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The Promise and Challenge of Solid-State Lighting

In time, solid-state devices should provide inexpensive, environmentally friendly illumination that changes the way we think about using artificial light.

Arpad Bergh, George Craford, Anil Duggal, and Roland Haitz

A vital and growing use of energy is the generation of electricity. In the US alone, producing electricity costs \$60 billion a year. But the cost of electrical energy should not be measured in dollars alone—there is the environmental cost of smog and carbon dioxide pollution associated with electricity production.

About 20% of electricity is used for lighting. The most widely used sources of artificial illumination are incandescent and fluorescent lamps, but this is about to change: Solid-state lighting (SSL) devices promise to replace conventional light sources, with impressive economic and environmental savings. In the US, expenditures for lighting may be reduced by \$100 billion over the period 2000–2020. By the year 2020, electricity used for lighting may be cut by 50%, sparing the atmosphere 28 million metric tons of carbon emission annually.[1]

Not only will SSL lead to energy and environmental savings, but it will change the way we think about lighting. SSL devices are vibration and shock resistant, and exceptionally long-lived. They will allow for a wide variety of lighting, including artificial lighting similar to natural daylight. Moreover, with appropriate circuitry, the color and intensity of the lighting can be controlled. Because SSL devices can be coupled to light pipes, light may be flexibly and efficiently distributed. SSL devices also offer interesting design possibilities—they can be manufactured as flat packages of any shape that can be placed on floors, walls, ceilings, or even furniture.

SSL sources can be made with either inorganic or organic semiconductors. An SSL device that uses inorganic semiconductors is a light-emitting diode (LED). Its essential elements are an electron-carrying n-layer and a hole-carrying p-layer. When a forward voltage is applied to the structure (negative to the n-layer and positive to the p-layer), electrons are injected from the n-layer and holes from the p-layer. Electrons and holes can radiatively recombine, emitting a photon. The wavelength and color of the photon is determined by the difference in the energy levels of the electrons and holes.

A light-emitting device built with organic semiconductors is an OLED; its physics is described in box 1 on page 44. An OLED works very much like an LED except that it features an electron injecting contact (cathode) instead of the n-layer and a hole injecting contact (anode) instead of the p-layer. LEDs provide point sources for light such as incandescent lamps, while both LEDs and OLEDs can replace area sources such as fluorescent lamps.

A brief history of SSL

Nick Holonyak Jr, working at General Electric, gave the first practical demonstration of LEDs in 1962.[2] Over the course of the 1970s, the physics of LED illumination was explained in detail,[3] and by the end of the decade, LEDs had replaced incandescent bulbs for indicator lamps and Nixie tubes (small plasma discharge vacuum tubes) for numeric displays. Starting in the mid- to late 1980s, a new type of SSL source was developed based on organic semiconductors.[4,5] The performance of these OLED devices improved dramatically in the 1990s, a consequence of worldwide efforts to develop full-color, flat-panel displays. By the turn of the century the demonstrated performance of OLEDs clearly showed that they had the potential for use in general illumination.

The 1990s also saw two major breakthroughs in inorganic LED technology. Workers at Hewlett Packard[6] and Toshiba[7] used AlInGaP to develop high-brightness red and amber sources and Shuji Nakamura at Nichia demonstrated that it was possible to produce high-brightness green and blue LEDs.[8] The performance of LED devices, like that of their organic counterparts, steadily increased during the 1990s. Since LEDs can be fabricated in all the primary colors, they will, in time, serve as a source of white light for general purposes.[9]

Already, LED devices are viable choices for a variety of jobs requiring monochromatic light.[10,11] For example, in practically all monochrome signaling applications, LEDs substantially outperform filtered incandescent lamps. Consider a typical 12-inch-diameter red traffic signal as a particular case. The conventional traffic signal uses a long-life 140-W incandescent lamp generating a white flux

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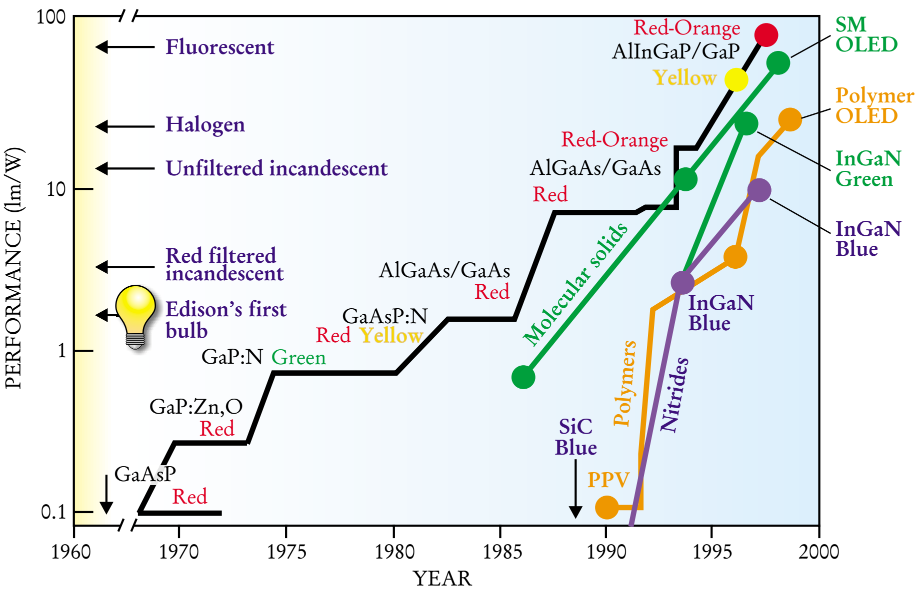


FIGURE 1. PERFORMANCE improvements of inorganic and organic light-emitting diodes over time. The black line summarizes almost three decades of work with a variety of inorganic structures, and ends with the most efficient LED produced to date. The mid-1990s witnessed the development of high-performance, nitride-based LEDs, indicated by the blue line that sprouts a green branch. The nearly straight green line shows the improving performance of OLEDs whose organic layers are small molecules (SM), while the orange line shows performance improvements of OLEDs whose organic layers are polymers. Near the vertical axis, black arrows indicate several benchmark efficiencies of conventional lighting devices.

of nearly 2000 lumens. The red filter transmits 200 lm. The corresponding LED solution by LumiLeds uses 18 LED lamps to produce better than 200 lm of red light while consuming only 14 W, including the losses in the power conversion circuit.

Increasing value for money

Figure 1 summarizes the steadily increasing performance of both LEDs and OLEDs. The definitions of performance and other terms used to describe the quality of an SSL device appear in box 2 on page 45. Figure 2 focuses on commercially available red LEDs but introduces a new variable: the cost per lumen. After all, the penetration of LEDs into the power-signaling market depends critically on both performance and cost. The figure shows that the cost per lumen has been steadily falling even as performance has consistently increased. By the year 2000, the cost per lumen for red LEDs had dropped to $.06/lm. At this price, the LEDs in a typical 25-lm application contribute only $1.50 to the cost of the complete unit.

Nonetheless, LED devices are over two orders of magnitude more expensive than commercial incandescent light bulbs for general illumination. White LEDs now cost about $.20/lm. If red LEDs can be taken as a guide, and the cost per lumen of white LED lamps falls by a factor of 10 each decade, then white light produced by LEDs will cost $.05/lm by around 2005 and $.01/lm by about 2012. With this predicted cost, a 50 lm/W LED lamp will pay for itself through energy savings over 3000–10 000 hours in 2005 and over 500–1500 hours in 2012.

With an efficacy of 50 lm/W, however, SSL cannot take the place of fluorescent lamps, which have efficacies in the range of 60–100 lm/W. To displace fluorescent lamps, SSL devices will need to reach a superior efficacy of 150–200 lm/W for white light and a cost per lumen substantially lower than $.01/lm. With further innovation, both LEDs and OLEDs have a good chance of hitting these targets.

The production of larger LED chips that can be driven at high current densities will be critical to reducing the cost of LED devices. Figure 3 shows the substantial progress that has been made in the past few years in increasing the luminous flux obtained from single LEDs driven at high current densities.[12] Typical conventional LED indicator lamps are 0.25 mm square and are mounted in packages that can handle about 0.1-W input power. High-performance chips have an output of 1–2 lumens per device. Larger chips, up to about 1 mm^2 in size, and packages capable of handling several watts are now available with outputs of tens of lumens and hundreds of milliwatts of optical power. Such packages are increasingly used for red, amber, and green traffic signaling lights. Even larger chips, emitting hundreds or even thousands of lumens at higher current densities per package, will be required for general illumination.

Bringing down the price of semiconductor material by improving the quality and rate at which epitaxial reactors produce semiconductor wafers is crucial to reducing the overall cost of LED lamps. Other keys to cost reduction include designing low-cost revolutionary packages with high reliability and low thermal impedance, and increasing the area of substrates while reducing their cost.

Silicon shows promise as a substrate for nitrides—LED devices that emit across the spectrum from green into the ultraviolet. The possibility of LEDs built on Si substrates is exciting, but high-performance devices have not yet been demonstrated due to problems such as differences in the thermal coefficient of expansion between deposited semiconductor and substrate, and lattice mismatching wherein the lattice sizes of the deposited semiconductor and the substrate are different enough that lattice defects cause significant amounts of energy to be thermalized.

OLEDs have the advantage over LEDs of being amenable to inexpensive, large scale processing so that cost targets should be relatively easy to achieve. More effort will be needed to obtain the efficiencies and lifetimes necessary if OLEDs are to be used for general-purpose lighting.

SSL devices for white lighting are already being used in certain cost-insensitive jobs. Examples of such uses include illumination for equipment subject to strong accelerations and lighting of objects where space is at a premium, like glove compartments. White LEDs are also used for such special applications as providing nighttime lighting for the text frieze inside the dome of the Jefferson Memorial in Washington, DC. If SSL devices continue to be improved at their current rate, it might take the industry 15–20 years to capture the specialized markets it currently serves, and several decades to replace conventional lighting.

The emergence of efficient LED devices signals a lighting technology paradigm shift that has not been lost on industry and government. Major government-sponsored industry consortia already exist or are currently being formed in Europe, Japan, Korea, and Taiwan, with the goals of saving energy and gaining market share in the emerging SSL industry. We believe there is a need for a national initiative to develop SSL. Such an initiative should reduce the need for new power plants, hasten the day in which the US consumer enjoys the reduced energy and environmental costs of SSL, and secure a place for the US in the new lighting industry.

The isle of white

One way to generate SSL white light is to efficiently mix the outputs of devices providing red, green, and blue light. A nice feature of this mixing technique is that one can control the hue of the light by varying the mix of primary colors. Efficient mixing and color control are both complex issues, however, particularly when uniform performance must be maintained at a variety of ambient temperatures and over a long time. The angular distributions of intensity, the changes of intensity with temperature, and degradation rates are not the same for devices producing different colors.

SSL devices and phosphors together can generate

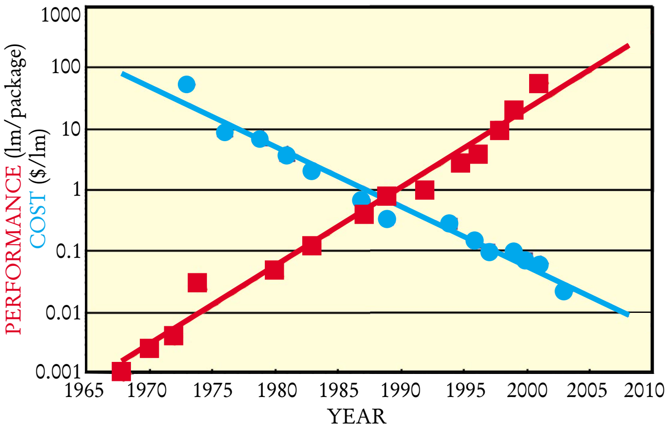
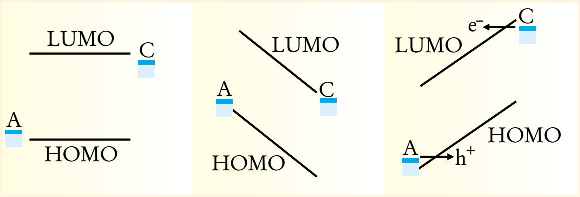


FIGURE 2. EVOLUTION OF PERFORMANCE in lumens per package (red squares) and cost in dollars per lumen (blue circles) for commercially available red light-emitting diodes. The figure covers the period 1968–2008, beginning with the first high-volume LED sales and ending with projections seven years into the future. The flux per package has been increasing by a factor of 20 per decade, both because packages have contained increasing numbers of LEDs and because the performance of individual LEDs has improved. The cost per lumen has been decreasing by a factor of 10 each decade. At present, high-brightness green and blue LEDs are substantially more expensive than red LEDs.

Box 1. OLED Physics

An organic light-emitting diode, such as that illustrated in figure 4, consists of one or more organic layers sandwiched between two metal electrodes, one of which must be transparent. The organic layers are typically undoped, insulating, pi-conjugated molecules such as tris-(8-hydroxyquinolate)-aluminum (Alq) or polymers such as poly(p-phenylene vinylene) (PPV) or polyfluorene (PF). These materials have essentially no free charges. Hence the charges that run through the OLED during operation are injected into the organic layers from the electrode contacts.

The left illustration below provides a schematic of the relevant energy levels of the components of a single-layer OLED. The organic layer is a highly disordered, amorphous film and so it is usually characterized in terms of molecular energy levels—the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO). The cathode, (C) which injects electrons into the device, should have a low work function, allowing its energy to be close to that of the LUMO: A good energy match between cathode and LUMO means that not much energy is lost when electrons are injected. Likewise, the anode (A) should have a high work function and an energy close to that of the HOMO. Typically, the cathode is made of a reactive metal such as calcium, lithium, or magnesium, either singly or alloyed with another metal, while the anode is formed from indium tin oxide, a transparent conductor with a relatively high work function.



There is a built-in potential difference across an OLED at thermal equilibrium and zero bias due to the equilibration of the Fermi levels of the two electrical contacts. The center illustration shows a manifestation of this equilibration: The HOMO and LUMO energies are functions of position as one moves across the OLED. Charge cannot get injected into the organic material until the OLED's built-in potential is overcome by an external forward voltage. When such a voltage is applied, the HOMO and LUMO energies are as indicated by the illustration at right, which also shows electrons and holes successfully injected onto the organic layer. Note that the essential physics of OLEDs is analogous to that of p–n junctions: The HOMO and LUMO are analogous to valence and conducting bands, respectively; the hole-injecting anode is analogous to the p-side of the junction; and the cathode corresponds to the n-side.

Once electrons and holes are injected into the organic layer, they drift under the influence of the applied field toward the opposite polarity contacts. The electron and hole mobilities in the disordered layer are low—more than a million times lower than in traditional semiconductors such as silicon—so a high field is required for appreciable current. Thus, the organic layers must be thin (on the order of 100 nm) for low-voltage operation. As electrons and holes hop from site to site, they sometimes land in the same place and form a neutral bound excited state, or exciton. With properly chosen materials, a significant fraction of these excitons relax by emitting a photon so as to generate light.

The color of the emitted light and the electrical characteristics of the OLED depend on the specific organic material and details of the device design. OLEDs that emit colors spanning the visible spectrum and even white OLEDs have already been demonstrated. A good deal of research has been aimed at understanding the basic physics of OLED operation.[15] Even so, scientific and engineering details pertaining to the physics of light emission, charge injection, and charge transport still need to be clarified, particularly for the more complicated structures that appear to be required for high-performance devices.

Box 2. The Quality of Solid-State Light Devices

In order to discuss the quality of an SSL source, one needs to consider both how efficiently the electrical power supplied to the device is converted into radiative power and how that radiative power affects the eye. In this box, we present the vocabulary commonly used in the discussion.

The radiative power emitted by an SSL device divided by the electrical power input is called the power-conversion efficiency (PCE). Even if every electron and hole injected into an SSL device combined to create a photon that escaped from the device, the PCE would be less than 100%. Because of ohmic losses, the electrical energy supplied to the electrons and holes is always greater than the energy released when electrons combine with holes.

Of course, not every injected electron–hole pair yields an emitted photon. The fraction of injected electrons that combines with holes to produce photons is called the internal quantum efficiency.

Typical light-emitting diode chips in an SSL device have a high index of refraction so that some of the photons produced in the device are internally reflected. The fraction of photons that escape from the device is termed the light-extraction efficiency. By definition, the product of internal quantum efficiency and light-extraction efficiency is the external quantum efficiency. The external quantum efficiency multiplied by the ratio of the photon's energy to the electrical energy supplied to the combining electron–hole pair yields the PCE.

The sensitivity of the human eye varies with color, so a device emitting a watt of yellow light will be perceived as brighter than a device emitting a watt of blue light. The luminosity coefficient gives a relative scale of color visibility. It peaks at 680 for light with a wavelength of about 555 nm (yellow–green) and drops to 30 at 450 nm (blue) and to 70 at 650 nm (red). Radiated power multiplied by the luminosity coefficient is a measure of visual impact called the luminous flux. When the radiated power is measured in watts, the unit associated with the luminous flux is the lumen (lm). The luminous flux divided by the power input is defined as the overall luminous efficiency, also known as the efficacy or performance, and is typically expressed in units of lumens per watt. Equivalently, the performance is the PCE multiplied by the luminosity coefficient. Performances of SSL devices and typical conventional light sources appear in figure 1.

white light. For instance, when a blue-emitting SSL device shines on a yellow-emitting phosphor, the resulting light appears white to the eye. A major limitation of this approach is that the color rendering is poor: Illuminated objects do not have their true color. For example, a red object illuminated with a combination of blue and yellow light appears black. Better color rendering can be obtained by using the light from a UV-emitting device to excite an appropriate color combination of phosphors to make white light. The technique of combining an SSL device with a phosphor facilitates color mixing and control. A disadvantage is that some energy is wasted converting higher-energy photons to lower-energy photons.

OLEDs can emit white light intrinsically. As shown in figure 4, the organic layers of a white OLED contain a variety of organic molecules, each of which generates light of a particular wavelength. The appropriate combination of molecules yields a mix of colors resulting in white light.

Other possibilities for obtaining SSL white lighting generally can be implemented with a variety of inorganic and organic materials. The SSL industry has yet to determine which approach will be the most cost effective. The approaches in this article all have their particular strengths and weaknesses, and there are problems concerning lifetime, stability, photon extraction, and other issues that need to be addressed for all SSL white-light sources. Solving these problems will require major effort by researchers in industry, academia, and the national laboratories.

LED performance details

High-performance inorganic LEDs are now available that produce light spanning the visible spectrum. The AlInGaP material systems produce red, orange, and amber light whereas AlInGaN systems generate green, blue, and near-UV light. The technologies used in building these systems are well established and a variety of manufacturers are producing devices in high volume.

The internal quantum efficiency can approach 100% in properly designed, direct-bandgap, heterostructure LEDs with low defect densities. An extraction efficiency greater than 60% has been demonstrated, and higher efficiencies may be possible in optimal structures. Resonant cavity emitters and photonic bandgap structures, in particular, may yield better light extraction from LEDs. The highest external quantum efficiency for a visible LED reported to date is 55% at 650 nm; the power conversion efficiency at the specified wavelength is 45%.

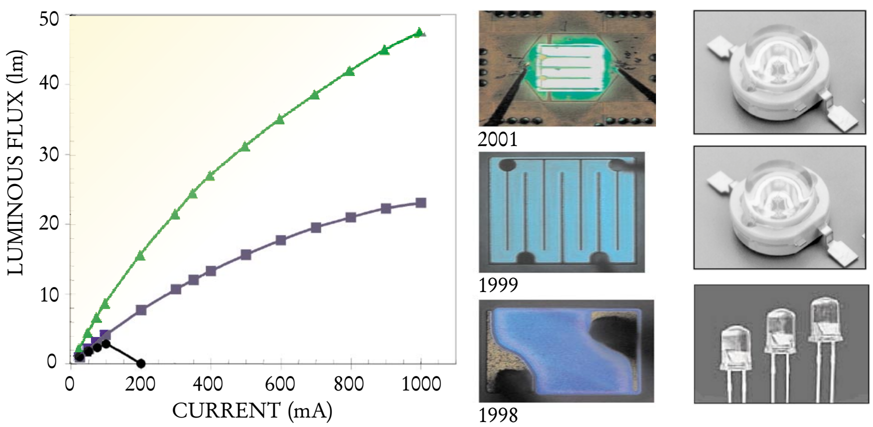


Figure 3. Luminous flux as a function of current for several types of blue and green light-emitting diodes operating at a temperature of 300 K. The 1998 device (black curve) is a conventional low-power LED. The 1999 device (purple curve) is a 1-mm^2 chip mounted in a power package with the epitaxial side up in the usual manner. The most recent LED (green curve) is a "flip chip" mounted upside down on a silicon submount. Its light is emitted through a transparent sapphire substrate. The LEDs and the colors they emit are shown in the center column of photographs. The black and white photographs in the right column show the housings that contain the LEDs.

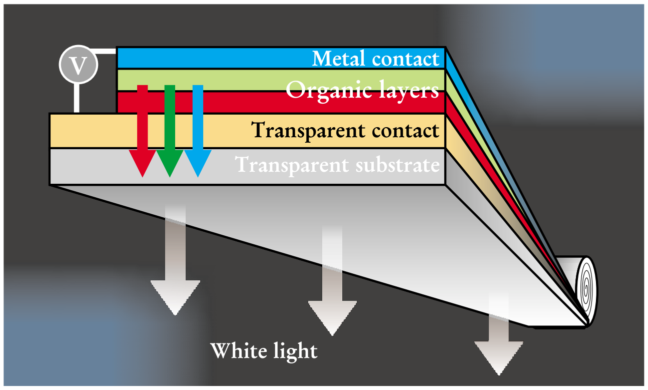


Figure 4. An OLED schematic. In an OLED, one or more layers of organic material are sandwiched between two metal contacts, at least one of which must be transparent. With the appropriate mix of molecules in the organic layers, OLEDs can emit white light.

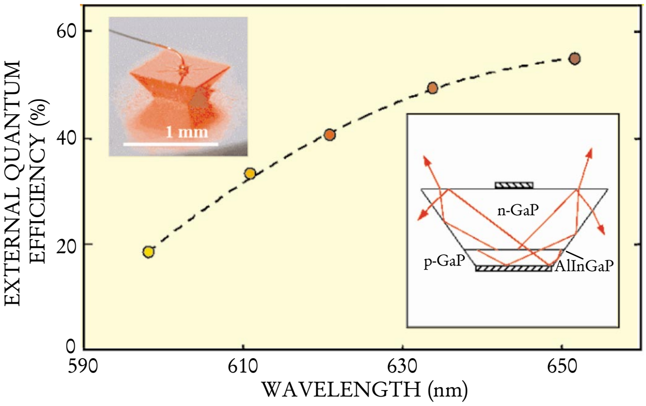


Figure 5. External quantum efficiency versus wavelength for the highest-efficiency light-emitting diode. The LED (photo inset) is an AlInGaP heterostructure device driven with a DC current of 100 mA and operating at a temperature of 300 K. The lower right inset gives a schematic of the device, showing how its shape—a truncated inverted pyramid—minimizes internal absorption. The internal quantum efficiency of the device is believed to be close to 100%, so each injected electron generates a photon inside the chip. Device performance is limited by how well the light can be extracted.

The device that achieved these impressive efficiencies is an AlInGaP heterostructure whose lattice is well matched to that of a gallium arsenide substrate. GaAs, however, absorbs internally reflected light, limiting the extraction efficiency. Therefore, the GaAs substrate is replaced with a gallium phosphide wafer that is transparent to the red light. The GaP wafer is attached to the AlInGaP heterostructure using wafer bonding at elevated temperature and pressure.[13] Forming the chip in the shape of a truncated inverted pyramid (TIP) further improves the extraction efficiency by minimizing the number of internal reflections—less light is absorbed, and more escapes from the device.[14]

Figure 5 shows the TIP structure of the chip and also the external quantum efficiency of the device as a function of wavelength. The efficiency is highest at 650 nm and falls at shorter wavelengths: As the wavelength decreases the chip makes a transition from a direct semiconductor to an indirect one, for which holes and electrons cannot recombine spontaneously. The transition occurs in the green spectral region for an AlInGaP lattice matched to GaAs, so high-performance AlInGaP devices are limited to the red, orange, and amber spectral regions.

The AlInGaN systems, often called nitrides, have a direct bandgap throughout the visible spectrum and into the UV. The efficiencies of nitride devices are highest in the blue–UV region and decrease at longer wavelength as alloys with higher indium concentrations are grown. We do not know whether this decrease with In concentration is fundamental.

Unlike AlInGaP, which can be grown matched to a GaAs lattice, AlInGaN cannot be grown onto a well-matched substrate. Sapphire (Al_2O_3) is the most commonly used substrate, but some manufacturers also use silicon carbide. The lattice mismatch between the substrates and the epitaxial layers results in high defect densities, typically in the range of $10^{10}/cm^2$. Despite various techniques that reduce defect densities, such densities are still higher with nitrides than with other materials. Developing approaches for lowering defects is one important line of nitride research. Another is to find alternate substrates, possibly GaN or AlInN.

Figure 6 gives the best power-conversion efficiencies that have been reported for LEDs and lasers. If color mixing is to yield the 150 lm/W of white light necessary to compete with fluorescent lamps, SSL devices producing red, green, and blue light must operate with a power-conversion efficiency of about 50%. Red LEDs are almost there, but nitride devices producing green light need to have their efficiencies enhanced by a factor of 5 to 10, and those producing blue light need to improve by a factor of 2 to 3. The challenge to increase nitride efficiencies to 50% is formidable, but should be reachable as we improve our understanding and develop appropriate new technologies.

Whether high-performance lasers can be fabricated through the visible spectrum is not yet clear. (For reports on the development of short-wavelength diode lasers, see Physics Today, April 1996, page 18, and the articles "Blue–Green Diode Lasers" by Gertrude F. Neumark, Robert M. Park, and James M. DePuydt, June 1994, page 26, and "Blue Diode Lasers" by Noble M. Johnson, Arto V. Nurmikko, and Steven P. DenBaars, October 2000, page 31.) Lasers do have an advantage over LEDs in that the light beam is perpendicular to the end of the cavity so that there is little internal reflection to compromise light extraction. Vertical cavity lasers should be less expensive than edge-emitting lasers since they can be processed and tested in wafer form, which gives them a leg up if lasers are to be important for illumination. In short, laser illumination remains a possibility in the long term, but there needs to be a series of technical breakthroughs.

OLED technology

There are two main classes of OLED devices: those made with small organic molecules and those made with organic polymers. The nature of the organic material does not affect the essential physics of the OLED. To date, both classes perform about equally well and it is difficult to say which class, if either, will ultimately prevail.

The two types of OLED devices are produced differently, but in both cases, the fact that the organic layers are highly disordered opens up the possibility that they can be produced cheaply. Small organic molecules are usually sprayed onto a substrate along with a carrier that

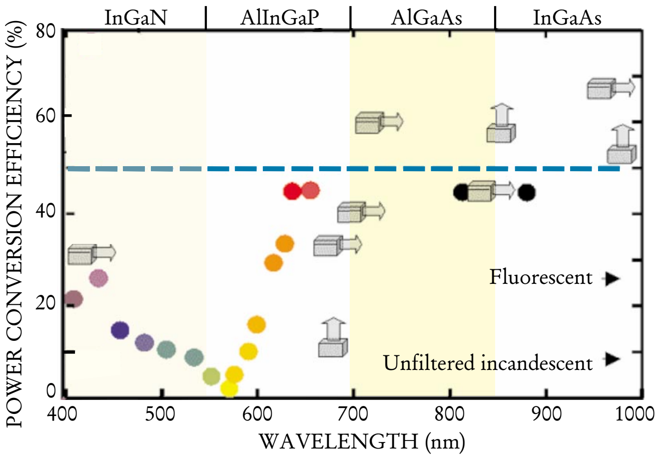


FIGURE 6. BEST POWER CONVERSION EFFICIENCY versus wavelength for light-emitting diodes (colored circles), edge-emitting laser diodes (icons with arrows on sides) and vertical-cavity laser diodes (icons with arrows on top). The formulas on the top line indicate the types of heterostructures appropriate to various wavelength ranges. The leftmost formula, InGaN, describes nitride structures such as those discussed in the text, but not containing aluminum. The dashed line shows the 50% power-conversion efficiency that solid-state light devices must reach if color mixing is to compete with fluorescent lamps as a source of white light.

must be evaporated. Small molecules and polymers may be deposited using techniques such as ink-jet printing and spin coating, in which a few drops are placed on a substrate that, in turn, is spun so as to uniformly distribute the organic material. Unfortunately, present fabrication techniques require that the organic material be deposited onto a glass substrate in a batch process that limits the potential cost savings. Organic polymers are amenable to a roll-to-roll process, in which an organic liquid passes between two hot rolls and polymerizes into a continuous sheet. Such a process would minimize production costs, but it requires a mechanically flexible substrate instead of glass. Researchers at several laboratories have already demonstrated that it is possible to build OLEDs on flexible polymer films, but they have yet to achieve practical device lifetimes.

There's another difficulty for OLEDs built on polymer films. Compared to glass, films are relatively permeable to water and oxygen, which degrade OLEDs. There are two reasons for this degradation: Efficient devices employ highly reactive electrode materials such as calcium, and many organic layers are susceptible to photo-oxidation. Potential solutions include building hermetic barrier layers onto the polymer films, designing efficient devices that don't require reactive electrode materials and designing organic layers that are inherently resistant to photo-oxidation. For now, OLEDs are typically made on glass substrates and covered with a second piece of glass to keep water and oxygen away.

OLED performance is currently adequate for many display applications, and a few monochrome OLED displays are already available commercially. Today's OLED performance, however, is not yet adequate for general illumination. If OLEDs are to serve for lighting, they must be able to generate illumination-quality white light and operate at increased efficiency and lifetime at high brightness. In addition, the production problems just discussed need to be solved so that OLED costs come down.

The generation of illumination-quality white light is probably the easiest challenge to meet, partly because of the wealth of possibilities for making new materials through organic chemistry and partly because of the enormous design flexibility that disordered organic materials allow. We have already noted, for instance, that one can make an intrinsically white OLED simply by mixing molecules that emit different colors.

During the past ten years, OLED technology has progressed enormously: Efficacies have increased by about two orders of magnitude and the operating lifetime at display brightness levels has increased from less than 1 hour to better than 10 000 hours. Still, the best power conversion efficiency for OLED devices at the brightness levels required for lighting is currently around 5–10%. OLED lifetimes tend to decrease with increasing brightness, and understanding and eliminating degradation mechanisms will take a great deal of effort

Continued innovations in designs and materials should eventually allow SSL devices to serve as sources of general illumination. If SSL devices do replace current light sources—a process that can be greatly hastened by a national initiative—then the light bulb may well come to appear as quaint and inflexible as the phonograph record does today.

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