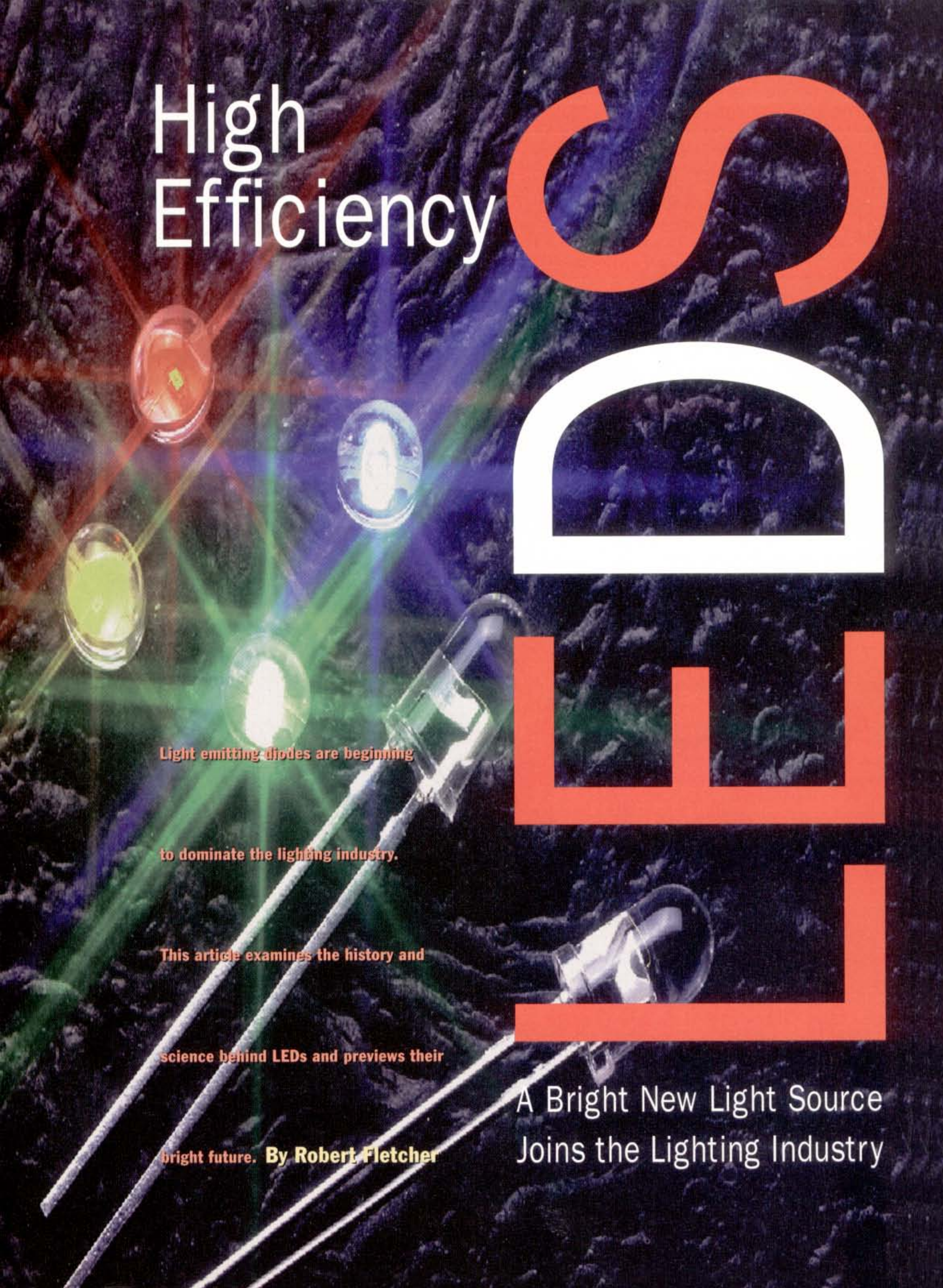

High Efficiency LEDs

A Bright New Light Source Joins the Lighting Industry

Light emitting diodes are beginning to dominate the lighting industry. This article examines the history and science behind LEDs and previews their bright future. By Robert Fletcher

A dramatic change is unfolding in the lighting industry today, though most people are probably not even aware of it. The incandescent light bulbs in many indoor and outdoor applications are being replaced by light-emitting diodes, the well-known LED. Because of the tremendous advances made in LED technology over the past decade, these solid-state devices have moved far beyond the lowly status of "idiot light." The first major application for this new generation of LEDs has been in the automotive industry where, for example, the center high-mount stoplight (CHMSL) in many automobiles is an LED assembly. One can easily recognize an LED CHMSL by its thin strip of light that is usually a deeper shade of red than its incandescent counterpart. Complete LED assemblies comprising the tail lights, brake lights, and turn signals are being designed into some automobiles that will soon appear in showrooms. An altogether different application, though more conspicuous, is the substitution of LEDs for incandescent light bulbs in red traffic signals throughout many municipalities in the U.S., Canada, and other countries. Even more astounding is that the lighting industry is now looking at LEDs as a source for white light illumination. News items have appeared in recent weeks describing alliances between large manufacturers of incandescent and fluorescent light bulbs and semiconductor companies involved in LEDs. The main advantages of LEDs in all these applications are high reliability, long life, and energy efficiency.

What has happened in the LED industry to bring about this change? Quite simply, during the past 15 to 20 years researchers have developed new compound semiconductor material systems with greatly improved quantum efficiencies. Combined with improvements in semiconductor crystal growth techniques, advanced device-structure engineering, and improved device processing techniques, the light output performance and efficiency of LEDs has improved 50-fold. Furthermore, these high-performance LEDs are now available with light emission spanning the entire visible spectrum from red to violet. The relatively recent availability of bright blue and green LEDs has in fact opened the gates for a flood of applications previously unavailable. For example, red, green, and blue LEDs are required for large-screen full-color video displays used for stadium and arena events, and the three-color combination also promises to be a most efficient way to produce white light sources for illumination, a concept that has gone from pipe dream to reality.

LED basics

An LED in its simplest form is a semiconductor p-n junction device that, when forward biased, emits photons as the electrons and holes recombine near the junction. The energy of the photons is determined primarily by the energy bandgap of the semiconductor where the recombination occurs. Compound semiconductor materials composed of column III and V elements are the materials of choice for LEDs because they have the direct bandgap properties and the bandgap energies necessary for efficiently producing visible photons.

To understand the significance of the recent advances in LED technology, it is useful to review the evolution of LED materials and their performance, as illustrated in Figure 1. The vertical axis in the figure is the light output performance of the LEDs measured in lumens of visible light emitted per watt of electrical power applied to the device. The lumen is a measure of light flux as perceived by the human eye and takes into account the change in eye sensitivity with wavelength. (Note that the vertical scale is logarithmic.) The LED performance data were derived from standard 5-mm lamps driven at 20 mA DC. For comparison, the typical luminous performance of filtered and unfiltered incandescent lamps is indicated along the vertical axis.

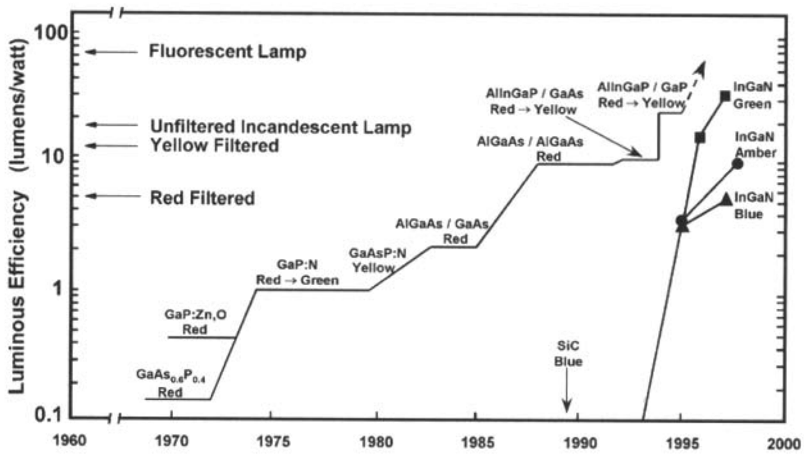

Figure 1. The evolution of LED performance, or luminous efficiency, measured in lumens of visible light emitted per watt of electrical power applied. Measurements on all the LEDs were taken at a forward bias current of 20 mA at room temperature. For reference, values for fluorescent and incandescent lamps with and without colored filters are indicated. A typical 60 W light bulb emits about 1000 lm of visible light, yielding a luminous efficiency of 17 lm/W.

From the mid-1960s through the early 1980s, the only semiconductors available to produce LEDs were gallium phosphide (GaP), grown by liquid-phase epitaxy (LPE), and alloys of gallium arsenide phosphide (GaAsP), grown by vapor-phase epitaxy (VPE). These compound semiconductors meet the requirement for high bandgap energy to emit visible photons, but they are mostly indirect bandgap materials and normally incapable of efficiently producing light. Nevertheless, they can be made into rather efficient radiative materials by doping with isoelectronic impurities, such as nitrogen or zinc oxygen.[1–3] The range of colors produced by these materials is limited to the red to yellow-green part of the spectrum (~700–555 nm) with light output efficiencies on the order of 1 lm/W. Because the brightness of these LEDs is relatively low, their use is generally limited to indoor applications where ambient

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light will not diminish their output. Status indicators on electronic equipment and consumer appliances and digital clock displays are familiar examples of these applications.

A large jump in LED efficiency occurred during the 1970s and early 1980s when researchers at various institutions developed the AlGaAs material system for producing bright red LEDs in the 650-nm range.[4–6] With the development of AlGaAs devices, LED light output performance increased to 2–8 lm/W. (AlGaAs, grown by LPE, is produced in various epitaxial configurations of differing complexity and cost, accounting for the range of performance in Fig. 1.) This performance jump was highly significant because, for the first time, the efficiency of an LED was comparable to the efficiency of a red-filtered incandescent lamp. Now bright enough for outdoor use, LEDs began to appear in some niche applications. The automobile CHMSL and the New York City Times Square type of moving message sign were among the first applications of these LEDs.

During the development and commercialization of AlGaAs devices, another material system, AlGaInP, was aggressively being investigated, primarily in the U.S. and Japan. It was known that LEDs composed of AlGaInP, grown by metallorganic vapor-phase epitaxy (OMVPE), should possess not only the high efficiency of AlGaAs devices but also offer a much wider band of color emission spanning red to green. Theory was indeed born out, and in the early 1990s, Hewlett-Packard and Toshiba introduced the first high efficiency AlGaInP LEDs in red-orange (~620 nm) and amber (~590 nm).[7, 8] AlGaInP LEDs at yellow-green wavelengths around 560 nm can be produced, but the efficiency is poor, and they are not commercially viable. The typical performance of red to amber AlGaInP devices ranges from 10–25 lm/W. In fact, the brightest LEDs ever produced have been transparent substrate AlGaInP devices operating around 607 nm at an efficiency in excess of 50 lm/W.[9] This efficiency exceeds the 22 lm/W efficiency of a tungsten-halogen lamp.

AlGaAs and AlGaInP LEDs are manufactured in two basic configurations, absorbing substrate (AS) and transparent substrate (TS). These two configurations account for the different levels of performance indicated in Figure 1. TS devices, though about twice as bright as AS, require a more complex manufacturing process and are therefore more expensive. For the epitaxial growth of AlGaAs and AlGaInP LED structures, light-absorbing GaAs is the substrate of choice, chiefly because both AlGaAs and AlGaInP crystals can be grown with the same lattice constant as the GaAs. For virtually all LEDs, lattice matching is critically important to minimize the formation of crystal defects, primarily dislocations, in the light producing layers. These dislocations act as non-radiative recombination sites and drastically reduce the quantum efficiency in the LED. Typically, the density of the dislocations must be kept below 10^4 cm^{-2} to avoid significant non-radiative effects.

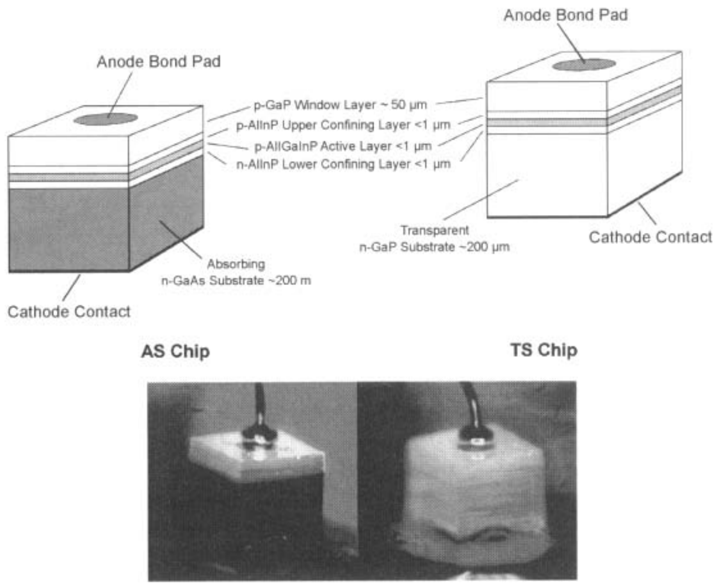

Figure 2. AlGaInP LED chip structure diagrams and photomicrographs of the corresponding devices in operation: The absorbing substrate (AS) device is on the left, and the transparent substrate (TS) device on the right. Each chip measures approximately 220 µm on each side. The multilayer devices shown are called double heterostructures because the active layer where the light is generated is sandwiched between material of a different crystal composition. [Photos reprinted from F.A. Kish *et al.*, "Very high-efficiency semiconductor wafer-bonded transparent-substrate (AlGa)InP/GaP light-emitting diodes," Appl. Phys. Lett. **64**, 2839–2841 (1994).]

The disadvantage of GaAs as a substrate is that it absorbs about half the light produced in the LED layers, that is, all the light emitted in the direction of the substrate. Such an AS AlGaInP device structure is illustrated schematically in Figure 2. The device is essentially a cube about 220 µm on a side with an anode contact on the top epitaxial surface and a cathode contact on the back substrate surface. Light is emitted from the top surface and sides of the epitaxial layers.

An obvious way around the problem of substrate absorption is simply to remove the GaAs after the epitaxial growth. Unfortunately, the device layers are only a few micrometers thick, much too fragile for subsequent processing into chips without a supporting substrate. An approach that works is to replace the GaAs with a transparent material after the epitaxial growth. For AlGaAs LEDs, this transparent substrate is a layer of high aluminum content AlGaAs itself, approximately 120-µm thick and grown during the epitaxial process right on top of the active device layers. Once the growth process is complete, the original GaAs substrate is removed by selective chemical etching, and what remains is an LED structure supported by the thick transparent AlGaAs layer.[10] In AlGaInP LEDs a different approach is used. Here, the GaAs is chemically etched away, leaving the freestanding epitaxial layers. A transparent gallium phosphide (GaP) substrate is then attached using a technique called semiconductor wafer bonding.[9] (Wafer bonding has been around for a number of years in the silicon industry for bonding silicon to silicon or silicon to quartz; it is also used to bond compound semiconductors to glass in the manufacture of photocathodes.) Wafer bonding involves heating the two materials and applying uniaxial pressure to achieve a chemically bonded interface. The technique is highly successful for the production of TS AlGaInP, and the light output of the resulting LEDs is approximately double that of their AS counterparts.

Bright blues and greens

The latest revolution in LED technology, and the most dramatic, has been the development and introduction of bright blue and green LEDs using the InGaN material system. (Blue LEDs made from silicon carbide have been available since the late 1980s, but their low-light output and high cost has rendered them somewhat insignificant.) As shown in Figure 1, the introduction and rapid rise in performance of InGaN devices has been nothing short of meteoric. Luminous performance for typical blue LEDs is already about 7 lm/W and for green about 25 lm/W, which is comparable to AS and TS AlGaInP performance. Part of the reason that InGaN LEDs have reached such a high performance level early-on is that they are inherently TS devices grown on substrates of transparent sapphire or SiC. Thus InGaN technology has been spared the AS-to-TS evolutionary phase.

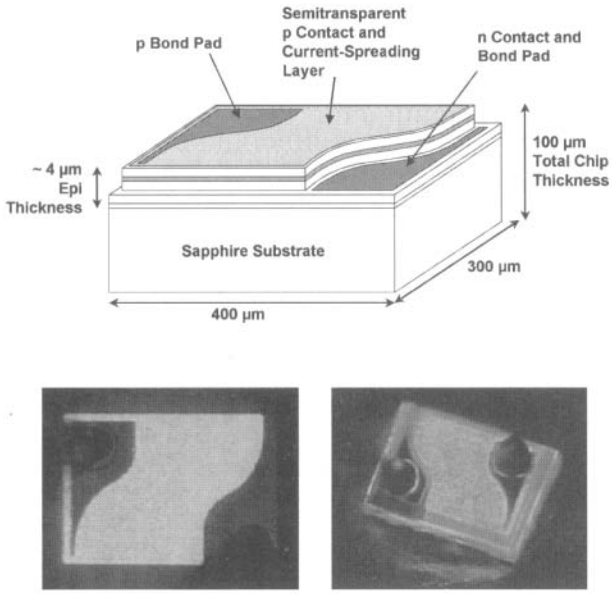

Figure 3. An InGaN LED chip structure diagram and photomicrographs of blue (bottom left) and green (bottom right) devices in operation. (For color versions of these images, see page 2.) Observe that both electrical contacts are made to the epitaxial layers since the sapphire substrate is an electrical insulator. As with the AlGaInP devices in Figure 2, this is a double heterostructure device. However, in InGaN, the active layer is only about 20 Å thick and is more specifically referred to as a quantum-well structure.

Nichia Chemicals Ltd. first introduced blue InGaN LEDs in 1993 and green LEDs shortly thereafter.[11] The commercial introduction of InGaN devices by Nakamura and his team at Nichia Chemical took the LED industry by surprise, and Nichia continues to maintain a lead in the technology today, though that lead has narrowed significantly. Nakamura's success, however, was enabled in part by a large foundation of knowledge constructed through the persistent efforts of Akasaki and his group working over a period of more than two decades.[12–14] Following Nichia's famous announcement of their success in 1993, research in InGaN grew explosively. In the short span of four years, other companies were able to develop their own unique versions of InGaN LEDs, among them Toyoda Gosei, Cree Research, and Hewlett-Packard Co.

A unique characteristic of InGaN LEDs is that there is no substrate material available that lattice-matches the InGaN crystal. Nevertheless, both sapphire (Al_2O_3) and silicon carbide (SiC) are suitable substrates for InGaN growth. The lattice spacing in a sapphire crystal is close to 50% larger than the lattice of InGaN, leading to epitaxial layers that are full of dislocations and other lattice defects with densities of 10^9 cm^{-2} or more. In other LED materials this level of defects would be disastrous, but in InGaN, the defects appear to have little effect on overall efficiency of the LEDs. This behavior has been, and continues to be, the subject of intense study and debate. At this time the vast majority of InGaN LEDs are produced on sapphire, including those of Nichia, Toyoda Gosei, and Hewlett-Packard.

In SiC, the lattice constant is only a few percent smaller than the InGaN crystal, resulting in defect densities somewhat less than for InGaN on sapphire. To date, however, InGaN-on-SiC LEDs are not as efficient as InGaN-on-sapphire devices. Also, the limited availability and high cost of commercial SiC substrates is generally prohibitive. Cree Research uses the SiC approach to produce InGaN and manufactures their own SiC substrates.

A schematic for an InGaN device on sapphire appears in Figure 3. Below the schematic are photomicrographs of blue and green InGaN chips in operation. The structure of these LEDs is obviously different from the AlGaInP chips in Figure 2. Because the sapphire substrate is electrically insulating, both anode and cathode connections are on the top epi-side of the chip. The anode contact is made directly to the top p-type surface layer, and contact to the underlying n-layers is made by etching down a few micrometers through the p-layers to expose the n-layers beneath. Also present is a semi-transparent current-spreading layer consisting of a very thin layer of metal, such as gold. Because the p-type layers in an InGaN device have a relatively high resistance, this metal film is necessary to spread the current evenly across the junction area. Fortunately, the metal film is thin enough (~100 Å) to be transparent to the light generated at the junction beneath it. InGaN devices grown on SiC, which is electrically conductive, are similar in structure to AlGaInP chips in Figure 2 with the anode connection made to the top epi surface and the cathode connection made through the backside of the substrate.

Bright lights, big markets

The markets for LEDs in high-brightness applications have grown at a staggering rate since the introduction of bright amber and red AlGaInP. Today, there are four main application industries using bright LEDs of all colors: the automotive industry for both exterior and interior lighting, the traffic management industry for traffic signals and highway information signs, the display industry for large-screen video displays and variable message signs, and most recently, the general lighting and illumination industry. Every application has its own demands for brightness, color, reliability, and package type.

Automotive

The automotive industry has used high-brightness LEDs for the longest time, having designed CHMSLs and decorative lighting assemblies using TS AlGaAs LEDs in the late 1980s. Automobile manufacturers demand a high level of performance for brightness and reliability at a low cost. LED manufacturers entering the automotive market have had to learn to make LEDs that withstand the extreme conditions of temperature, humidity, vibration, and mechanical stress that an automobile must endure. In fact, TS AlGaAs LEDs are no longer used in automotive applications because of their sensitivity to humidity, and AlGaInP devices have taken their place. Advances enabled by AlGaInP technology have included the introduction of amber LEDs for use in turn signals, improved packaging of the LED chips to allow higher drive current (thus reducing the number of LEDs needed in a lighting assembly) and novel LED interconnect schemes that reduce cost and improve reliability. On buses and large trucks, LED brake lights and turn signals are appearing at a much faster rate than on automobiles, largely because design and installation of LED assemblies for these vehicles is relatively simple.

There are many advantages of LED lighting over incandescent lighting. LEDs have no filament to burn out, and they should in fact last the lifetime of the car. They are insensitive to vibration and, for example, can be mounted in the trunk lid of a car, remaining unharmed when said lid slams shut. An LED light assembly can be much thinner than its incandescent counterpart; thus, instead of cutting holes in the rear panel of the car for the tail lights, only a stamped indentation is required, plus a small hole for the electrical leads. LEDs use much less power than incandescent bulbs, relinquishing electrical power for operating additional electronic components in the car or allowing the weight of the car to be reduced by using a smaller alternator and lighter-gauge wiring. Also, an LED assembly can conform to almost any surface contour, allowing designers of new model cars greater flexibility in originating novel design concepts. Finally, LEDs turn on almost instantly, compared to the 200–300 ms it takes for a filament to light up. A driver following a car at 60 mph can thus react more quickly to an LED brake light, thereby gaining several meters of additional stopping space.

Traffic management

In the area of traffic management, high-brightness LEDs are appearing in many sectors. Portable message signs in construction zones have been on the highways for several years. In this application, LEDs can operate from a solar panel and batteries, thus eliminating the need for a generator and its associated fuel and maintenance costs.

Yet the most significant application for LEDs in traffic management is in the traffic signals themselves. It is estimated that there are 260,000 signalized intersections in the U.S. alone, and many of these intersections include redundant sets of lights and turn arrows as well as pedestrian crossing signals. As many as 20 of these lights may be illuminated at once with an estimated energy consumption over 18,000 kWh/year at a cost of over $1,400/year. The cost to maintain the intersection, especially to replace burned-out bulbs, is also substantial. So far, only the red traffic lamps have been replaced by LED modules in many cities throughout the U.S. and Canada. However, this alone can cut the energy consumption at an intersection by more than half, saving almost $800/year. With an initial cost for a single LED module of $200, it would take about three years to recover the investment, based on energy savings alone.[15] However, the modules should last five years or more (they have not been around long enough to know exactly how long they will last), and additional savings should come from reduced maintenance costs. Of course, the next step is to replace the green lights with InGaN LED modules, and this process is just beginning.

Displays

Outdoor message signs and large screen video displays are another major application area for LEDs, easily consuming many tens of millions of high-brightness devices per year. Today, there are thousands of variable message signs in place throughout the world that use AlGaInP red and amber LEDs for advertising and communicating news or other information. Downtown Tokyo and Times Square in New York City are probably the most famous locations for signs of this type. Appearing more and more frequently, however, is the large-screen full color video LED display used in entertainment arenas and sports stadiums. With the recent introduction of bright blue and green InGaN LEDs added to the already available red AlGaInP devices, it is now possible to make a large screen video display with exceptional color reproduction. In fact, because the blue and green emission from LEDs is more saturated than the blue and green phosphors in a CRT display, color reproduction from an LED display is quite superior.

General lighting

Perhaps the oldest application of all lighting in which LEDs are just beginning to appear is white-light illumination. Although an individual LED emits a narrow spectral band of light, by mixing together the emission from red, green, and blue LEDs in the proper proportions, white light, or almost any color hue, can be created. With the realization of bright LEDs in the three primary colors, there is now enormous potential for creating highly efficient white-illumination sources that could replace traditional incandescent and fluorescent bulbs. Although this is not likely to occur in the immediate future, the groundwork is being laid.

Besides combining the light from discrete devices, another way to obtain white light from LEDs is to draw on the same process used to obtain white light from fluorescent light bulbs. Take a short wavelength blue InGaN LED and coat it with a phosphor. The phosphor absorbs the blue light and re-emits it in a broad spectrum of light at longer wavelengths. Some of the first white LEDs of this type used a yellow emitting phosphor that absorbed only a portion of the blue LED light, resulting in a mix of blue and yellow light perceived as white by the human eye. The proportions of blue and yellow light emitted, controlled by the amount of phosphor applied to the LED chip, determines the shade of white produced—yellowish white or bluish-white. The spectral quality of the white light can also be adjusted by adding different phosphors that emit green and red light, thus producing a full-spectrum of white light, similar to daylight, with good color rendering for illumination purposes. Still another technique is to add organic dyes to the epoxy encapsulant surrounding the blue LED chip to convert the blue light to any color desired. Thus a single type of LED chip could be used to make essentially any color of LED. Violet or ultraviolet InGaN LEDs are also candidates for the phosphor and dye conversion techniques.

The phosphor technique for making white-light LEDs is relatively straightforward and inexpensive to implement, and these products are already available on the market. Yet, the most efficient method for obtaining white light from LEDs is to mix the light from discrete red, green, and blue chips or lamps. This is likely to be the approach used in the development of products for general illumination. However, in spite of the impressive performance figures for efficiency just presented, the obstacles of cost and scaling have yet to be overcome before LEDs can compete with incandescent and fluorescent light sources for general illumination. A single incandescent bulb, for example, produces ~1000 lm of light, whereas it takes several hundred conventional LEDs to produce the same amount of flux. Furthermore, though it costs no more to manufacture a 100 W light bulb than it does a 40 W bulb, with LED lighting, cost is directly proportional to flux. Thus, producing twice the flux requires twice the number of individual LEDs, or LEDs with larger chips—the result is the same. The "lumen/dollar" figure of merit is another way to compare the difference between light sources, and today, incandescent lighting provides about 1000 lm/$, whereas LED lighting provides only about 1–10 lm/$, a substantial difference. The way to defeat this scaling problem is to reduce the cost of manufacturing LED lamps and assemblies and design methods to drive individual LED chips as hard as possible to get more flux out of them.

What's next

The advances in LED technology over the last two decades have clearly been substantial and have paved the way toward new and exciting applications for solid-state semiconductor lighting. With the two leading LED material systems, AlGaInP and InGaN, we have achieved high light-output efficiency throughout the visible spectrum from red to blue. Superior efficiency, reliability, and lifetime of LEDs, as compared to incandescents, make them especially attractive for specialized applications, such as interior and exterior automobile lighting, large-screen video displays, traffic signals, and many others not mentioned here. However, these applications represent only a fraction of the potential for semiconductor lighting. The ultimate goal over the next few years, of course, is to move LED light sources beyond the niche-application market and into the mainstream lighting and illumination market. However, before an LED lamp appears next to a light bulb on the store shelf, still more improvements in LED materials, chip design, package design, and cost reduction are required. With a solid technology foundation now in place, the possibilities for LEDs are enormous, and they are sure to expand over the next few years into virtually every lighting and illumination market segment.

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