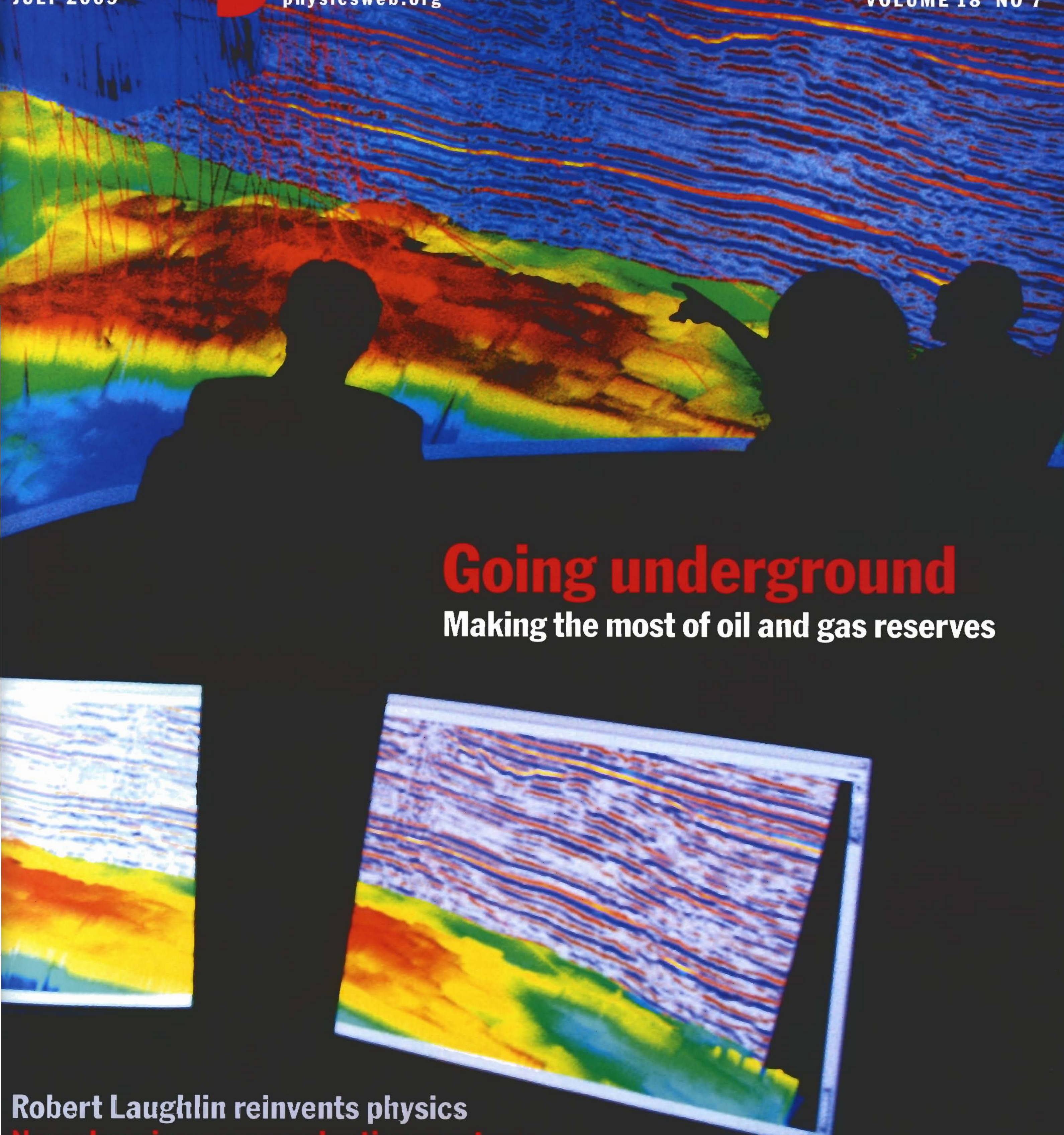
Physics World

JULY 2005 physicsweb.org VOLUME 18 NO 7



Going underground

Making the most of oil and gas reserves

Robert Laughlin reinvents physics

New clues in superconducting mystery

The rise of solid-state lighting

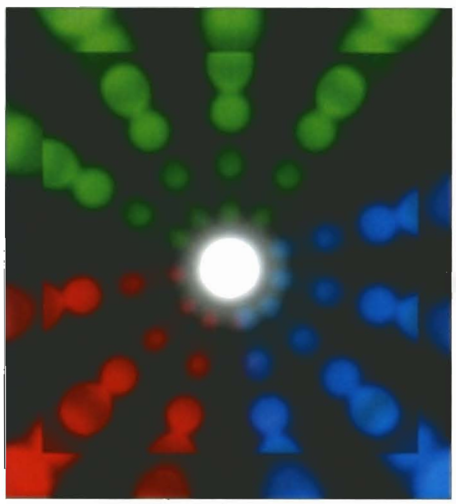
More efficient and versatile than traditional incandescent bulbs, solid-state lights based on LEDs are on the verge of transforming electric lighting forever

The solid-state lighting revolution

Nadarajah Narendran

FOR THE last 125 years we have been able to shine light whenever and wherever we need it by simply flipping a switch. This revolution started when Thomas Edison developed the first commercial electric light bulb in 1879, and very little has changed since. The reason for this is partly because new technologies have all followed the same old paradigm: fragile, gas-filled glass envelopes with metal end-caps that produce an orb of steady, white light. However, this may soon change with the dawn of the second lighting revolution: solid-state lighting.

Unlike existing incandescent sources, which provide light that is static in space and time, solid-state sources can produce light that changes in colour, intensity and distribution, based on lighting needs and time. This could allow us, for example, to illuminate and decorate our living spaces with glowing walls and ceilings, avoiding the need for intrusive light fixtures. Furthermore, solid-state lighting consumes 50% less energy than traditional sources, while also reducing environmental waste and pollution.



LOS ALAMOS NATIONAL LABORATORY

Bright future – LEDs are already being employed in buildings, car headlights and aircraft cabins.

Solid-state dream

The dream of efficient solid-state lighting was set in motion 40 years ago when monochromatic light-emitting diodes (LEDs) became a commercial reality. Whereas an incandescent bulb produces light by heating a tungsten filament to an extremely high temperature, LEDs rely on the motion of electrons in semiconductor devices. This means that LED light sources are more efficient because more energy is converted into light than into heat. Furthermore, LEDs can also have longer lifetimes because they do not suffer degradation due to heat.

An LED is basically a junction between a "p-type" semiconductor, which is deficient in electrons, and an "n-type" semiconductor, which has an excess of electrons (figure 1). These different electronic properties are achieved by doping a pure semiconductor such as gallium arsenide with atoms that can add extra negative or positive charges (which are known as "holes"). When a voltage is applied across the device, the electrons and holes recombine at the p–n junction to produce photons. The wavelength or colour of this light depends on the size of the energy gap between the conduction and valence bands of the semiconductor.

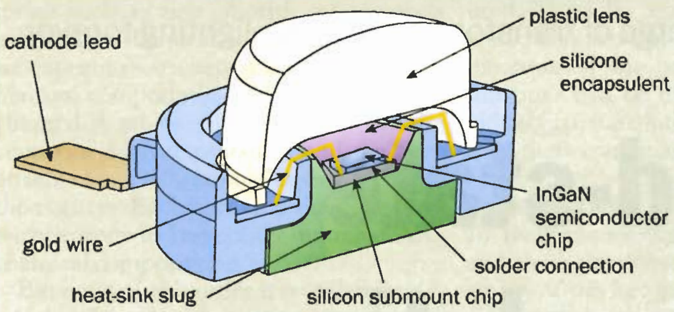
The first LEDs, demonstrated by Nick Holonyak and colleagues of General Electric in the 1960s, were made from gallium arsenide phosphide (GaAsP). These devices emitted low-brightness red light and were commonly used as numerical displays in early calculators. Although the efficiency of LEDs grew steadily during the next 30 years, the light output of gallium-based LEDs, including gallium phosphide (GaP) and aluminium gallium arsenide (AlGaAs) devices, remained low and was limited to the red and green end of the spectrum. This meant that these devices were used solely as indicators, such as on/off lights in electronic applications.

The interest in using LEDs for illumination purposes did not begin until the early 1990s, when high-brightness LEDs based on aluminium indium gallium phosphide (AlInGaP) were developed by researchers at Hewlett Packard. These devices were bright because they could be grown on transparent substrates that did not absorb the light. Soon afterwards Shuji Nakamura, then at Nichia Chemical Industries in Japan, developed the first commercial high-brightness blue LED using gallium-nitride materials (see *Physics World* February 1998 pp31–35). Nakamura went on to develop white LEDs and highly efficient green LEDs based on gallium nitride.

Today, LEDs span the entire visible range, with AlInGaP semiconductors producing red to amber light and InGaN devices operating at green to blue wavelengths. This has paved the way for white-light LEDs that could be used for general illumination.

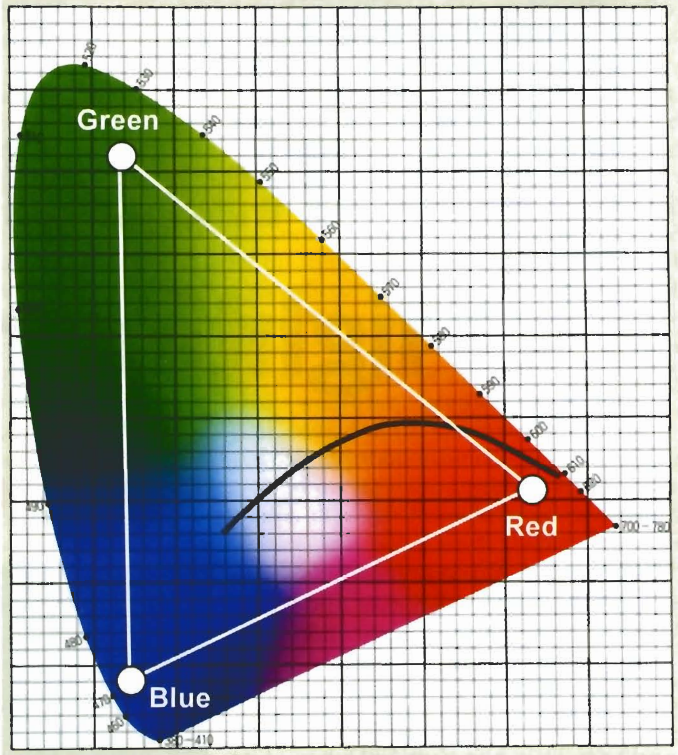
The potential for even higher efficiencies and longer lifetimes (more than 50 000 hours, which is at least 50 times

1 How an LED works



This "Luxeon Star" LED developed by Lumileds is one of the highest brightness LEDs in the world, with an output of up to 120 lumens. Its hexagonal shape allows several modules to be connected and powered in a close-packed configuration for maximum light output per unit area, but its basic components are the same as those in most LED sources. A small semiconductor chip is placed within a reflector and connected to two wires that carry current to the p–n junction. The light exiting the chip is collected by the reflector and projected in one direction (upwards here). The transparent encapsulation has several functions: it provides protection to the semiconductor chip; it helps increase light extraction by reducing the index of refraction mismatch between the chip and the reflector; and it acts as a lens to further shape the beam.

2 Colour co-ordinates



The most popular way to describe the appearance of light is to use a "chromaticity" diagram, such as this Commission Internationale de l'Eclairage 1931 chart, in which colour is described in terms of two co-ordinates. The outer perimeter of the chart is the locus of the monochromatic sources in the visible region (the numbers show the wavelength of the light in nanometres), while the dark solid line is the chromaticity of the radiation of black-body sources. Usually, manufacturers design their sources to lie on or close to this line because it is typically associated with white light. However, the actual appearance of a source also depends on many other variables, including luminance, spatial extent and surrounding colours.

longer than an incandescent lamp), combined with the low environmental impact of high-brightness LEDs, have led to an explosive growth in LED research over the last five years. Realizing the potential of the technology, governments in the US, Europe and Asia have set up funding initiatives to accelerate the development of solid-state light sources and their applications. Meanwhile, to capitalize on this growth, traditional lighting companies such as Philips and General Electric have formed joint ventures with major semiconductor companies including Agilent Technologies and Emcore, while OSRAM SYLVANIA integrated Siemens' semiconductor group.

The solid-state challenge

So, what is holding back the transition from the "dark" ages of incandescent lamps and fluorescent tubes to the dynamic world of solid-state lighting? One problem is the low overall light output of the LED, which is caused by two factors.

First, the electrons and holes in an LED do not always produce light when they recombine – sometimes they produce heat. The percentage of electron–hole pairs that do recombine to produce photons is referred to as the internal quantum efficiency. This figure depends on the quality of the semiconducting material and the manufacturing process. In the red wavelength region, for instance, the internal quantum efficiency is almost 100%, while in the latest blue LEDs it is about 50%.

The second factor that determines the output of an LED is called the extraction efficiency. Various optical effects such as total internal reflection and Fresnel reflection mean that less than 30% of the photons generated inside an LED chip actually leave the device as visible light. The rest are reflected back and forth within the chip until they are eventually absorbed. In addition to reducing the output, this also generates heat that can cause defects in the crystal, which further reduce the output. It is therefore important to find ways of extracting more of the photons that are generated within the LED.

There are several ways to improve the extraction efficiency, such as using different chip geometries, texturing the surface of the chip, and creating resonant-cavity structures like those in laser diodes. One of the most successful geometric approaches is the truncated inverted pyramid, which can lead to extraction efficiencies of more than 60% by reducing total internal reflection. Introducing roughness onto the surfaces of the chips can also reduce the amount of light trapped in devices. For instance, researchers at OSRAM Opto Semiconductors in Germany recently produced a very high-brightness LED using thin-film technology by texturing the internal surfaces of the device with microreflectors.

A crucial performance indicator of any white-light source is the luminous efficacy, which is a measure of the total light output of the source compared with the energy it consumes. The total light output is called the luminous flux, which is measured in SI units called lumens, so the luminous efficacy has units of lumens per watt. In practice, the luminous flux is obtained by weighting the radiant flux of the source by the response function of the human eye, because the eye has a different sensitivity to light depending on its wavelength. This function has the form of a bell curve that peaks at a wavelength of 555 nm and has a width of about 300 nm.

The incandescent bulbs commonly used to light our homes,

What will the lighting revolution look like?

Solid-state light sources can take on many forms, from traditional bulbs and tubes to futuristic glowing surfaces and back-lit screens. By far the most widespread applications of LEDs to date are "EXIT" signs and traffic signals. In the latter, honeycomb-like arrangements of coloured LEDs (right-hand image) are replacing the traditional white incandescent bulbs positioned behind coloured filters (left-hand image), although the latest LED traffic signals may be harder to distinguish from traditional ones because they use different optics to maximize the light output. The same applies to brake lights on cars, where manufacturers often use additional optics to give the LED source a more uniform appearance.

LEDs can cater for the demand for visually pleasing light fixtures that do not resemble traditional devices, but there may be applications in which LEDs need to replace and therefore resemble traditional sources. While it is not difficult to make LEDs that look like traditional bulbs and that even fit into existing light fittings, their performance could be poor because the heat generated has to be carried away by conduction and convection. In contrast, most of the heat in an incandescent bulb is radiated away. Unless this heat is managed properly, it will get trapped within the fixture and will reduce the lifetime of the LEDs.

In order to reap the full benefits of solid-state lighting technology, it is better to configure LEDs differently and apply them in novel ways to illuminate our living and working spaces. Due to their small size, ruggedness and long lifetimes, LEDs can be embedded into buildings and revolutionize electric lighting with applications like glowing walls and ceilings. However, for such a transformation to take place, we also need a change in the infrastructure of our buildings and how power is distributed and controlled. As well as seeking ways to incorporate solid-state lighting into building structures, our group at the Lighting Research Center, along with several industrial partners, has started to address this issue by investigating ways to make lighting changes as easy as altering furniture arrangements and interior decorations.

for example, are rated at 15 lumens per watt, while a typical linear fluorescent lamp is rated at 85 lumens per watt. Commercially available white LEDs currently produce about 30 lumens per watt, although prototype devices developed by CREE Lighting in California and North Carolina, and also by my group at the Lighting Research Center in New York, can reach efficacies greater than 75 lumens per watt.

Some of these devices will be on their way to the marketplace within the next two years, and the US solid-state lighting industry has set itself the target of developing white LEDs with efficacy values in excess of 150 lumens per watt by 2012. Such a device would use 90% less energy than an incandescent light bulb and only half the energy consumed by a fluorescent lamp with the same light output.

But luminous efficacy is not the only parameter that matters when developing a light source – the light must also have certain colour properties if it is to illuminate an object or space effectively. For example, while it is possible to create white light by mixing light from two monochromatic light sources, the resulting light of such mixing would not render the colours of objects very well because the colour of an object depends on the particular wavelength of light it reflects. If the light does not contain that wavelength component, the object will appear black. A light source that contains wavelengths throughout the visible spectrum therefore has much better colour-rendering properties than a narrow-band source.

White-light LEDs

There are currently two basic approaches to creating white light with LEDs: the first is to excite a phosphor with blue or near-ultraviolet light from an LED; the second approach is to mix light from three or more coloured LEDs in appropriate proportions. The first approach uses predominantly cerium-doped yttrium aluminium garnet (YAG:Ce) phosphors, the original material used to make white LEDs. In this device, some portion of the short wavelength (blue) radiation generated by the LED is absorbed and remitted in the mid to long wavelength (yellow to red) region of the visible spectrum. The combined radiation is perceived by the eye as white light, but this light is not entirely satisfactory for general illumination applications because it has poor colour properties. This has prompted manufacturers to use blends of two or three different phosphors to improve the colour of white LEDs. Another drawback of phosphor-converted white-light LEDs is the loss of energy when phosphors convert light from one wavelength region to another, which reduces the overall efficiency of the device.

Since the goal is to develop white LEDs with a higher light output, researchers are now trying to identify alternative, more efficient phosphors and ways to implement them within white LEDs. Recently, my group at the Lighting Research Center developed a method called scattered photon extraction, which has offered significant improvement in luminous efficacy. Unlike traditional white LEDs, in which the phosphor layer is placed just above the semiconductor junction, we moved the phosphor layer away from the semiconductor and shaped the LED lens to allow the photons that would typically be absorbed inside the LED to escape as visible light.

The alternative approach to generating white light – that of combining several coloured LEDs – is more flexible than the phosphor method. This is because an array of multicoloured LEDs can produce many shades of coloured light *and* white light by changing the output ratios of the individual coloured LEDs. Three LEDs – one red, one green and one blue – for example, each correspond to a point on the chromaticity diagram, R, G and B, and therefore form a triangle (figure 2). By changing the ratio of the light output of these devices, it is possible to create any colour with chromaticity values within this triangle, including white light with an appropriate R, G and B mixture.

In principle, mixing monochromatic light to produce white light should be more efficient than the phosphor-conversion method because energy is not lost due to down conversion. In practice, however, additional optical components are needed to mix the light from the different LEDs and this introduces losses. As a result, phosphor-converted white LEDs are currently more efficacious than mixed-coloured systems.

Niche lighting

Once manufacturers have overcome the challenges of perfecting the colour and increasing the light output of LEDs, where might we expect to see solid-state lighting in action? An early 1970s popular-science magazine once pictured a living room lit with LED panels composed of red, green and blue LEDs. General illumination such as this is indeed the ultimate goal for LEDs, but the technology has already demonstrated its capabilities in several niche lighting applications.

One obvious use for LEDs is in applications that require coloured light. At present the most common way to create coloured light is to place optical filters in front of traditional light sources, but the absorption of the unwanted colours wastes a lot of energy. LEDs, on the other hand, produce nearly monochromatic light at a particular wavelength very efficiently. Since the late 1990s high-brightness LEDs have been replacing traditional incandescent bulbs in traffic signals because they use much less energy (typically about 20% of that used by incandescent bulbs) and do not require frequent replacement. This is one application where the incandescent light bulb will become antiquated within the next few years (see box on page 27).

But the use of coloured light is not limited to signs, signals and displays. During the past few years LED technology has been exploited by architects in order to create visually appealing environments. Arrays of multicoloured LEDs are being incorporated into light fixtures, supplied by companies such as Color Kinetics in Boston and TIR Systems in Canada, to provide colour-changing options. Some retail stores, for example, are already using LEDs to accentuate the environment and capture the attention of customers. Similarly, restaurants and other hospitality venues are adopting solid-state lighting to create different ambiences. And the growing trend for home cinema may create the first large scale application of LEDs for residential use. Indeed, Philips will soon incorporate LEDs into flat-panel televisions with the aim of enhancing the viewing experience by changing the ambient lighting surrounding the screen depending on the colour of the content featured.

Aesthetics aside, light with a certain spectral content may also have physiological impacts, such as regulating the sleep–wake cycle. Blue light, for example, has been shown to help people with sleep disorders, and researchers in our group have recently used LEDs to improve the sleeping habits of patients in long-term care facilities.

As for white-light LEDs, in practice these can outperform conventional lighting systems in some niche lighting applications, such as the fluorescent tubes used in supermarket freezers. In a cold environment, the pressure of the mercury vapour inside the tubes drops, reducing the light output and limiting the lifetime of fluorescent lamps – which is not a problem with LEDs.

One industry that is sure to benefit from these solid-state sources, which are not affected by the high vibrations that can cause traditional light sources to fail, is transport, specifically airlines and car manufacturers. Some airlines are already using the changing colours of LEDs within passenger cabins (see figure 3), and the new Volkswagen Golf Plus has tail-lights manufactured by lighting specialist Hella that use LEDs to produce both red and amber lights.

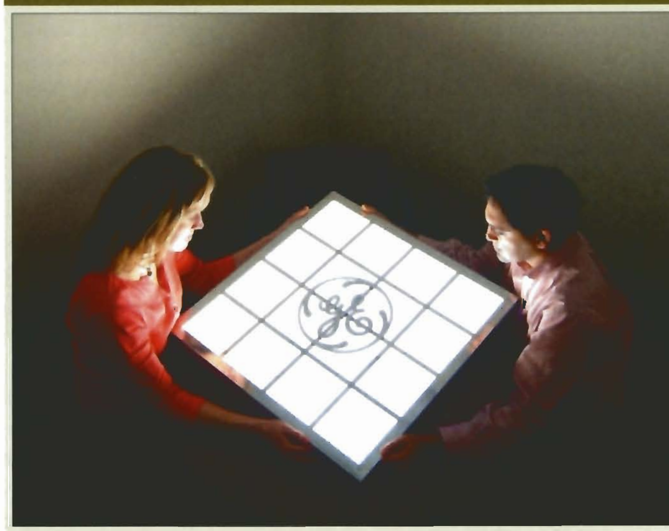
High-brightness white LEDs will soon provide more efficient general illumination of aircraft cabins, and solid-state car headlights will enable "advanced forward lighting" systems in which the beam can change depending on the situation. For instance, when you make a right turn the beam can shine to the right side of the vehicle to provide more visibility, or perhaps the spectrum could change during foggy conditions to allow for better visibility and reduced distraction (e.g. by increasing the content of longer wavelength, "yellowish" light). Last year Audi released the first LED daytime-running lights using high-power white LEDs from Lumileds. Solid-state headlights present more of a challenge because they need to be extremely bright, but they could make their debut in production models as early as 2008.

3 LEDs in the air

BOEING

Boeing will soon introduce solid-state lighting into its next-generation commercial aircraft to provide different lighting during different times of the flight. Meanwhile, Airbus has introduced the first LED reading lights in passenger airliners. We can soon expect white LEDs – which have a longer lifetime and consume much less power than traditional incandescent sources – to provide general illumination within aircraft cabins.

4 The future is flat



GENERAL ELECTRIC

This solid-state lighting panel made by GE consists of several panels of OLEDs and produces diffuse white light with an efficacy of 15 lumens per watt.

Organic LEDs

All the LEDs we have discussed so far are made from inorganic semiconductors such as gallium arsenide. But another solid-state lighting technology that has seen rapid advancements is the polymer light-emitting diode, also called the organic light-emitting diode or OLED. Unlike LEDs, which produce high-intensity, point-source light, OLEDs produce low-brightness diffuse light over large areas. This means that OLED technology can be used to create self-luminous displays that do not require backlighting. But the ultimate dream is to create sheets of paper-thin flexible light sources that would provide unique alternatives to, say, the fluorescent lighting in office environments.

Towards the end of the 1980s, Richard Friend and co-workers at Cambridge University in the UK demonstrated OLEDs using conjugated polymers. They showed that a polymer called polyphenylene vinylene emitted yellow-green light when it was sandwiched between two electrodes and an external voltage was applied. Since then the technology has rapidly advanced, and now several companies around the world, such as Cambridge Display Technology, General Electric, Universal Display Corporation and DuPont, are in the process of developing products for the marketplace.

OLED technology is presently trailing LED technology in terms of efficiency and lifetime, and most devices currently on the market are small, nearly monochrome displays for logos. However, OLEDs will eventually provide a cheaper and more efficient alternative to the LEDs and associated optics that are used in mobile-phone displays, increasing the lifetimes of batteries, for example.

On a larger scale, researchers at General Electric's Global Research Center recently demonstrated a two-foot-square light panel made from OLEDs that produces more than 1200 lumens of white light with an efficacy of 15 lumens per watt (figure 4). The challenge now is to demonstrate that organic electronic devices can be produced cost-effectively on plastic sheets, so it will be at least a few more years before we see OLEDs being used in white-lighting applications.

This is true for the solid-state lighting industry in general. Although LEDs are showing promise for many applications, it will be several more years before we see the technology impacting on the general illumination market. For white-LED technology to gain widespread use, the overall efficiency and colour proprieties of its light have to further improve, while the cost must continue to come down.

With many companies around the world increasing their production of LEDs, and with many applications groups gearing up to use them, the market penetration for LEDs will grow rapidly. Solid-state lighting is a question of "when" not "if", and the lighting revolution is already well under way.

Further reading

M Figueiro 2005 Research matters: the bright side of blue light *Lighting Design and Application* **35** 16–18

S Nakamura *et al.* 1995 High-brightness InGaN blue, green and yellow light-emitting diodes with quantum well structures *Japan. J. Appl. Phys.* **34** L797–L799

G Stringfellow and M Craford (ed) 1997 *High Brightness Light Emitting Diodes* (San Diego, Academic)

A Zukauskas *et al.* 2002 *Introduction to Solid-State Lighting* (New York, Wiley)

Links

LEDs magazine: www.ledsmagazine.com

Lighting Research Center: www.lrc.rpi.edu/programs/solidstate/index.asp

Lighting.com: www.lighting.com

Solid State Lighting website: www.netl.doe.gov/ssl

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