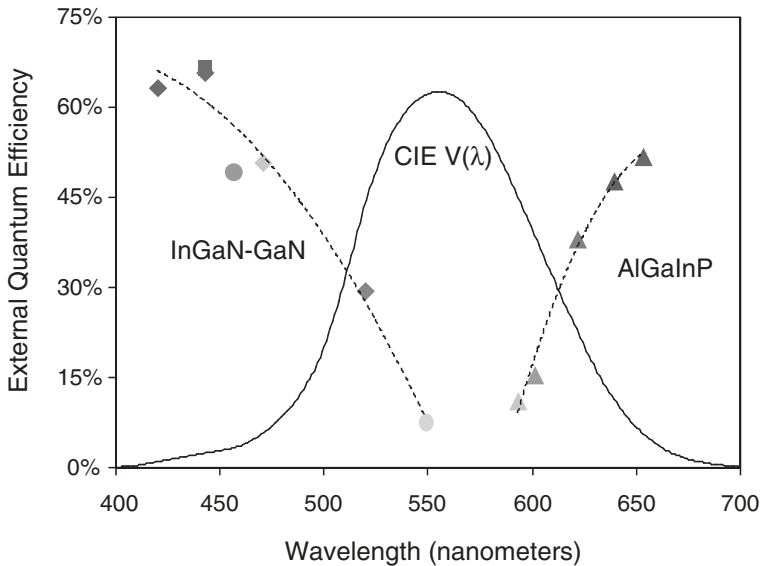


FIGURE 2 Best-reported external quantum efficiencies for high-power InGaN-GaN and AlGaInP LEDs vs. emission wavelength at reasonable operating current densities. Also shown is the human eye responsivity as determined by the photopic luminosity function,  $V(\lambda)$ , wherein one Watt of optical power at 555 nm corresponds to 683 lumens. Sources: Krames, 1999, 2009; Michiue et al., 2009; Sato et al., 2008, and Vampola et al., 2008.

It is an unfortunate truth that, as Figure 2 shows, the most efficient LED wavelengths are at either side of the visible spectrum (i.e., towards the UV or infra-red). For AlGaInP, the reason for the lower performance at shorter wavelengths is that AlInP is an indirect band-gap semiconductor, and increasing the substitution of Ga by Al for shorter wavelength emission fundamentally reduces the probability of radiative (vs. nonradiative) transitions.

For InGaN, the reason for decreased efficiency at longer wavelengths can be attributed to the miscibility gap between GaN and InN (El-Masry et al., 1998), the increasing strain with higher InN mole fractions, and the fact that this wurtzite (asymmetric) crystal generates polarization-induced built-in electric fields at hetero-interfaces (Bernardini et al., 1997) that perturb the conduction- and valence-band profiles of layer structures and complicate the efficient recombination of electrons and holes.

By working on a non-basal plane of GaN, polarization fields can be reduced, and the 550 nm data point of Figure 2 is, in fact, from a “semi-polar” (11–22) orientation InGaN-GaN LED (Sato et al., 2008) and not the conventional “polar” (0001) orientation. Although considerable improvement is possible (and expected) in the “green gap” region, the present performance of LEDs is nevertheless already very competitive and, in many cases, far superior to, conventional lighting technologies.

## WHITE LEDs

Although the combination of separate blue, green, and red LEDs can be tuned to make white light, the most common approach applied in industry is to down-convert blue, violet, or UV light into longer wavelength light by using phosphors, which are excited by the LED primary emission. The phosphors are typically applied in various ways around or on top of the LED chip. The most common method is to use YAG phosphor powder (typically mixed in an organic binder) to overlie a blue LED chip emitting in the range of 440–460nm. The blue LED chip excites the YAG, which produces yellow light. The YAG phosphor powder loading is tuned to allow a precise amount of the primary blue light to “leak” through. When done properly, the combination of the leaked blue light and the yellow phosphor emission yields a white light chromaticity in the 4,000–7,000 Kelvin (K) correlated-color-temperature (CCT) regime with a fairly high conversion efficiency. To generate “warmer” white chromaticities (2,700–4,000K), red phosphors are typically added to the mix (Mueller-Mach et al., 2002).

Figure 3 shows the relative efficacies of white-light generation at ~ 2,900K by: (i) tungsten-filament incandescence; (ii) a tri-phosphor fluorescent lamp (FL); and (iii) an LED with blue-pumped phosphors. The incandescent tungsten (household filament bulb) radiates as a blackbody and at 2,900K generates by far most of its radiation in the infrared range (i.e., heat). The overlap with the visible spectrum is very poor, and involving the blackbody spectra irradiance with  $V(\lambda)$

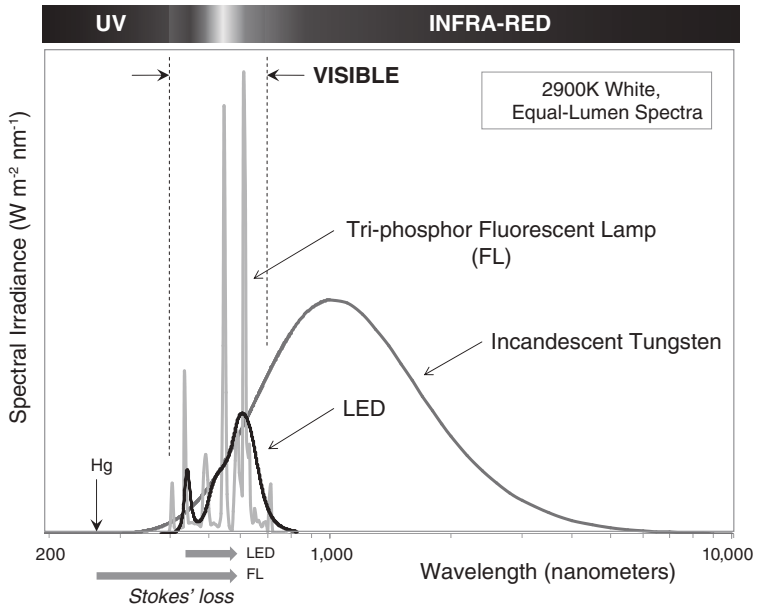


FIGURE 3 Equal-lumen spectra of white light emitters based on (i) incandescent tungsten, (ii) tri-phosphor fluorescence, and (iii) phosphor-converted LEDs, all at a CCT of  $\sim 2900\text{K}$ . The incandescent bulb radiates most of its energy outside the visible spectrum (400–700nm) as heat. The Stokes energy loss for down-conversion is indicated for the fluorescent lamp (FL) and LED.

gives a maximum luminous efficacy for this source of  $\sim 16$  lumens per electrical Watt ( $\text{lm}/\text{W}$ ). In practice, incandescent bulbs perform at a lower level ( $\sim 10\text{--}15$   $\text{lm}/\text{W}$ ) than this theoretical limit.

The tri-phosphor FL (ii) uses line-emitting phosphors excited by the mercury (Hg) vapor discharge at 254nm. The phosphors are specifically selected so that their emission peaks are in the eye-sensitive region, and indeed the maximum luminous efficacy for the FL spectrum in Figure 3 is quite high, 360  $\text{lm}/\text{W}$ . However, the enormous Stokes' loss in photon energy from 254nm to  $\sim 550\text{--}600\text{nm}$  caps the maximum luminous efficacy (in  $\text{lm}/\text{W}$ ) to  $\sim 150$   $\text{lm}/\text{W}$ . In practice, other loss mechanisms also come into play, and typical performance for tube FLs are in the 80–90  $\text{lm}/\text{W}$  range.

The LED (iii) in Figure 3 uses a blue emitter to pump a combined green and red phosphor mix to obtain the desired CCT of 2,900K. The high intensity of

blue light at the chip surface typically requires using fast-decaying phosphors to provide broad emission. The result is an emission spectrum that closely resembles the targeted blackbody curve in the visible-spectrum regime.

One might assume that this provides a more *natural* appearing light, compared to the high-intensity peaks of the FL spectrum, but as of this writing the author is aware of no studies of the effects of smooth vs. spiked spectra on human perception. The smoother spectrum brings a penalty in luminous efficacy, compared to the FL, and the maximum for the LED in this case is 310 lm/W. However, for a blue-pumped LED the Stokes loss is only ~ 20–25 percent, putting the maximum achievable efficacy at ~ 250 lm/W. Thus the obtainable luminous efficacy for the LED is 60–70 percent higher than for FLs and more than 15 times higher than for incandescent lamps.

Figure 4 shows the performance evolution of “warm white” (2,700–4,100K) high-power LEDs and an indication of projected performance from a recent report commissioned by the U.S. Department of Energy (DOE, 2009). Future LED performance is projected to be ~ 160 lm/W by 2018, which is still far from

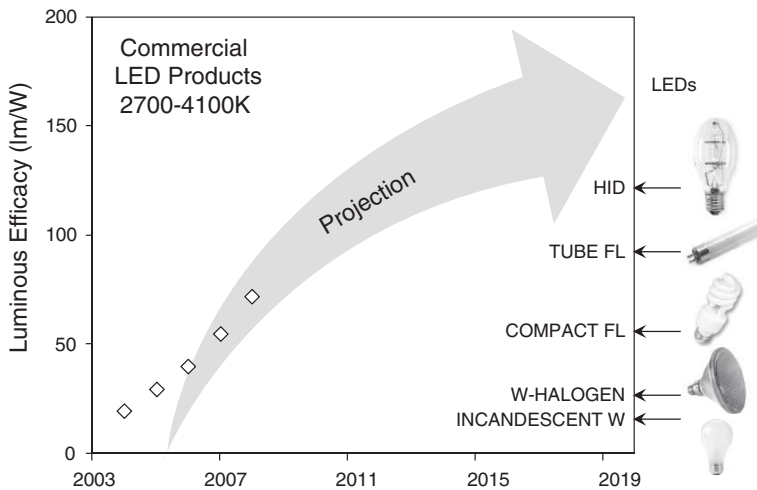


FIGURE 4 Evolution of luminous efficacy (lumens per electrical Watt) for commercial “warm white” (2700–4100K) LED products as well as a projected performance based on information compiled for the U.S. Department of Energy. At right, typical luminous efficacies are indicated for conventional lighting technologies including incandescent tungsten, tungsten-halogen, compact fluorescent, tube fluorescent, and high-intensity-discharge lamps.

the maximum attainable performance described above. Nevertheless, even at the targeted performance level, LEDs would outperform all known technologies for generating white light, including high-intensity-discharge (HID) lamps.

## CONCLUSIONS

As LED technology approaches its 50th anniversary, it appears well positioned to penetrate the general lighting market and change the world as we know it. LED-based light sources promise to provide reduced energy consumption, longer operating lifetime (and thus reduced waste), and no generation of materials known to be hazardous to the environment, such as lead or mercury. In addition, the low-voltage drive and fast switching speed of LEDs means lighting for the future could look very different from the lighting we know today. It may include dynamic control features for automatic mood-setting or tuning of intensity and color to increase workforce productivity or simply to elevate people's moods. These additional features, combined with the energy savings and other "green" aspects of LEDs, ensure that LED-based solid-state lighting has a very bright future.

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