# Prospects for LED lighting

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More than one-fifth of US electricity is used to power artificial lighting. Light-emitting diodes based on group III/nitride semiconductors are bringing about a revolution in energy-efficient lighting.

Since the development of incandescent light bulbs in the late 1800s, various methods of producing white light more efficiently have been investigated. Of these, white-light sources based on light-emitting diodes (LEDs) look set to have a considerable impact on issues such as energy consumption, environment and even the health of individuals. Roughly 22% of the electricity generated in the United States is dedicated to lighting applications[1]. If all conventional white-light sources in the world were converted to the energy-efficient LED light sources, energy consumption could be reduced by around 1,000 TW h $yr^{-1}$, the equivalent of about 230 typical 500-MW coal plants, reducing greenhouse gas emission by about 200 million tonnes (ref. 2).

White-light sources based on reliable and energy-efficient LEDs have only recently been made possible through developments in semiconductors (Fig. 1 shows a white-light LED in action). It is possible to generate light in semiconductor materials (such as GaN or AlInGaP) by injecting electrons into the conduction band of the material and providing lower-energy sites ('holes') in the valence band into which they can fall, thereby creating light of a colour corresponding to the energy gap between the conduction band and valence band, also called the bandgap. A light-emitting diode is an electronic device integrating electrical access to the bandgap structure and allowing for efficient light generation.

LEDs essentially consist of three different types of materials layered on top of each other. The bottom layer has a high concentration of free electrons (for example n-type GaN doped with Si) followed by multiple alternating thin layers (1–30 nm) of material with a smaller bandgap (InGaN/GaN), also called quantum wells. The sandwiching of a smaller-bandgap material (InGaN) between layers of larger-bandgap material (GaN) creates a well that spatially traps electrons and holes, allowing them to recombine efficiently, generating light with the wavelength of the smaller-bandgap material. Above this 'active layer', there is a layer of material with a high concentration of holes (p-type GaN doped with Mg).

Until recently, the only high-luminosity LEDs available emitted red light. For white light, however, two or more wavelengths are required to generate a broad spectrum of light that is a better approximation of a black-body radiation curve, such as that of the Sun. One way to produce additional colours is to use a material that absorbs light of one wavelength and emits at longer wavelength. Phosphors are commonly used for this task and a select few have received considerable attention, such as rare-earth-doped yttrium aluminium garnets (YAG:RE). For example, cerium-doped YAG can absorb blue and ultraviolet light and emit yellow light relatively efficiently[3]. Crucial to this process is the fact that higher-energy light (for example ultraviolet or blue) is converted to lower energy (for example yellow or red). Therefore, LEDs emitting red light cannot be used for white-light generation using phosphors; instead a short-wavelength ultraviolet, violet or blue LED is required.

Early attempts to produce blue-emitting semiconductors focused on SiC, but these devices proved inefficient (0.03% efficiency[4]) owing to the material's indirect bandgap. The GaN revolution has since provided efficient ultraviolet, violet and blue light emitters. GaN is a direct-bandgap semiconductor material with a 3.45-eV bandgap, which corresponds to near-ultraviolet light (364 nm). GaN was first investigated as a potential material for LEDs in the late 1960s by Paul Maruska and Jacques Pankove at the Radio Corporation of America (RCA) and in later years additionally by Isamu Akasaki and co-workers at Nagoya University in Japan and by Shuji Nakamura at Nichia Corporation.

After many years of research, great advances were made by growing high-quality GaN on a foreign material, sapphire ($Al_2O_3$), in 1986 (ref. 5) and then by demonstrating p-type conductivity in GaN doped with Mg by activating the material in a post-growth anneal[6]. These breakthroughs led to the first high-efficiency blue LEDs of the time (1.5% efficiency[7]) in 1992, and then to the first viable blue and green LEDs at efficiencies up to 10% in 1995 (ref. 8). Recent developments[9] have also yielded high-brightness, yet still rather inefficient, yellow LEDs.

Largely owing to these achievements, it is now possible to generate white light using LEDs. The three most popular approaches are shown in Fig. 2a. These are a blue LED with yellow phosphors; an ultraviolet LED with blue and yellow phosphors (or red, green and blue phosphors); and a device that combines red, green and blue LEDs. Figure 2b presents

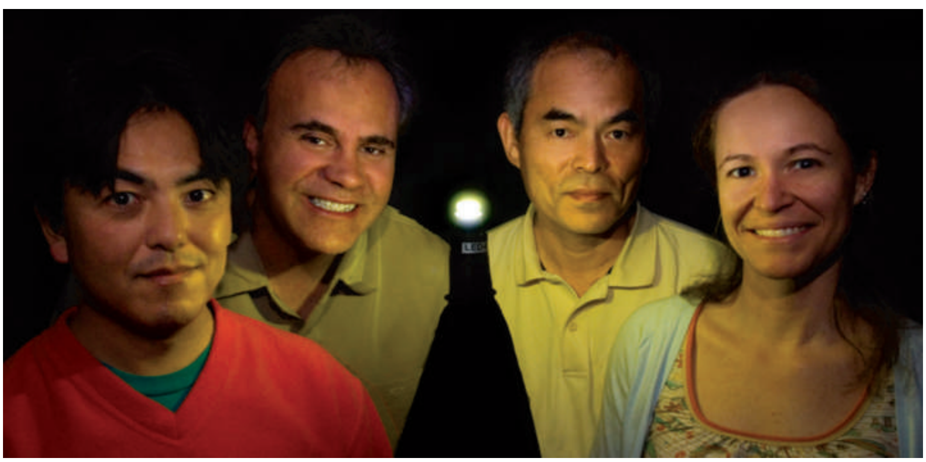

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**Figure 1 |** White light from a cone-shaped LED illuminates researchers from the University of California, Santa Barbara. From left to right, Hisashi Masui, Steve DenBaars, Shuji Nakamura, Natalie Demille.

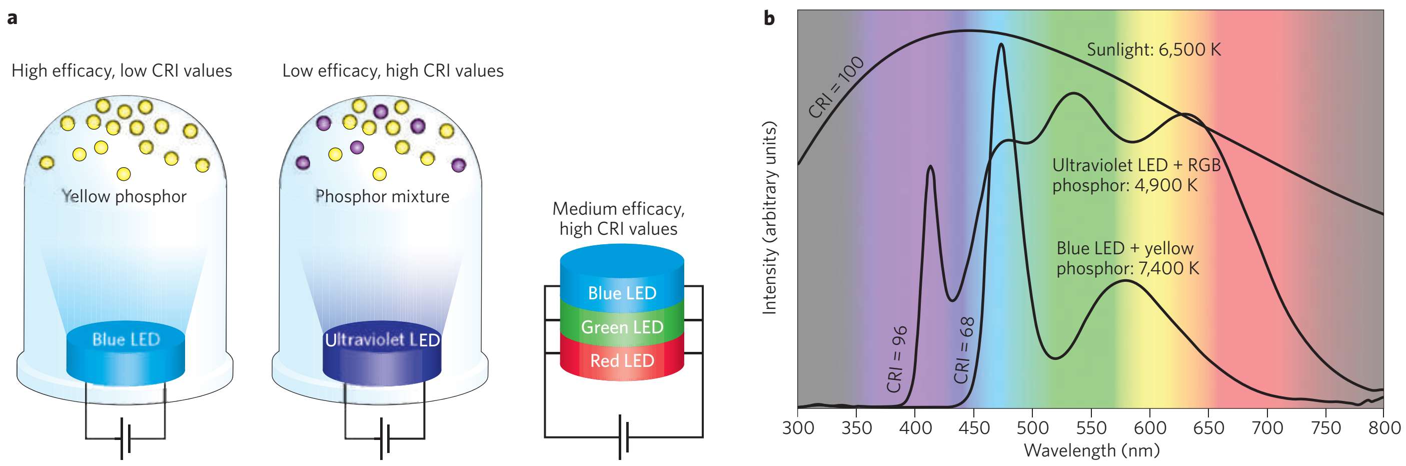


**Figure 2 |** White light based on LEDs. **a**, Three dominant ways to produce white light based on LEDs. **b**, Comparison of the spectrum of ideal sunlight with two LED-based white-light sources.

the spectra for two phosphor-based white LEDs and sunlight.

Naturally there are pros and cons to each of the schemes. The advantage to using a blue LED and a yellow phosphor is its high theoretical efficacy, which is attractive for the creation of a cheap, bright white-light source. However, this benefit comes at the expense of a lower value for the colour-rendering index (CRI; see Box 1 for definition), which is typically so low that such devices are undesirable for indoor use. Ultraviolet LEDs with phosphor mixtures provide a better CRI value and are suitable for indoor applications but at the expense of poorer efficacy. To control white light dynamically, the third approach, a combination of three (or more) LEDs of different wavelengths is attractive, and may lead to higher efficacies than the ultraviolet–phosphor LEDs, but will generally be the most expensive option until further advances are made. The historic development of luminous efficacy for the most common white-light sources is shown in Fig. 3.

## Performance parameters

There are several key performance parameters to consider when discussing LEDs. Recent research has heavily focused on improving the external quantum efficiency (EQE), which is commonly defined as the product of the injection efficiency, the internal quantum efficiency (IQE) and the extraction efficiency. The injection efficiency is the ratio of electrons being injected into the quantum wells to those provided by the power source, the IQE is the ratio of photons generated to the number of electron–hole recombinations, and the extraction efficiency is the ratio of photons leaving the LED to those generated.

**Box 1 | The metrics for judging a white-light source**

### Luminous efficacy

To quantify the energy efficiency of a white-light source, it is common to consider its ability to produce a visual sensation. This quantity, called luminous efficacy, derives from convoluting the spectral power distribution of the light source with the spectral sensitivity of the human eye, which peaks at 555 nm (green). Luminous efficacy is calculated by taking the ratio of the produced visual sensation (expressed in lumens, where 1,700 lumens is roughly equal to the light output of a 100-W incandescent bulb) to the electrical power required to produce the light (expressed in watts).

### Colour temperature

White light may be classified as being warm, neutral or cold and is referenced with respect to the white light emitted by an ideal white-light source, for example black-body radiation sources such as the Sun or a body at a certain temperature. As the temperature of an ideal black body is raised from 2,000 K to 10,000 K, the emitted white light goes from reddish ('warm') through to bluish ('cold'). LEDs can currently be engineered from warm through to cold (2,500 K to 10,000 K), although cost and efficiency factors need to be considered. Without filters, incandescent bulbs typically glow a warm yellowish white. Fluorescent lights are generally bluish, but recent phosphor engineering has pushed their colour into the warmer, yellowish white.

### Colour-rendering index

Another important parameter is the ability to reproduce colours of an object as seen under an ideal white-light source, such as the Sun. By illuminating eight standard colour reference samples, first with an ideal white-light source (at the same colour temperature as the source being tested), then with the white-light source of interest, it is possible to quantify the deviation in reflected spectra. From these deviations, the colour-rendering index (CRI) is determined. In this scheme sunlight and incandescent bulbs have a value of 100, which is ideal. Other white-light sources reproduce the colour of objects with varying degrees of perfection, signified by a lower CRI. Generally, values above 80 are considered sufficient for indoor lighting, whereas lower values are acceptable for outdoor lighting (street lights). Metal halides have CRI values between 85 and 95, LED-based white-light sources 60–95, fluorescent lamps 50–90, mercury vapour 20–50 and sodium lamps 5–20.

In the case of white-light generation using phosphors, a conversion efficiency factor (the ratio of emitted longer-wavelength photons to shorter-wavelength absorbed photons) also needs to be factored into the EQE determination.

Future progress should depend on improvements in each of these areas: IQE; light extraction efficiencies; elimination of significant roll-off in EQE when operating LEDs at high currents to push today's peak laboratory EQE values

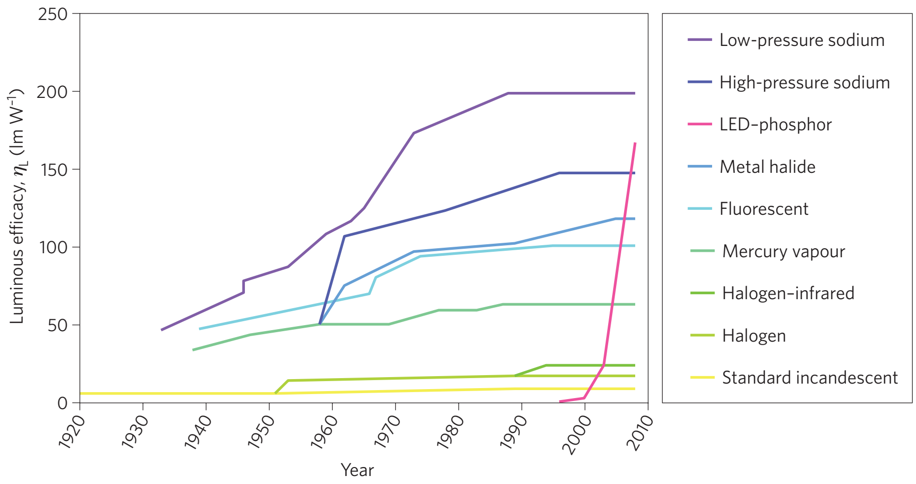


**Figure 3 |** Historic development of the most common white-light sources and improvements in their ability to produce white light efficiently. The theoretical limit for luminous efficacy $\eta_L$ is less than 420 lm W$^{-1}$ for good-quality white light, and 263 lm W$^{-1}$ for a blue LED combined with a yellow phosphor. For definition of luminous efficacy, see Box 1. (Data from refs 2, 21.)

of ~75% (ref. 10) to higher values; and phosphor conversion efficiency.

The IQE of today's best LEDs is at least 75% (ref. 10) and may even be approaching 80%. To make further improvements towards 100% IQE, non-radiative recombination centres need to be eliminated. More importantly, a shift is needed in growing the LEDs, from polar to nonpolar or semipolar crystallographic directions instead, to eliminate strain-induced electric polarization fields currently seen within the quantum wells[11]. Generally speaking, polar devices, which are currently the dominant devices produced in industry, are proving to be inferior to nonpolar devices as recombination is not as efficient. This topic is currently an important research area, as semiconductor growth techniques in nonpolar crystallographic directions are still immature[12]. Growing in nonpolar or semipolar directions allows the device structure to be further optimized, for example by increasing the thickness of the quantum wells[13], thereby further increasing the IQE.

When it comes to the extraction efficiency, because of large differences in the refractive indices of air and the GaN materials system, a considerable fraction (90–95%) of the generated photons within the LED are trapped by total internal reflection. Methods under investigation include ways to increase the amount of light hitting the LED–air interface at near-perpendicular values to reduce the occurrence of total internal reflections (for example, surface roughening techniques to generate microscale cones on the surface[14], optimizing the exterior shape of the LED chip and patterning the sapphire substrate to reduce light scattering), and methods of eliminating the passage of light through certain layers of material by integrating or embedding photonic crystals into the LED[15].

An important mystery that needs to be solved in the near future is the decrease in EQE seen when operating at higher current densities (over 10 A cm$^{-2}$) when trying to increase the luminous flux (currently about 160 lumens per power LED chip, roughly equivalent to a 30-W incandescent bulb). This 'efficiency droop' may be associated with enhanced Auger recombination[16], or possibly carrier overflow from the quantum wells due to the high carrier population[17]. Although the exact cause has not yet been determined, it is believed that using thicker quantum wells and altering the structure to lessen carrier overflow will reduce this to the point that it will be possible to operate at higher efficacies and currents. Progress is also being made in optimizing the phosphor materials and mixtures to improve conversion efficiencies[18] and improve the quality of the white light through longer-wavelength phosphor emission. This needs to continue[19].

## Bright future

White-light sources based on LEDs have a promising future. Continued advances are expected to exceed Haitz's law[20], which forecasts that every 10 years the amount of light generated by an LED increases by at least a factor of 20, while the cost per lumen drops by at least a factor of 10. The ultimate goal for LED-based white lighting is to replace all incandescent bulbs and compact fluorescent lamps to provide an energy-efficient and long-lasting option for everyday use. It is anticipated that cost-effective drop-in replacements for incandescent bulbs will be readily available in the next couple of years once mass-produced LEDs have comparable metrics to the best LEDs in research laboratories today and the electronic circuits that operate LED structures have improved efficiencies and form factors.

Ultimately it is clear that LEDs will result in reduced energy costs for lighting, and will also eliminate the exposure to mercury found in fluorescent bulbs. Although initial costs may seem steep to an end-user (LEDs are today around 50 times as expensive as incandescent light bulbs and around seven times the cost of compact fluorescent lamps, based on normalized light output), when averaged out over the lifetime of the product LEDs are actually already a cheaper solution (around a seventh of the price of incandescent bulbs and two-thirds the price of compact fluorescent lamps) and will soon become more so.

So what are the ultimate limitations to white LED performance? The key constraints, the theoretical maximum efficacy (~260 lm W$^{-1}$) and, when operating under high currents the thermal management and degradation of the polymer material that encapsulates the LED and suspends the phosphor materials. Despite these limitations and current challenges, it is anticipated that further advances in white LEDs will revolutionize the lighting industry and lead us into a more energy-efficient and bright future. ❐

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