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SEMICONDUCTORS / OPTOELECTRONICS

FEATURE

LED Lighting: Blue + Yellow = White

Giving LEDs the blues was the key to replacing the incandescent bulb

By RICHARD STEVENSON / JANUARY 2011

Back in the 20th century, just about the only LED you normally saw was the one that lit up when your stereo was on. By the noughties, tiny light-emitting diodes were also illuminating the display and keypads of your mobile phone. Now they are backlighting your netbook screen, and soon they'll replace the incandescent and compact fluorescent lightbulbs in your home.

This revolution in lighting comes from the ever-greater bang the LED delivers per buck. With every decade since 1970, when the red LEDs hit their stride, they have gotten 20 times as bright and 90 percent cheaper per watt; the relation is known as Haitz's Law, and it applies also to yellow and blue LEDs, which were commercialized much later.

The forerunners of the white LEDs that are now going into lightbulbs were the chips that backlit handsets starting about a decade ago. Back then, they used tens of milliamps and consumed a watt for every 10 lumens of light they produced. They were also tiny—just 300 micrometers on a side. Since then, the chips have more than tripled in size, to a millimeter square or more, current has shot up to an ampere or so, and efficiency has rocketed to around 100 lm/W. They now have everything they need to dominate lighting, except for a low enough price. But that, too, will soon come.

Even now, white LEDs are competitive wherever replacing a burned-out lamp is inconvenient, such as in the high ceilings and twisty staircases of Buckingham Palace, because LEDs last 25 times as long as Edison's bulbs. They have a 150 percent edge in longevity over compact fluorescent lights, and unlike CFLs, LEDs contain no toxic mercury. That means it isn't a pain to dispose of them, and you don't have to worry that your house has become a hazard zone if one breaks.

Making these white-emitting chips bigger and driving them harder has been quite easy; it was increasing the efficiency that required a radical redesign of the device's architecture. To produce the first generation of white LEDs, engineers would deposit a stack of carefully chosen gallium nitride and indium gallium nitride layers on a semitransparent substrate to yield blue-emitting devices; then they'd add a yellow-emitting phosphor on top to turn the output white. However, this design traps a lot of light within the chip and sends another fraction in the wrong direction, through the substrate.

To address both weaknesses, engineers coated the nitride film—a combination of GaN and InGaN layers—with a metal that acts as a mirror, then flipped the assembly over, removed the substrate, and roughened the underlying surface. In the resulting chip, because most of the rays impinge on the textured top surface at a shallow enough angle to avoid reflecting back, nearly all the light can get through to the world outside.

Europe's leading LED manufacturer, Osram Opto Semiconductors, in Germany, and the two U.S. LED giants Cree and Philips Lumileds are all using variations of this approach. Japan's Nichia, the world's biggest LED manufacturer, has a different way of doing things. Its engineers also roughen the top surface, but they do this by etching a hexagonal pattern into the substrate, which they do not subsequently remove from the gallium nitride film.

These second-generation white LEDs hit the market three or four years ago. Since then interest has rocketed: "If you go to any [lighting] show now, they might as well be called the LED show," says Rick Hamburger, director of segment lighting at Philips Lumileds.

Commercial success followed. White LEDs now illuminate parking lots, streets, and civic buildings. Exactly when they make it into most homes will depend on the price. I just bought a really high-quality, warm-white LED bulb in the United Kingdom from Philips for about US $55; my lamp consumes just 7W while emitting as much light as a 40-W incandescent. (Products that give off a harsher, blue-tinged light go for as little as $10.) I calculate that if I use it for 4 or 5 hours a day, it should pay for replacing the incandescent bulb in about five years.

The manufacturing cost should fall as production yields rise and substrates grow. "At the moment, one-third of the LEDs in the world are made on 2-inch wafers," says Mark McClear, who directs new business development at Cree. Toolmakers are now offering equipment for 3-inch, 4-inch, and even 6-inch substrates, and Cree plans to start using the largest of these platforms in the next 18 months.

Another way to drive down the cost is to increase the light output at a particular current. That's one of the goals of the U.S. Department of Energy's 2010 solid-state lighting road map, which calls for more than doubling the lumens per watt in commercial LED products by 2015. Or engineers could try to build better packages for handling additional heat so they could crank the current up higher and get more light out of each LED.

Of course, LEDs give us much more than just a more efficient, longer-lasting bulb. They're small, cool in operation, and easy to place in walls, automobiles, appliances, even the heels of children's shoes. When designers fully exploit their potential, LEDs will light up places we'd never thought to use them, thus changing the look of our world.

With price the only remaining hurdle and falling all the time, it's clear that this technology will be a winner in the long run. The one potential casualty that no one is talking about: jokes about changing the lightbulb, which may be heading the way of the dodo.

About the Author

Richard Stevenson, a Ph.D. in physics based in Britain, has written many pieces for *IEEE Spectrum* on the incremental improvement of light-emitting diodes. But he says it was only this month's story, "LED Lighting", that allowed him to draw the big picture. He traces how the humble diode graduated from being the "on" button in your stereo to replacing the lightbulb itself through new techniques that squeeze ever more light out of chips.

COMPANY TO WATCH:

Soraa, *Fremont, Calif.* Soraa, a California-based university spin-off cofounded by LED trailblazer Shuji Nakamura, is pioneering a different approach to making gallium nitride devices. By making light-emitting chips on a different cut of the GaN crystal, it can build brighter devices, free from the strong internal electric fields that hamper light emission.

DEPARTMENTS

The Lightbulb That Really Is a Better Idea

Photo: Getty Images

LED bulbs change the lighting equation

By PAUL WALLICH / JANUARY 2011

Five years ago they were in the lab; now you can buy LED lightbulbs at a hardware store. Should you? They produce as much light as incandescent bulbs for less than a fifth the electricity and heat, they last up to 20 years, and they fit in standard sockets.

Even more important, today's models—unlike previous generations of superbright light-emitting diodes—produce a light that is natural enough to satisfy most incandescent buyers. Compact fluorescents, even in their warmer incarnations, produce spectra with a handful of sharp peaks. The spectrum of a warm-white LED, by contrast, is relatively smooth, much more like that of a glowing filament. LEDs also turn on instantly, with constant brightness, unlike CFLs. What's more, they beat CFLs where CFLs beat incandescents, by lasting even longer and saving you even more on your electricity bill. And, of course, an LED bulb looks much more like a regular lightbulb than does the CFL corkscrew.

Ironically, although LED bulbs produce far less heat than incandescents, dissipating what heat they do create is the primary factor limiting their brightness. LED bulbs, like other electronic equipment, must remain below 90 °C to get certification from Underwriters Laboratories. The drivers, the LED junction, and the phosphors might be able to withstand higher temperatures, but unless UL changes its rules, that's irrelevant.

That means the maximum heat budget for an LED, once it's stuffed into an A19 envelope (the iconic incandescent bulb shape that's been produced in the billions over the decades), is between 8 and 14 watts, says Ray Chock of Philips Lumileds Lighting Co. The high end of that range, however, requires more heat-sinking than is practical in consumer lighting. Current warm-white LED bulbs top out somewhere under 100 lumens per watt, compared with about 15 for incandescents, meaning the brightest current LED bulb is roughly equivalent to a 60-watt incandescent bulb.

By the end of 2012, lighting engineers expect LEDs to get 150 lumens per watt. But this number is complicated by the strong trade-off between color temperature and lighting efficiency. Color temperature is a measure of the spectral distribution of a light source; for incandescent bulbs it corresponds roughly to the surface temperature of the heated filament. Ordinary incandescent bulbs typically operate at about 2700 kelvin and produce the familiar yellow-white glow, while halogens, whose complex chemical process lets filaments run hotter and bluer, typically operate at about 3200 K.

For LEDs, things work a bit differently. The semiconductor itself produces a much bluer light than most consumers—especially those in the United States—want. So manufacturers lower the color temperature by painting on phosphors that absorb much of the blue and re-emit it as yellow and red light. But as more long-wavelength phosphors get added, more energy gets lost in the conversion process. Consider for example, LED manufacturer Cree's XLamp MX-3 bulb. It comes in a 6500-K version that produces roughly 94 lumens per watt, while a 3500-K version (only slightly bluer than halogen) emits a mere 77. So exactly how much efficiency you get depends on whether you want to feel like you're next to a cozy fireplace or under a cloudless arctic sky.

A WORTHY INVESTMENT?

But enough of aesthetics. The real question about these new lights is economic: At US $20 to $70 a bulb, are LEDs worth the investment? Compared with incandescents, they certainly are. A $30 LED that's equivalent to a 40-watt incandescent will save 800 kilowatt-hours or about $80, over its rated 25 000-hour life, plus another $10 or so in replacement bulbs, plus whatever your time is worth to do the replacing. Compared with CFLs, though, LEDs aren't as economical: You'd save maybe 50 kWh and no more than $10 for replacements [see table, "A Worthy Investment?"]. The upshot is a quicker adoption of CFLs and a high-tech catch-22—if more people would acquiesce to the steep initial cost of LED bulbs, economies of scale would kick in, and prices would come down.

In truth, the economic analysis is a bit more complicated than that, because one of the premises of the payback calculation is that 25 000-hour life span. That's 10 or 20 human years—and not that many people or even businesses stay in the same location that long. In effect, LEDs are a capital investment, while incandescents and CFLs are consumables.

And these economics feed back into the technology in an interesting way. You might think that A19 envelope—and being able to fit your bulb into the billions of standard light sockets around the globe—would be a holy grail for LED developers. Not so. Much of their work involves ways to bypass standard sockets completely.

By making fixtures specifically designed to dissipate LED heat, engineers can pack more lumens into their bulbs. Consider the standard recessed ceiling fixture. For a retrofit LED bulb, it's the worst possible application because there's hardly any air circulation to carry away the heat. On the other hand, an LED-specific fixture can have heat-dissipating fins that extend invisibly for as much as several feet in each direction from the light source, something that Chock says Philips is working on. Custom designs for track lights and floor, table, and desk lamps can bring similar advantages.

So even as you try to figure out which of your current fixtures might be suitable for LED bulbs, expect them to be far more commonly seen at new stores, restaurants, and offices.

	SYLVANIA ULTRA LED	PHILIPS AMBIENT LED	SYLVANIA SOFT WHITE INCANDESCENT	SYLVANIA MICRO CFL
Wattage or wattage equivalent	40	25	40	60
Cost per bulb at 25 000 hours of use	US $20	$28	$0.75	$2
Number of bulbs	1	1	17	2–3
Cost of bulbs	$20	$28	$12.75	$4–$6
Kilowatt-hours needed	175	125	1000	325
Energy cost (at average U.S. cost of $0.10/kWh)	$17.50	$12.50	$100	$32.50
TOTAL COST	$37.50	$40.50	$112.75	$36.50-$38.50

Note: Prices are approximate and may have changed since retail visits were made in mid-2010. Lamps are not precisely equivalent but are representative of available stock at that time. The incandescent and CFL bulb prices are per bulb, bought in packs of four.