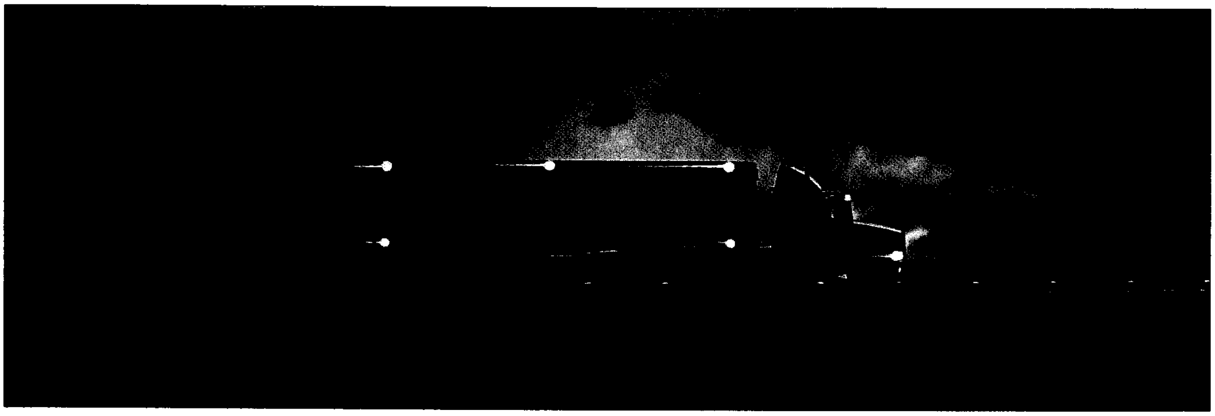
# Higher visibility for LEDs



Hewlett-Packard Co.

*The luminance and luminous efficiency of light-emitting diodes (LEDs) in the last few years have reached such high levels that they can replace incandescent lamps in running lights on trucks. Particularly where safety is involved, the longer life and inherent ruggedness of the solid-state devices make them a highly desirable substitute; the lower maintenance cost of the LEDs is a boon to any application.*

*More light—some of it blue—from less power unveils bright vistas of new applications for the latest light-emitting diodes*

Ken Werner Contributing Editor

Ubiquitous, reliable, boring—those are the words many electronics engineers would use to describe light-emitting diodes (LEDs). Yet slow, steady advances in materials and structures now allow companies to produce red LEDs bright and efficient enough to replace incandescent lamps in automotive brake lights and traffic signals. Moreover, LEDs take about a million hours to degrade to half power, greatly reducing maintenance costs.

Even full-color outdoor video displays based on LEDs are now possible. A Japanese company with no track record whatever in semiconductor devices seems to have discovered the long-sought Holy Grail of LED technology—a blue LED with a luminous efficiency high enough to make it adequately bright at reasonable power levels.

Back in 1962, when the technology was first commercialized by General Electric Co., the visible-light LED was arguably the simplest solid-state light-producing electro-optical device imaginable [Fig. 1]. It consisted of a forward-biased p-n junction fabricated in a III-V compound—a semiconducting material composed of chemical elements from columns III and V of the periodic table. When the bias voltage reached the level associated with the material's energy gap ($E_g$), injection of minority carriers—electrons into the p material and holes into the n material—became appreciable, and significant conduction occurred. The minority carriers combined with majority carriers, liberating photons with an energy approximately equal to $E_g$.

The earliest material for visible-wavelength LEDs was gallium arsenide phosphide (GaAsP), with an energy gap that could be as large as 2.03 electron volts for an appropriately chosen ratio of As to P. The wavelength of the emitted radiation, l, equals the product of Planck's constant, *h*, and the speed of light in a vacuum, *c*, divided by $E_g$; so for an $E_g$ of 2.03 eV, the wavelength was 610.5 nm—which is red.

The early LEDs had a luminous efficiency of less than 0.2 lumen per watt. There were two reasons for the poor luminous performance of these early LEDs: low internal quantum efficiency and low extraction efficiency. Indeed, the history of LED development to date has centered on the Herculean effort to improve the device's quantum and extraction efficiencies.

**A LITTLE DEVICE PHYSICS.** An LED's internal quantum efficiency is simply the number of photons generated divided by the number of minority carriers injected. In an LED, most of the minority carriers are electrons injected into the p-doped region, so that the mental picture can be simplified to one of electron injection alone.

I. I. Stanley Inc.

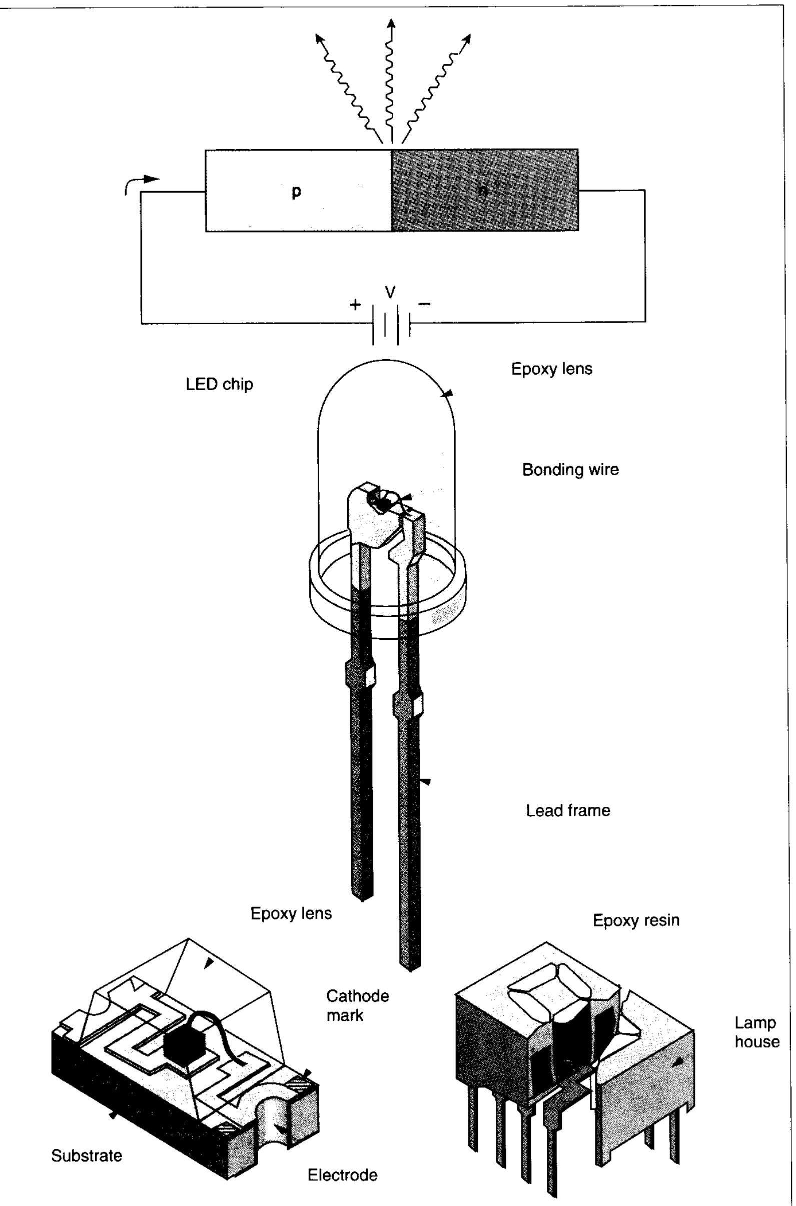
*The electronic outdoor signs that festoon the urban landscape in Asia constitute a high-volume application for LEDs.*

Combining an injected electron with a hole to produce a photon is called, logically enough, a radiative recombination. If all the injected electrons recombined and all the recombinations were radiative, the internal quantum efficiency would be 100 percent. Device designers can make nearly all injected electrons recombine without much difficulty, but ensuring a high proportion of *radiative* recombinations is another story.

If an injected electron remains free in the p-region long enough, it will encounter a hole and recombine radiatively. But other kinds of transitions compete with radiative recombination for each injected electron. The important common characteristic of these other transitions is their failure to produce photons—that is, they are nonradiative recombinations [Fig. 2]. These transitions occur at crystal imperfections of various sorts and dissipate their energy into the crystal lattice as heat.

Characteristic lifetimes of injected elec-

0018-9235/94/$4.00©1994 IEEE



Source: (top) *Flat-panel Displays and CRTs*, L.E. Tannas Jr., ed., Van Nostrand Reinhold, 1985; (center and bottom) LED catalog, I.I. Stanley Inc.

*[1] A basic visible-light-emitting diode is a simple electro-optical device. It utilizes a forward-biased p-n junction [top] in a semiconductor material that has a band gap capable of producing photons with visible wavelengths. Devices are in many forms, including [anticlockwise from center] lamp-type, chip-type, and numerical-display structures.*

trons before they encounter a radiative recombination ($\tau_r$) or a nonradiative one ($\tau_{nr}$) can be determined for any semiconducting material. If $\tau_r$ is much less than $\tau_{nr}$, the internal quantum efficiency will be very close to 100 percent, as in gallium arsenide (GaAs) devices. (For them, a typical $\tau_r$ is 5 x $10^{-9}$ second.) Unfortunately for visible-light applications, GaAs emits in the infrared part of the spectrum, and most other semiconductors have a much lower internal quantum efficiency.

The external—or overall—quantum efficiency of any LED is often much lower than its internal quantum efficiency because many photons never leave the device. Finding ways of improving the extraction efficiency—the percentage of generated photons that actually find their way out of the device—has contributed as much to overall performance as have the more exotic efforts to improve internal quantum efficiency. Discussion of these approaches can wait till later. For now, a return to the semiconductor energy gap and the wavelength of light produced by an LED is in order.

The energy gap of a semiconductor is the minimum energy separating the valence band and the conduction band. Each band contains the possible combinations of energy and momentum for one type of carrier—the valence band those for the carriers of positive charge (holes) and the conduction band those for the negative charge carriers (electrons).

The simplest situation occurs when $E_g$ is found at the point where the hole and electron momenta are both zero [Fig. 3, left]. An electron and hole can then readily combine and in so doing emit a photon, because the interaction conserves energy and momentum. Energy is conserved because the energy of the emitted photon equals the energy lost by the electron as it combines with the hole. Momentum is conserved because the electron and hole momenta were both essentially zero to begin with, and photons have almost no momentum.

This kind of gap is called a direct energy gap, and the semiconductor that contains it is called a direct semiconductor. Clearly, direct semiconductors favor radiative recom-

## Defining terms

**Brightness:** a subjective attribute of light. It is described as varying over a range from very dim to blinding and is often used, erroneously, in place of luminance [see below], an objectively measurable quantity. With all other conditions constant, increasing the luminance will increase the sensation of brightness, but the relationship between luminance and brightness is highly nonlinear.

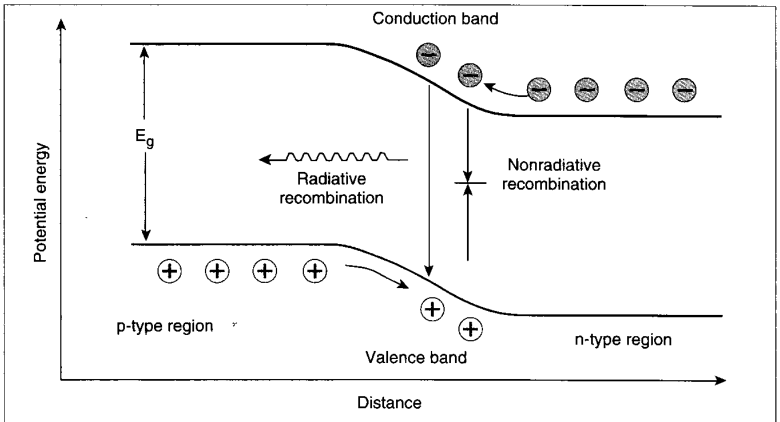
**Light:** radiant energy able to stimulate the retina and initiate a visual sensation. (Note that this definition excludes ultraviolet and infrared wavelengths, whereas physicists—including those working with LEDs—tend to call them all light.)

**Luminance:** the luminous intensity per unit area projected in a given direction. The SI unit is the candela per square meter, sometimes called a nit. The foot-lambert, while deprecated by metric purists, is still in common use. (1 fL equals 3.426 $cd/m^2$.)

**Luminous efficiency:** the ratio, measured in lumens per watt, of luminous flux (see below) to the electric power that produced it. Since a true efficiency can only be expressed as a percentage, this use of the word "efficiency" is not formally correct. Therefore, in the information-display and illumination engineering worlds, "luminous efficacy" is sometimes used. The equivalent term in the LED literature is "luminous performance."

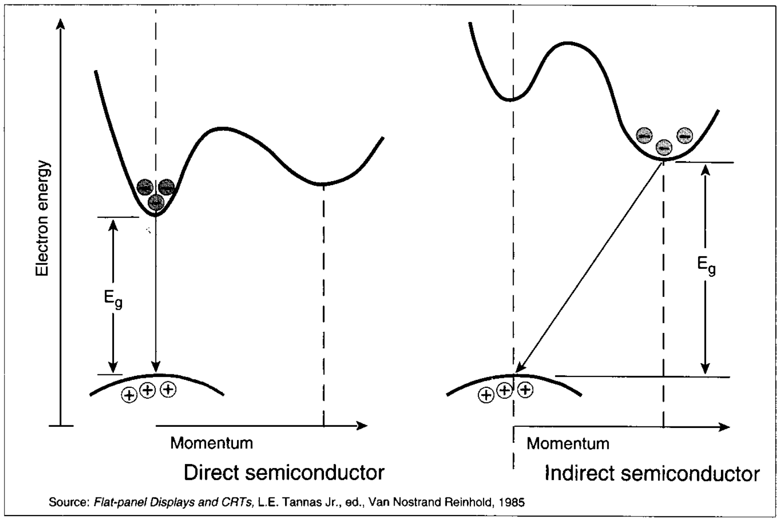
**Luminous flux:** "visible power" measured in lumens. At a wavelength of 555 nm—the yellow-green light to which the human eye is most sensitive—1 W of radiant power is equivalent to a luminous flux of 680 lm. The eye's sensitivity falls off sharply; at 510 and 610 nm, 1 W is equivalent to only 340 lm.

**Luminous intensity:** the luminous flux per solid angle emitted from a point, measured in lumens per steradian, or candelas (cd).



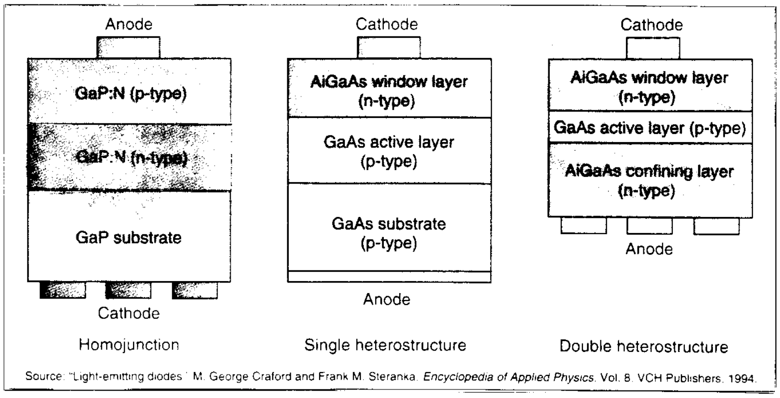
Source: *Flat-panel Displays and CRTs*, L.E. Tannas Jr., ed., Van Nostrand Reinhold, 1985

*[2] In an LED, electrons injected across the p-n junction combine with holes in radiative recombinations, which produce photons, or in nonradiative recombinations, which do not.*



Source: *Flat-panel Displays and CRTs*, L.E. Tannas Jr., ed., Van Nostrand Reinhold, 1985

*[3] Electrons in the conduction band of a direct semiconductor have essentially zero momentum and can directly recombine with a hole, producing a photon. In an indirect semiconductor, a more complicated interaction is required to conserve momentum.*



Source: "Light-emitting diodes," M. George Craford and Frank M. Steranka, *Encyclopedia of Applied Physics*, Vol. 8, VCH Publishers, 1994.

*[4] The simplest LEDs [left] are formed by epitaxially growing an n-type film on a substrate and creating a p-type junction in the film. They are called homojunction devices because both sides of the junction are formed from the same basic material. A single heterostructure [center] overcomes some of the limitations of homojunction devices by using a different material for the p and n sides of the p-n junction. In a double heterostructure [right], an additional layer of material confines injected electrons within the active layer.*

bination. Unfortunately, the only colors available from early direct semiconductors suitable for visible LEDs were shades of red.

A wider range of colors was available from another class of devices, indirect semiconductors, in which the holes still cluster around zero momentum but the electrons cluster around a nonzero momentum [Fig. 3, right]. Thus a recombination that emitted only a photon of energy $E_g$ would conserve energy but not momentum, and therefore cannot occur.

The only way a radiative recombination can take place in these circumstances is for the interaction to produce a particle (or something capable of acting like a particle) that can carry away the initial electron momentum. Fortunately, an appropriate something exists: a quantum of vibrational energy in the crystal lattice—a phonon—that produces heat transfer to (or from) the lattice. Thus the interaction of concern is one in which an electron in the conduction band combines with a hole in the valence band, simultaneously producing a phonon and a photon. The combined energy of the resultant phonon-photon pair equals $E_g$ and the sum of the initial electron momentum and the phonon momentum equals zero.

One of the principles of particle physics is that, if an interaction can happen, it will. But the combination of conditions that allows an indirect radiative recombination to occur is far less likely than the simpler set of conditions that permits a direct radiative recombination. As a result, indirect semiconductors are characterized by a longer recombination time ($\tau_r$) and a larger ratio of recombination to nonrecombination ($\tau_r/\tau_{nr}$) than are direct semiconductors, as well as relatively low quantum efficiencies.

**DIRTY TRICKS.** Many commercial devices are made from such indirect semiconductors as gallium phosphide (GaP), which produces green, and silicon carbide (SiC), which produces blue. From the beginning, there was intense interest in improving the luminous performance of these devices.

One approach is to add an isoelectronic impurity—one from the same column of the periodic table as the element it replaces. An example is nitrogen in GaP, designated GaP:N. Each nitrogen atom creates a localized strain in the crystal that can trap an electron. The electrons are bound so firmly that there is little uncertainty as to their position. But there is, according to the Heisenberg uncertainty principle, a large statistical uncertainty in their momentum. The uncertainty is large enough for each electron to have a significant probability of having zero momentum and undergoing a direct radiative recombination. This quantum-mechanical trick raises the radiative recombination rate, but not enough to rival the rate in direct semiconductors.

Another trick is to use such three-element alloys as $GaAs_{1-x}P_x$ and such four-element alloys as $(Al_xGa_{1-x})_{0.5}In_{0.5}P$. The energy gap can be varied by altering the proportions of the elements in the alloy, and many of these semiconducting alloy systems change from an indirect to a direct semiconductor at some composition—some value of $x$ in the chemical expressions above—that dramatically increases the quantum efficiency. When GaAsP contains 70 percent GaP, for instance, its quantum efficiency is about $2 \times 10^{-5}$. When it contains 25 percent GaP, its quantum efficiency is $8 \times 10^{-3}$.

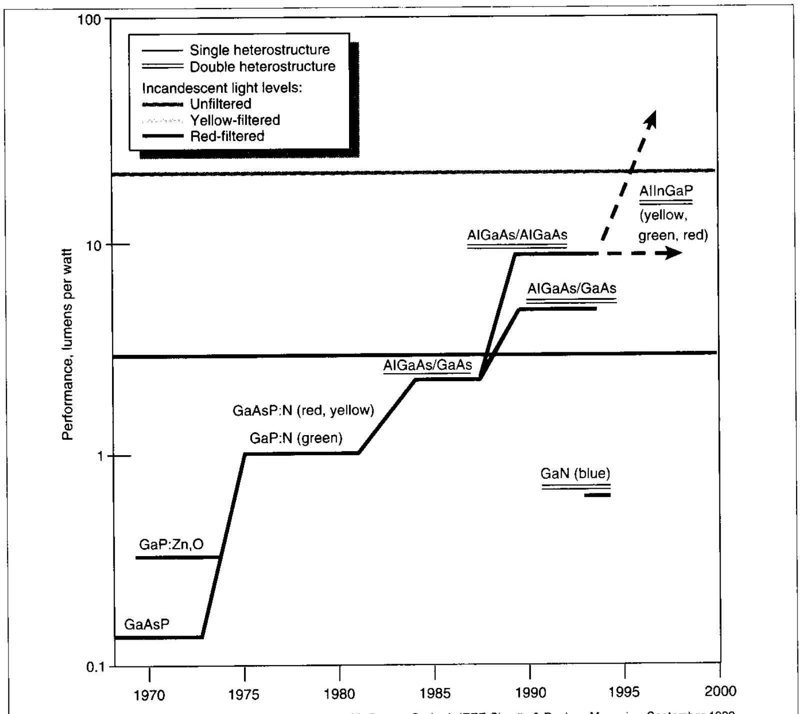
**FABRICATING LEDs.** To what extent have these materials developments allowed LED designers to develop highly efficient devices in different colors? Consider the structure of a GaP:N diode [Fig. 4, left]. The n-type film is epitaxially grown on the substrate, and the junction is formed by diffusing a p-type dopant into the film or by changing the dopant during the growth of the epitaxial film. In either case, both sides of the junction are formed from the same basic material, so devices of this kind are called homojunction devices.

These devices can be made easily and economically, but they have severe limitations. To maximize quantum efficiency, designers would like to dope both sides of the junction heavily. However, this produces a deep junction—one quite far below the anode contact in Fig. 4. As a result, in direct semiconductors, many photons are absorbed by the semiconducting material before reaching the anode surface where they are emitted. But if the junction were shallow (which would also result in a lightly doped layer that would not produce or convert injected electrons efficiently), a lot of the injected electrons would reach the surface before they could recombine and produce photons. (Surface recombination is usually nonradiative.)

In indirect semiconductors, photons are absorbed much less readily, so junctions can be deep. However, heavily doping the n-type side of the junction (as is needed for effective electron injection) inevitably shortens the nonradiative lifetime. The standard compromise is suboptimal doping and reduced device efficiency.

Many of the tradeoffs inherent in homojunctions can be resolved by using different materials for the two sides of the p-n junction—which is called a single heterostructure or single heterojunction [Fig. 4, center]. The device is fabricated by growing a window layer of n-type AlGaAs on the active layer of p-type GaAs. The window layer is transparent to the photons generated in the active layer, and can therefore be made thick enough to minimize surface recombination. Even though the n-type window layer is lightly doped, its proximity to the GaAs p-type layer, with its smaller band gap, produces efficient electron injection.

**STRUCTURAL ADVANCE.** This structure was a distinct advance in LED technology. Devices based on it typically have an external quantum efficiency of 4 percent and a luminous performance of 2 lumens per watt. But problems remain. Some of the injected electrons penetrate deeply into the active region before recombin-



Source: "LEDs Challenge the Incandescents," M. George Craford, *IEEE Circuits & Devices Magazine*, September 1992.

*[5] The luminous performance of LEDs has risen by a factor of 100 over the last 25 years, and more improvements are in sight. A milestone was passed when the performance of red LEDs exceeded that of red-filtered incandescent lamps, opening the automotive brake-light market to solid-state devices. Full-color displays require red, blue, and green, but until very recently no blue diodes performed well enough even in a laboratory.*

I. I. Stanley Inc.

### Some visible-light-emitting diodes characterized

| Structure | Material | Bandgap type | Peak wavelength, nm (color) | Typical performance, lm/W |
|---|---|---|---|---|
| Homojunction | GaAsP | Direct | 650 (red) | 0.15 |
| | GaP: Zn,O | Indirect | 700 (red) | 0.4 |
| | GaAsP: N | " | 630 (red),<br>585 (yellow) | 1 |
| | GaP: N | " | 565 (yellow-green) | 2.6 |
| | GaP | " | 555 (green) | 0.6 |
| | SiC | " | 480 (blue) | 0.04 |
| Single heterojunction | AlGaAs | Direct | 650 (red) | 2 |
| Double heterojunction | AlGaAs | Direct | 650 (red) | 4 |
| | AlGaP | " | 620 (orange) | 20[a] |
| | AlInGaP | " | 595 (amber) | 20[a] |
| | AlInGaP | " | 570 (yellow-green) | 6[a] |
| | GaN | " | 450 (blue) | 0.6 |
| Double heterojunction with transparent substrate | AlGaAs | Direct | 650 (red) | 8 |

Source: based on "LEDs Challenge the Incandescents," M.George Craford, *IEEE Circuits & Devices Magazine*, September 1992

(a) Best reported results; typical commercial performance not established.

ing, and many of the photons produced by these interactions are absorbed before making their way to the surface. Of course, photons emitted downward will be absorbed.

To utilize these wasted photons, designers developed a double heterostructure. An active layer is sandwiched between two layers fabricated from materials (or a material) different from that of the active layer with larger energy gaps [Fig. 4, right]. The upper layer is still called the window layer; the lower layer is the confining layer, whose larger energy gap keeps the injected electrons from penetrating beyond the heterojunction. This allows designers to make the active region thin, which minimizes absorption.

**GETTING THE LIGHT OUT.** The external quantum efficiency of an LED equals its internal quantum efficiency multiplied by the device's extraction efficiency. Extraction efficiency is usually much less than 1; extracting light from an LED semiconductor chip is difficult. Because of absorption losses, reflection at the junctions, and total internal reflection at emission angles greater than the critical angle—about 25 degrees for epoxy-encapsulated diodes—the extraction efficiency can be as low as 4 percent if the active layer is thin and emission through its edges is therefore negligible. As a result, even a superb LED material with an internal quantum efficiency of 100 percent will end up as a device having an external efficiency of only 4 percent!

Designers at companies such as Hewlett-Packard Co. in the United States and Toshiba Corp. and Stanley Electric Co. in Japan did not labor long and hard on problems of quantum mechanics and device structure to be defeated by problems in classical optics. They proceeded to make the active layer quite thick—up to tens of micrometers—which produced good edge emission and raised the extraction efficiency to more than 10 percent.

In double heterostructures, it is possible to grow a confining layer so thick—greater than 100 μm—that the substrate can be completely removed. The confining layer then serves as a new, transparent substrate. In a device with a transparent substrate, a great deal of the light that is emitted downward reflects from the back of the chip and escapes. As a result, the extraction efficiency can rise to about 30 percent.

Commercial red LEDs made of AlGaAs with a double heterostructure and transparent substrate currently produce in the vicinity of 10 lm/W. So do red, orange, and yellow LEDs made of AlInGaP with an absorbing substrate. Transparent-substrate AlInGaP devices about to enter commercial manufacturing are producing 20 lm/W.

Fred Kish and his colleagues at Hewlett-Packard have recently reported an orange, 40-lm/W device. This is one of a new family of transparent-substrate devices fabricated with semiconductor wafer bonding. The original n-type absorbing GaAs substrate on which the subsequent device layers have been grown is chemically etched away. The remaining layers are then wafer-bonded under heat and pressure to a transparent n-type GaP substrate about 0.25 mm thick.

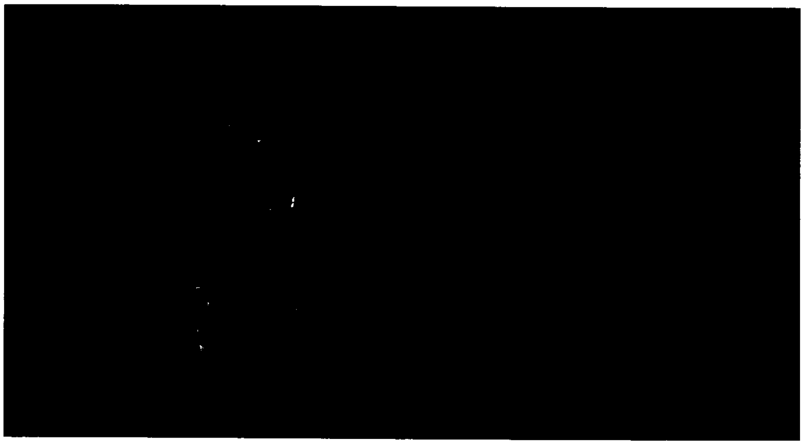
The 40-lm/W device from this family has a luminous performance that is better than that of an unfiltered halogen bulb. Across the entire visible spectrum, the new architecture produces devices with double the luminous performance of the best previous devices, according to Kish.

**MILESTONES AND USES.** When the first visible GaAsP LEDs were commercialized in 1962, they would have made Henry Ford feel pretty much at home: customers could have any color they wanted, as long as it was red. The luminous efficiency of these devices was 0.15 lm/W [Fig. 5], suitable for many indicator lamps and numerical readouts but nowhere near outshining the 3.5 lm/W of a red-filtered incandescent lamp.

With the development of isoelectronically doped indirect semiconductors in the mid-1970s, diodes became both brighter and more varied. Red and yellow diodes made with GaAsP:N and green diodes made with GaP:N were producing about 1 lm/W. Single-heterostructure AlGaAs/GaAs diodes raised the state of the art to 2 lm/W.

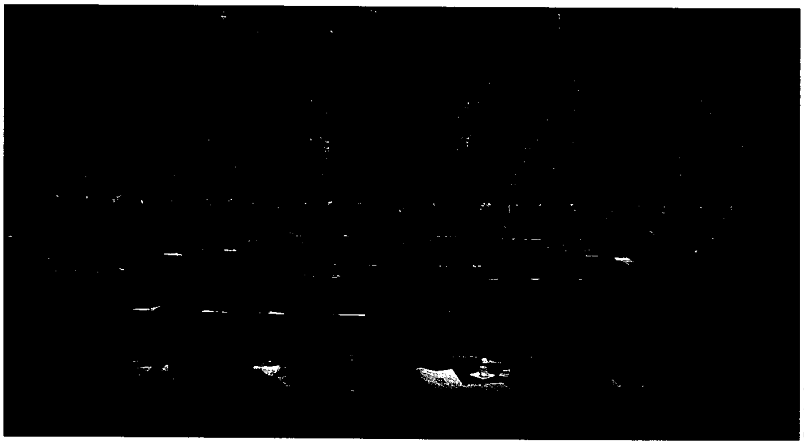
By about 1989, double-heterostructure AlGaAs/GaAs and AlGaAs/AlGaAs diodes exceeded the luminous efficiency of red-filtered incandescent lamps, opening up a lucrative market: the replacement of automotive brake lights [Fig. 6]. Several automobile models now use such LEDs in the braking lights mounted in the center of their rear windows—the so-called center high-mounted stop lights, or CHMSLs. Running lights for the sides of both cars and trucks are other possible applications.

Interior and exterior displays commonly use red AlGaAs, green GaP:N, and red, orange, and yellow GaAsP/GaP or GaAsP:N LEDs [Fig. 7]. The recently developed AlInGaP material system is already producing devices that are superior to all others in luminous efficiency between 590 nm (yellow) and 620 nm (orange). George Craford of Hewlett-Packard Optoelectronics predicts it will soon be the material of choice from 550 to 630 nm. Clarence Bruce, director of marketing for AND, Burlingame, Calif., says that AlInGaP will be the workhorse material for the next few years.



Hewlett-Packard Co.

*[6] The center high-mounted stop light seen in the latest cars is one of the high-volume applications opening to state-of-the-art LEDs that outperform red-filtered incandescents.*



Trans-Lux Corp.

*[7] Gaming displays built around LEDs create an impressive, informative, and reliable environment for horse players at the Mirage Casino-Hotel in Las Vegas, Nev.*

What's been missing is the color blue, with which manufacturers could make white LED lamps and full-color LED displays, including full-color outdoor and stadium displays. Eye-catching electronic billboards—relatively uncommon at present in North America and Europe (except in places like Times Square and Las Vegas)—are a standard feature of Asia's urban landscapes. The market for a bright, reasonably priced blue diode in such applications is huge.

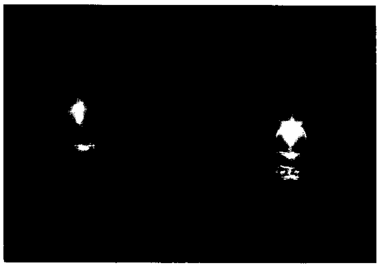
Blue diodes made from silicon carbide (SiC), with an indirect band gap of 2.86 eV, do exist. However, they suffer from a very low luminous efficiency of about 0.04 lm/W so research has focused on finding an isoelectronic dopant for SiC to boost its efficiency.

**TRUE BLUE.** But recently, almost out of the blue, a chemical company with no background in manufacturing semiconductor devices announced a double-heterostructure blue LED [Fig. 8] made from zinc-doped indium gallium nitride (InGaN) and aluminum gallium nitride (AlGaN). The company, Nichia Chemical Industries Inc., Anan, Tokushima, Japan, is the country's largest producer of fluorescent materials, including those for fluorescent lamps. It brought its GaN diode to market two years earlier than the most optimistic estimates of industry leaders. According to Tomoji Ogawa of Nichia America Corp., the company's success hinged on solving two long-term problems in the fabrication of GaN devices.

The first problem was that GaN usually comes out as n-type when grown, and producing high-quality p-type material has proved extremely difficult. But in 1991, Shuji Makamura, a principal scientist at Nichia, disclosed a technique for forming p-n junctions in GaN by converting magnesium-doped GaN to p-type using $N_2$ ambient thermal annealing. The current zinc-doped InGaN devices uses a variation on this technique.

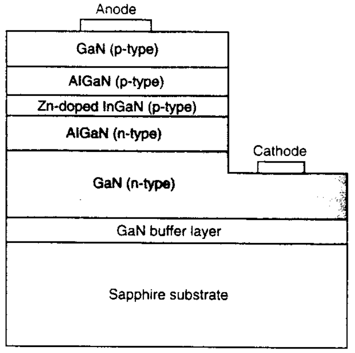
The second problem was that no substrate has a crystal lattice well-matched to GaN; the closest is sapphire ($Al_2O_3$), but the match is so poor that epitaxial GaN films grown on the sapphire have a high defect density. Progress came with the idea of using polycrystalline aluminum nitride (AlN) as a buffer layer between the sapphire and GaN to cushion lattice mismatch. Then, Nichia's Nakamura substituted polycrystalline GaN for the AlN and performance improved dramatically.

Nichia's commercial diode has an external quantum efficiency exceeding 2 percent, as compared to SiC's 0.02 percent. The units typically produce a luminous intensity of 1000 millicandelas, about 100 times greater than that of existing devices. (It is a peculiarity of the industry that luminous intensity is often specified in millicandelas even when the numbers involved are 1000 or more.) Widely available red and yellow LEDs produce 2000 mcd, and the bright orange, double-heterostructure AlInGaP LED recently introduced by AND produces 18 000 mcd.



Nichia Chemical Industries Ltd.

*[8] Blue gallium-nitride LEDs from Nichia Chemical Industries Ltd. outshine earlier silicon carbide diodes. The total luminous flux of each device shown above is actually the same; the apparent difference in brightness is due to the uneven angular distribution of their luminous intensity. The double heterostructure [below] of the devices is complex but overcomes difficulties in doping and in matching crystal lattices.*



Source: Nichia America Corp.

Nichia started manufacturing its blue diodes at a rate of 1 million per month in April and sells them for US $5 each in quantity. In comparison, the bright AND unit costs $5.73 each in quantities of 500, and Stanley's 3000-mcd red diode costs $2.00 to $2.50 in quantity. One industry marketing executive said that to sell in very large numbers, the prices must fall to less than $1.

AND's Clarence Bruce predicts that the price of today's brightest AlInGaP LEDs will fall to about 25 cents within the next five years. At that level, many small light bulbs in industrial applications should be replaced by LEDs, he said.

A potentially lucrative market is the replacement of incandescent light bulbs in traffic signals. The long-lived bulbs they now use are not expensive, but failures are potentially dangerous, replacement disrupts traffic, and the labor and equipment required to replace a bulb are expensive. The essentially unlimited lifetime of LEDs—degradation to half brightness has been estimated at 1 million hours—is therefore very attractive.

LEDs are packaged as traditional lamps, as chips that are automatically mountable from tape, and as modules for numerical displays, as well as being made into waterproof lamp modules. In another standard configuration, an LED and a photoreceptor are mounted in the opposite prongs of a two-armed plastic housing. The resulting unit serves to detect the presence of a floppy disk when it is installed in a disk drive or the presence of paper in a laser printer.

Rectangular LED light bars put two or more LED chips in an epoxy package and are used for backlighting stenciled messages. Long, thin, flexible packages containing dozens of LED chips are used as backlights for small liquid-crystal displays. Stanley is about to introduce a compact right-angle surface-mount LED package, which has not been available until now. As a result, Stanley's customer, Dialight, has had to mount a prism on top of a Stanley surface-mount LED. Stanley applications engineer Don Clary is enthusiastic about the possibilities.

**PLAYERS AND PROSPECTS.** The top tier of LED manufacturers comprises Hewlett-Packard, Matsushita, Sharp, Stanley, and Toshiba (in alphabetical order). Among the other manufacturers, AND is producing state-of-the-art products, and Nichia seems to have the only bright blue diodes.

Many vendors offer packaged LED displays and instruments for specialized applications. For one, Trans-Lux—the developer of the first large-scale moving display in 1923—makes a variety of displays for financial and gaming applications. Also, Teledyne produces its own LEDs and assembles them into instrument readouts, light bars, and indicators for avionics applications.

As pervasive as LEDs may seem today, they will likely become far more common. The rapidly improving luminous efficiency of LEDs will let them compete with incandescent bulbs in applications where reliability, rather than power consumption, is the key issue. Moreover, the new generation of devices will be far less demanding on the power budget of battery-operated systems than were older LEDs.

Development of the bright blue LED may open the way for white LED light sources that could be used as, for example, backlights for laptop computer screens. When—and perhaps before—the blue diodes drop in price, they will almost certainly lead to large full-color video screens, which manufacturers may well field as direct competitors of such CRT-based stadium displays as the Sony Jumbotron.

**TO PROBE FURTHER.** A clear and detailed review of the physics, fabrication, and evolution of light-emitting diodes can be found in "Light-Emitting Diodes," by M. George Craford and Frank M. Steranka, a chapter in the *Encyclopedia of Applied Physics*, Vol. 8 (VCH Publishers, 1994, ISBN 1-56081-067-X). Less demanding slices of this material appear in Craford's "LEDs Challenge the Incandescents," *IEEE Circuits & Devices Magazine*, Vol. 8 (September 1992), pp. 24–29, and "LEDs Get Brighter...Much Brighter" in *Information Display* magazine, Vol. 9 (February 1993), pp. 12-14. The most recent textbook on LEDs is *Light Emitting Diodes—An Introduction* by Klaus Gillessen and Werner Schairer (Prentice-Hall, 1987).

◆