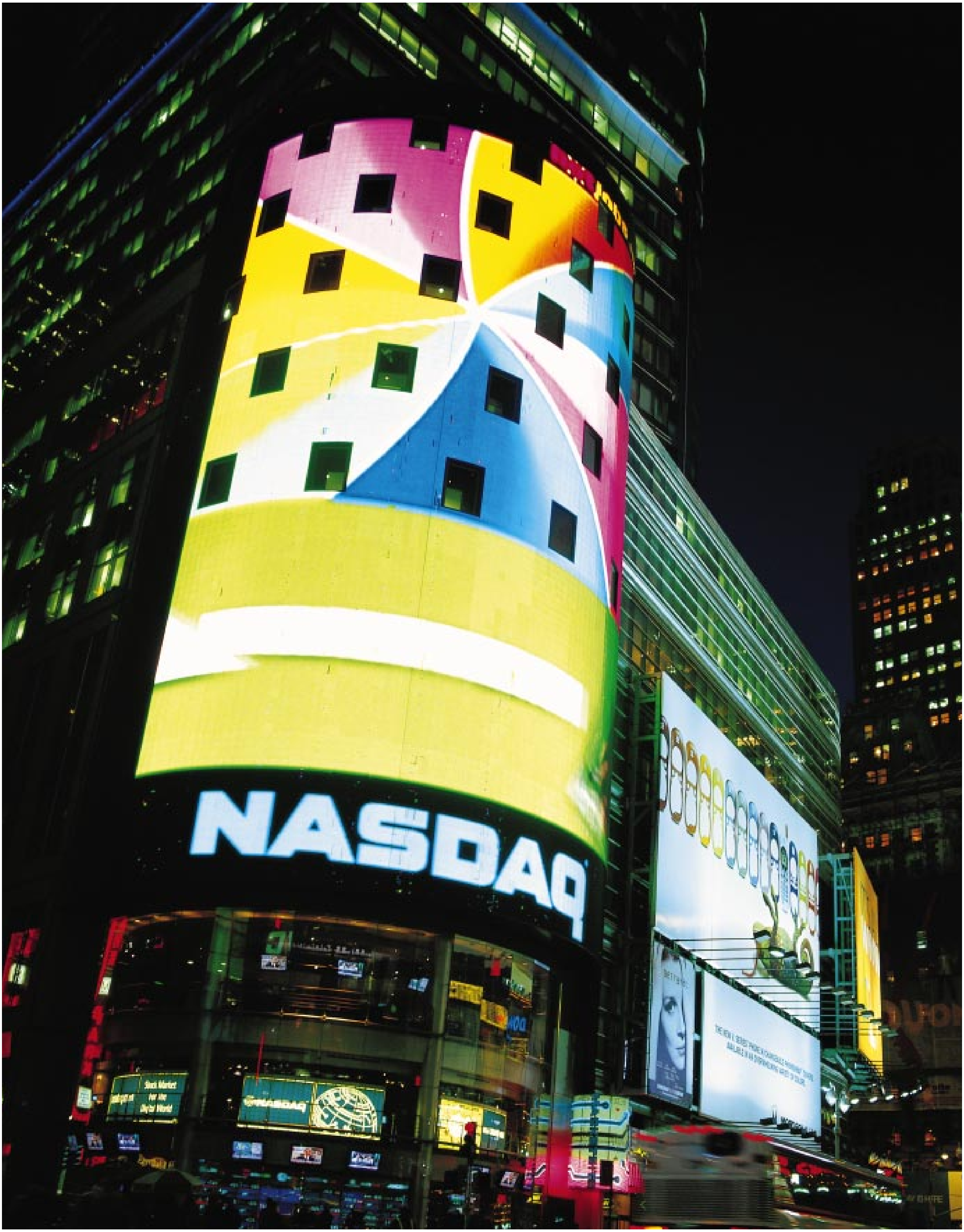


PETER MURPHY

Full-spectrum light-emitting diodes, or LEDs, are becoming widespread—and the race is on to develop white-light versions to replace Edison's century-old incandescent bulb

by M. George Craford, Nick Holonyak, Jr., and Frederick A. Kish, Jr.

In Pursuit of the ULTIMATE LAMP

In 1995 one of us (Holonyak) was honored to accept the Japan Prize for pioneering work in semiconductor light emitters and lasers. Asked to say a few words about tomorrow's technology, he simply pointed to the ceiling lights and said, "All of this is going."

A revolution is taking place, literally in front of our eyes, thanks to semiconductor devices known as light-emitting diodes, or LEDs. Most familiar as the little glowing red or green indicator lights on electronic equipment, LEDs are beginning to replace incandescent bulbs in many applications. The reason? LEDs convert electricity to colored light more efficiently than their incandescent cousins—for red light, their efficiency is 10 times greater. They are rugged and compact; some types last a phenomenal 100,000 hours, or about a decade of regular use. In contrast, the average incandescent bulb lasts about 1,000 hours. Moreover, the intensity and colors of LED light have improved so much that the diodes are now suitable for large displays—perhaps the most impressive example being the eight-story-tall Nasdaq billboard in New York City's Times Square.

Currently engineers are trying to lower the cost of manufacturing LEDs, improve their efficiency and extend their range of useful colors. In fact, it is possible to combine the output of red, green and blue LEDs to make white light, a cheap, mass-market form of which would be the brilliant prize of the industry. Such an LED could someday supplant, more than a century after Thomas Edison's invention, the incandescent lightbulb.

NASDAQ MARKETSITE TOWER, the world's largest video screen, uses 18,677,760 LEDs covering 10,736 square feet.

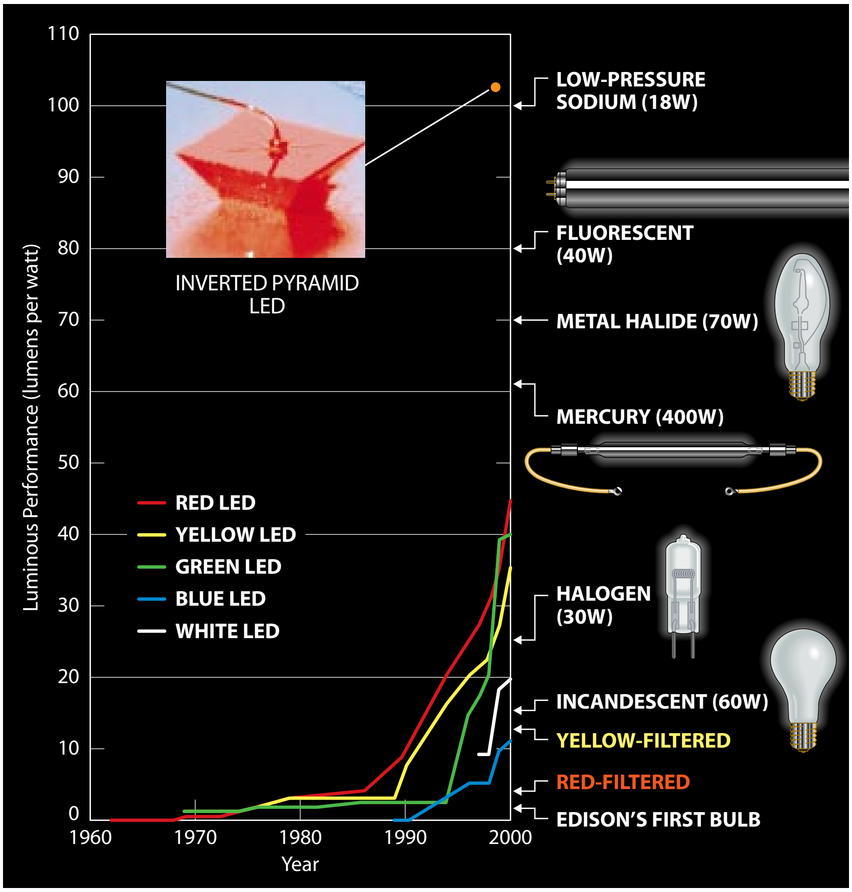
LEDs are already replacing lightbulbs in several instances, albeit in a fashion less dramatic than the giant Nasdaq display. The new applications are perhaps most noticeable to automobile drivers. In Europe 60 to 70 percent of the cars produced use LEDs for their high-mount brake lights, and the U.S. is beginning to move in that direction, too. LEDs are also being used for taillights and turn signals, as well as for side markers for trucks and buses. We expect that by the end of the decade LEDs will dominate the red and amber lighting on the exterior of vehicles. Larger and brighter LEDs are making their way into the red of traffic lights. About 10 percent of the nation's stoplights include LEDs.

Traditionally, traffic signals and other colored lamps use incandescent bulbs, which are then covered with a filter to produce the appropriate hue. Although filtering is cheap—the bulbs emit light that costs a mere fraction of a cent per lumen (the standard measurement unit of illumination)—it is a terribly inefficient way to produce light. A red filter, for example, blocks about 80 percent of the glow, so the amount of light that emerges drops from about 17 lumens per watt of power to about three to five lumens per watt.

In contrast, lumens cast by an LED stoplight may cost around 15 cents each to produce, but virtually all of them are of the right color. What is more, the LEDs in a stoplight consume only 10 to 25 watts, compared with the 50 to 150 watts used by an incandescent bulb of similar brightness. This energy savings pays for the higher cost of an LED in as little as one year. When this figure is considered with the reduced maintenance and labor costs of LEDs, it is easy to see why LEDs are becoming more popular with city planners.

Interior designers began to use LEDs a few years ago, when high-brightness models of all colors made their appearance. Because each LED gives off one distinct hue, users can have complete control of nearly the full spectrum. By putting differently colored LEDs together in an array, the user can adjust their combined light. For example, white light com-

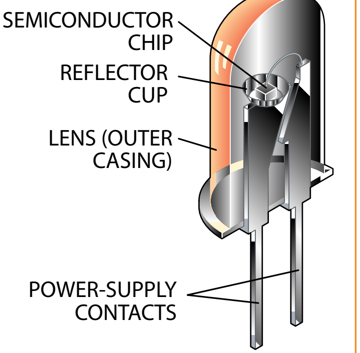
LED Performance



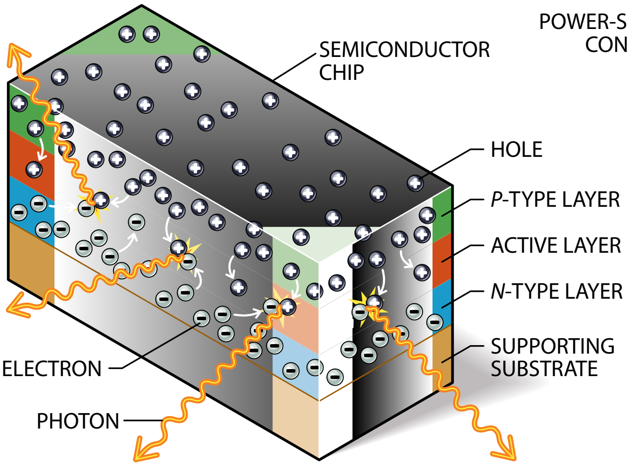
LIGHT-EMITTING DIODES have steadily improved and now outperform many other kinds of lights; the best is a prototype red-orange inverted pyramid LED.

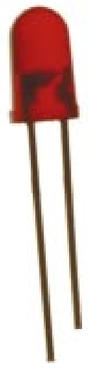
SEMICONDUCTOR CHIP is the key to an LED's glow. An applied voltage drives "holes" (positive charges) from the *p*-type layer and electrons from the *n*-type layer into the active layer. When they meet, they give off photons. The color of the photons depends on the chemical makeup of the layers, although some manufacturers house LEDs in colored lenses as a means of identification (*photograph*).

LED: The Inside View



The Heart of the LED





JARED SCHNEIDMAN DESIGN (*illustrations*); LUMILEDS LIGHTING (*photograph*)

posed of red, green and blue LEDs can be made to feel "cooler" by turning off more of the red LEDs and turning on more of the blue ones.

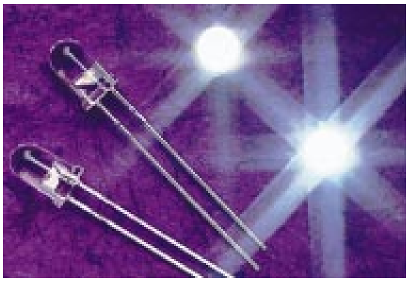
This flexibility offers novel ways of using light. Rather than, say, putting up new wallpaper or applying fresh paint, one can manipulate the color of a room by adjusting the ratio of wavelengths in the emitted light (the wavelengths of light determine the colors). The Metropolitan Museum of Art in New York City relied on just this kind of LED lighting to illuminate its display of the Beatles' *Sgt. Pepper's* costumes in 1999. (The lighting is also cool and will not damage the fabric.) Photographers would have total control of artificial light sources without the need for cumbersome filters or gels.

LEDs also offer intriguing possibilities for medical science. For example, LEDs' cool temperatures, precise wavelength control and broad-beam characteristics enable cancer researchers to study the photodynamic treatment of tumors more effectively. In this therapy, patients receive light-sensitive drugs that are preferentially absorbed by tumor cells. When light of the appropriate wavelength strikes these chemicals, they become excited and destroy the cells. By using an array of LEDs linked together, researchers can produce an even "sheet" of light that stimulates light-sensitive drugs without burning the patient's skin.

Up Close

Maybe the easiest way to examine light-emitting diodes in detail is to purchase a few of them, in the form of a $15 flashing-red LED bicycle light. Open up the casing, and you'll see a pair of AA batteries wired to a circuit board containing a series of clear, colorless, cylindrical knobs approximately $\frac{5}{16}$ of an inch high and $\frac{3}{16}$ of an inch in diameter. Each of these transparent knobs is a light-emitting diode. Press the "on" button, and the clear LED turns red, casting a color so brilliant that it can be painful to look at directly. If you turn it off and closely examine the LED, you will see what is the equivalent of a wire threading through its base—and what looks like a miniature cup about halfway up. This cup is a reflector, which holds a semiconductor chip about the size of a grain of sand. This chip is the LED's "heart."

Inside the chip, there is a layer that has an excess of electrons; the substance is called *n*-type (for "negative"). Another layer rests on top and is made of a material that has a dearth of electrons—or, as electrical engineers like to say, an excess of positively charged particles known as holes. This material is *p*-type (for "positive"). At the junction of the *n* and *p* layers is the so-called active layer, where light is emitted.


LUMILEDS LIGHTING

WHITE LEDs are possible, but affordable ones powerful enough to illuminate a room remain at least a decade away.

Applying a voltage drives electrons and holes into the active layer, where they meet. As they join, they emit photons—the basic units of light. The atomic structures of the active layer and adjoining materials on each side determine the number of photons produced and their wavelengths.

In early LEDs, made in the 1960s with a combination of gallium, arsenic and phosphorus to yield red light, electrons merged with holes relatively inefficiently: for every 1,000 electrons, only one red photon was produced. Such an LED generated less than one tenth the amount of light found in a comparably powered, red-filtered incandescent bulb.

Over time, however, dramatic improvements in output were realized, especially at the red end of the spectrum. In 1999 Michael Krames and his co-workers at Hewlett-Packard set an efficiency record, building LEDs that transform more than 55 percent of the incoming electrons into photons at the red wavelength. Chief among the reasons for these improvements has been the continued rise in material quality and the development of substances that allow the efficient transformation of electrons and holes into photons. One of the biggest boosts in efficiency came when scientists found that the materials do not have to be homogeneous. Instead each layer can have a different chemical makeup, so that when placed next to the active layer they can confine the electrons and holes better, thereby increasing the odds that an electron can combine with a hole to produce light.

Researchers have also learned to tailor the properties of the semiconducting layers. They can vary the material composition of the active layer and "dope" the layers with impurities. Doping alters the *n*- and *p*-type characteristics of the semiconductor layers. To take the simplest example, consider silicon. Silicon belongs to group IV of the periodic table: it has four electrons that are available for bonding with other atoms. In the crystal form, each atom shares electrons with neighboring atoms. When a small number of group III atoms—that is, those containing three electrons in their outermost energy level, such as boron—are incorporated into the crystal, the resulting structure has an insufficient number of bonds to share with the surrounding silicon atoms. Vacancies for electrons appear, creating holes and rendering the material *p*-type.

Conversely, elements that belong to group V of the periodic table, such as phosphorus, have an extra electron in their outermost energy level. When silicon is doped with phosphorus, the crystal gains electrons, making the material *n*-type.

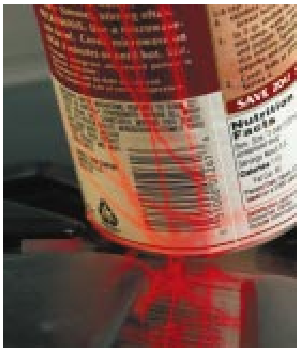
In LEDs, the crystal is not silicon but a mixture of group III and group V elements. By carefully controlling the concentration of aluminum, gallium, indium and phosphorus, for example, and by incorporating suitable dopants, typically tellurium and magnesium, researchers can control the formation of the *n*-side and the *p*-side, making LEDs that emit at the red, orange or yellow wavelengths. By the early 1970s red LEDs containing gallium arsenide phosphide were bright enough to illuminate the first calculators and digital clocks.

Another key to LED improvement lies in manufacturing techniques that reliably create viable, smooth crystals instead of lumpy, defect-riddled systems. The atomic lattices of the *p* and *n* materials must match up with those of the underlying supporting substrate and active layer. One such manufacturing

LEDs and Lasers

Although light-emitting diodes and laser diodes sound similar—in fact, both are made of semiconductor materials—they are very different beasts, designed to behave in different ways and to tackle different jobs.

Laser diodes take the form of a semiconductor material between what is essentially a pair of mirrors. The region between the mirrors is called the resonator cavity. When electricity goes through the semiconductor, it gives off photons, which then bounce back and forth inside the cavity, exciting other, nearby electron-hole pairs to release more photons at the same wavelength. The light increases continuously in intensity, with the photons marching in lockstep together as they oscillate between the two mirrors. If one of the mirrors allows just a small fraction of the light to escape, then some of the photons exit. All at the same wavelength and in phase, they produce an extremely narrow column of pure, bright light at a single wavelength. In physicists' terms, the photons are coherent.


PHIL DEGGINGER *Stone*

BAR-CODE SCANNING relies on semiconductor lasers.

This extremely well defined beam is one of the main characteristics of a laser. As such, it is something like a scalpel: sharp, thin and able, with proper optics, to do delicate work, such as reading the fine pits on a compact disc or scanning the bar codes in a checkout line.

By comparison, the widely scattered light of an LED is like the patter of raindrops. Because LEDs are not in a proper cavity (that is, not between mirrors), the photons they emit are, in a sense, incoherent. Light comes out not in a unidirectional column but in a broader, more diffuse pattern, composed of a spread of wavelengths from one area of the spectrum. The photons an LED produces may not be all at the exact same wavelength, but they are close enough so that they are perceived by the human eye as being the same color.

—M.G.C., N.H. and F.A.K.

method is vapor phase deposition, in which hot gases are channeled over a substrate to create a thin film. This technique was first incorporated into a high-volume LED manufacturing process at Monsanto in the late 1960s. In 1977 a different process of vapor phase deposition, one utilizing cool gases directed over a hot substrate, was demonstrated by Russell D. Dupuis, now at the University of Texas, to produce semiconductor lasers. This process, which enables the growth of a wider variety of materials, is now used to make high-quality LEDs. Shuji Nakamura, now at the University of California at Santa Barbara, used a variation of the technique to manufacture high-quality gallium nitride crystal capable of shining blue light. (For a profile of Nakamura, see "Blue Chip," by Glenn Zorpette; Scientific American, August 2000.)

In the mid-1990s a team at Hewlett-Packard found another way to enhance brightness—by reshaping the chip itself. Through careful manipulation, researchers can remove the original gallium arsenide wafer on which the active layer was grown, replace it with a transparent gallium phosphide wafer and sculpt an LED into the shape of an inverted pyramid. This shape decreases the number of internal reflections and thus boosts the amount of light escaping from the chip.

The Great White Hope

Thanks to these improvements in color and brightness, researchers have begun to zero in on making affordable, bright white LEDs. Low-power white LEDs with an efficiency somewhat better than incandescent bulbs are already available commercially, but high-power devices suitable for illumination are still far too expensive to be mass-marketed. The potential benefits of such a light, if made cheaply, are enormous. Instead of dealing with fragile, hot, gas-filled glass bulbs that burn out relatively quickly and waste most of their energy in the form of heat, consumers would own long-lasting, solid-state interior lights. In automobiles, for example, the LEDs would last the lifetime of the car. And the minimal power demands of LEDs mean that more energy is left in the automobile's battery for all the onboard electronic devices.

Society as a whole could benefit as well. Lighting represents about 20 to 30 percent of the U.S. electrical use, and even the best standard illumination systems convert no more than about 25 percent of electricity into light. If white LEDs could be made to match the efficiency of today's red LEDs, they could reduce energy needs and cut the amount of carbon dioxide pumped into the air by electrical generating plants by 300 megatons a year.

The first company to mass-produce affordable high-brightness white LEDs stands to capture an estimated $12-billion worldwide market for illumination lighting. That's why the big three players of lighting—Philips, Osram Sylvania and General Electric—are spending so much on LED research and development and why newer companies are springing up, such as LumiLeds, a joint venture between Philips and Agilent Technologies, for which one of us—Craford—is chief technology officer.

Low-power white LEDs are already used for cell-phone backlights and pedestrian walk signals. Second-generation,

LEDs Light the Deep

When marine biologist Greg Marshall of National Geographic Television wanted to film deep-diving animals such as sperm whales, he faced several problems. These creatures can plunge thousands of feet below the surface, to where it is virtually pitch-black and the pressures are enormous. Further compounding the situation is that any kind of visible lighting would affect his subjects' behavior, attracting or repelling them and their prey. By causing the whales to act abnormally, the standard underwater light would defeat the entire purpose of his project.

The solution: compact LEDs that emit light at the near-infrared wavelength, making for a light that the videotape can "see" but the animal cannot. When placed inside a hardy, torpedo-shaped metal cylinder containing an automatic camera, the devices act as invisible headlights, illuminating objects two or three meters away without altering the whales' behavior.

The small size of the LEDs meant that there was room to cram other equipment inside, such as devices to record audio, time of day, depth and duration of dive, direction, temperature and velocity. Dubbed Crittercam, the whole automatic camera package is small enough to be placed on the backs of whales, seals, dolphins, penguins, sea lions and other marine creatures, giving scientists a whale's-eye view of the sea. After filming, a time-release device in the harness lets go of the Crittercam, allowing it to bob to the surface where it can be retrieved, along with its precious footage.

SPERM WHALES from Crittercam, in a view lit by LEDs.

GREG MARSHALL *National Geographic Television*

Crittercam is the result of 14 years of experimentation, much of which was on suitable light sources. When the first blue LEDs came out commercially about four years ago—at $40 apiece—Marshall was one of the first to own one, which he purchased directly from the factory in Japan. (Unfortunately, he found that whereas blue-wavelength LEDs penetrated the deep ocean's gloom most efficiently, their light was too visible to his swimming subjects. Near-infrared became the choice instead. In other words, wavelength selection matters, a big advantage when it comes to LEDs.)

Marshall's effort paid off. Watching the footage from a Crittercam mounted to the dorsal fin of a shark is as exciting as watching the chase scene in a spy movie. And the camera has enabled marine biologists to observe behaviors never seen before, such as seals blowing bubbles and "singing" undersea as they perform courtship rituals. *—The Editors*

COLOR KINETICS (*top left*); LUMILEDS LIGHTING

CURRENT LED APPLICATIONS include (*clockwise, from top left*): exhibit lighting, such as that used on the Beatles' *Sgt. Pepper's* costumes in New York City's Metropolitan Museum of Art; traffic lights; auto taillights and turn signals; and outdoor signs.

higher-power LEDs suitable for, say, landscape and accent lighting are becoming available. But large-scale replacement of lamps for general-purpose illumination are not expected for a decade or two because of the difficulty in making white LEDs efficient and cost-competitive.

There are two main ways to generate white light from LEDs. One way is to combine the output of LEDs at the red, green and blue wavelengths, based on the additive principle of color theory. The problem with this technique is that it is difficult to mix the colors of the LEDs efficiently with good uniformity and control.

The second way relies on an LED photon to excite a phosphor. For example, one can package a yellow phosphor around a blue LED. When the energy of the LED strikes the phosphor, it becomes excited and gives off yellow light, which mixes with the blue light from the LED to give white light. Alternatively, one can use an ultraviolet LED to excite a mixture of red, green and blue phosphors to give white light. This process, similar to that in fluorescent tubes, is simpler than mixing three colors but is inherently less efficient, because energy is lost in converting ultraviolet or blue light into lower-energy light (that is, light toward the red end of the spectrum). Moreover, light is also lost because of scattering and absorption in the phosphor packaging.

In any case, the high cost of LED chips and packages currently makes both approaches prohibitive for illumination applications. The best commercial white LEDs now cost about 50 cents per lumen, compared with a fraction of a penny per lumen for a typical incandescent bulb.

Whichever method is chosen—and both will most likely be important for different applications—the key issues are to reduce production costs substantially and to improve performance. Still, it may be a while before consumers accept LEDs, which cost more up front but are cheaper over the span of a decade. As energy prices rise and the consequences of global warming become more urgent, LEDs should become more attractive. One solution to our energy and environmental problems, it seems, may soon come to light. SA

The Authors

M. GEORGE CRAFORD, NICK HOLONYAK, JR., and FREDERICK A. KISH, JR., have all won awards for their work on light-emitting diodes. Craford, who made the first yellow LED, managed the LED technology groups at Monsanto and Hewlett-Packard before becoming chief technology officer at LumiLeds Lighting in San Jose, Calif., a firm jointly created by Philips and Agilent Technologies to seek emerging LED applications. Holonyak, professor of electrical and computer engineering and physics at the University of Illinois, is credited as being the inventor of the first practical LED: the red gallium arsenide phosphide LED. He was also two-time Nobelist John Bardeen's first Ph.D. student. Kish is R&D and manufacturing department manager at Agilent Technologies. There he was one of the primary instigators of a new family of high-brightness red-orange-yellow LEDs, which were the first LEDs to exceed the efficiency of unfiltered incandescent bulbs and are now the dominant technology for traffic signals and exterior lights on automobiles. Both Craford and Kish were graduate students in Holonyak's laboratory.

Further Information

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