

# *PRACTICAL INTRODUCTION TO LEDs*

**L**IGHT BULBS are everywhere. There are over 20 *billion* light bulbs in use around the world today. That is, three for each person on the planet! We expect that within the next 10 years, the majority of these bulbs will be light-emitting diodes (LEDs). This is because LEDs can provide efficiency dozens of times higher than incandescent light bulbs. They can be as efficient as the theoretical limit for electricity to light conversion set by physics. This book is all about the practical aspects of LEDs and how you can make practical lighting designs using them.

## WHAT IS AN LED?

The purpose of this book is to tell you practical things about LEDs. So in this section, we're not going to regale you with jargon about "direct bandgap GaInP/GaP strained quantum wells" or such. Let's directly address the question: What is an LED?

The name "light-emitting diode" tells you a lot already. In the first place, the noun tells you that it is a diode. A diode conducts current in one direction and not the other. And that's what an LED does. While we'll explore the details of its electrical behavior in Chapter 4, the only thing to note for the moment is that it has a much higher forward voltage than the diodes usually used in electronics. While a 1N4148 has a drop of about 700 mV, an LED may drop 3.6 V. This is because LEDs are not made from silicon, but from other semiconductors. But other than that, an LED's electrical characteristics are very much like those of other diodes.

The words "light-emitting" tell you a lot more. Now all diodes emit at least a little bit of light. You can open up an integrated circuit (IC) and use a scanner to see which parts of the circuit are emitting light. This tells you which parts are conducting current. IC designers use this to help debug their ICs. However, the amount of light emitted by ICs is very small. Since the purpose of LEDs is to emit light, they have been carefully designed to optimize this performance. That's why, for example, they have a much higher forward voltage than normal, rectifier diodes. Rectifiers have been optimized to minimize their forward voltage while maximizing reverse breakdown

voltage. LEDs are optimized to produce the most light of the right color at the lowest power, and things such as forward voltage (by itself) don't matter. Of course, forward voltage does enter into how much power the LED dissipates, and we'll see in Chapter 5 how to characterize the light emitted versus the power dissipated.

## SMALL LEDs VERSUS POWER DEVICES

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Present-day thinking divides LEDs into two classes: small devices and power devices. Small LEDs became widely used in the 1970s. They come in all different colors, such as red, orange, green, yellow, and blue. They are the small T1¾ (5 mm) devices shown in Figure 1.1. Nowadays, there are literally tens of billions of them sold each year. They go into cell phone backlights, elevator pushbuttons, flashlights, incandescent bulb replacements, fluorescent tube replacements, road signage, truck taillights, traffic lights, automobile dashboards, and so on.

What characterizes these small devices is their power level, or as the industry thinks of it, their drive current. The typical red small LED, for example, has a drive current of 20 mA. At a forward voltage of 2.2 V, this is only 44 mW of power. (The efficacy is so low that this is just about equal to the heat dissipation as well.) Small white LEDs have a higher forward voltage (3.6 V, corresponding to 72 mW), and some small LEDs can be run as high as 100 mA. But fundamentally, this type of LED is used as an indicator, not a real light source. It takes 14 of them to make a somewhat reasonable 1 W flashlight, and hundreds of them to make a (dim) fluorescent tube replacement.

While the information in this book is applicable to these small LEDs, the main focus is on power devices. Power devices are typically 1–3 W devices that are usually run at 350 mA. Their dice (the actual semiconductor, as opposed to its package) are substantially larger than those of small LEDs, although their footprint need not be.



Figure 1.1 T1¾ (5 mm) LEDs.

These devices are typically used in places requiring lighting, rather than as indicators. Applications include flashlights, incandescent bulb replacements, large-screen TVs, projector lights, automotive headlights, airstrip runway lighting, and just about everywhere lighting is used. Of course, not all of these applications have yet seen widespread adoption of power LEDs, but they will soon.

## PHOSPHORS VERSUS RGB

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Most lighting designs are going to be made with white light (which includes incandescent “yellow” light). For this reason, this book concentrates primarily on white LEDs. However, what is described here for white LEDs can be straightforwardly applied to color LEDs. Color LEDs are very similar to white, albeit with differing forward voltage. The reason for the varying forward voltages is that the colored light (red, yellow, blue, etc.) is generated directly by the semiconductor material. The material is varied to get differing colors and the differences in material in turn cause differences in forward voltages.

However, white light cannot be directly generated by a single material (we are ignoring special types of engineered materials that are not yet in production). White light consists of a mixture of all of the colors. You already know this because white light can be separated into its constituent colors with a prism. White light thus has to be created. There are currently two main methods of generating white light with LEDs. In one method, an LED that emits blue light is used, and the blue light is converted to white by a phosphor. In the other method, a combination of different color LEDs is used.

The first method is the most common. A typical wavelength for the blue light generated by the LED is 435 nm. Why use blue light? This has to do with the physics of the way the white light is generated. The blue light is absorbed by a phosphor, and re-emitted as a broad spectrum of light approximating white. For the phosphor to be able to absorb and re-emit the light, the light coming out has to be lower in energy than the light going in. That’s just like any electronic component. Energy goes in, some is dissipated as heat, and the rest comes out again, transformed. So to get all of the colors in the spectrum that humans can see, the phosphor needs to have input at a higher energy (shorter wavelength) than the shortest color’s energy. For humans, this is about 450 nm, and so a 435 nm blue LED is the most energy-efficient way of generating white light using a phosphor.

Before turning to the second method of generating white light, we should say a few more words about the phosphor. There are various types of phosphors. Phosphors are designed to absorb one specific wavelength of light, and re-emit it at either one or more different wavelengths or in a band of wavelengths. LED phosphors are typically designed to do the latter. But there are limits to how broad a band of colors a phosphor can emit. So many LEDs use bi-band or tri-band phosphors to better cover the spectrum of light needed to approximate white. These phosphors are mixtures of two or three primary phosphors. These more complicated phosphors are typically used when better color rendition is needed (see the discussion of color rendering index (CRI) in Chapter 3).

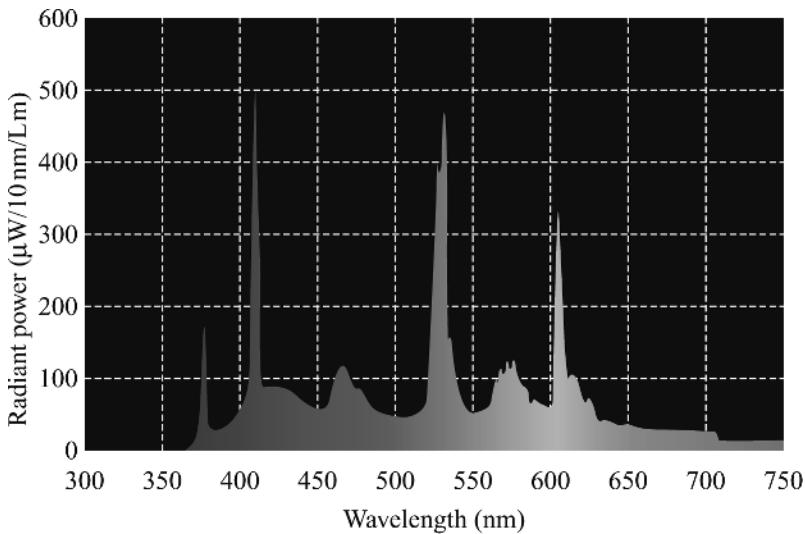


Figure 1.2 Fluorescent tube's spectral power distribution. (Source: [http://www.gelighting.com/LightingWeb/na/resources/tools/lamp-and-ballast/pop\\_curves.jsp?12](http://www.gelighting.com/LightingWeb/na/resources/tools/lamp-and-ballast/pop_curves.jsp?12).) (See color plate section.)

As a side note, we can comment briefly on fluorescent lights. In some ways, a fluorescent light is quite similar to an LED, but its fundamental mechanism of light emission is different. It generates a high-temperature plasma inside a tube, which emits light in the ultraviolet (UV) range (254 nm) rather than in the blue range. But after that, it too uses a phosphor to absorb the light and re-emit it in the visible range. Note that since the wavelength of the light is considerably farther away from the visible spectrum than the 435 nm generated electrically by the LED die, the efficiency ultimately possible for a fluorescent is intrinsically lower than that possible for an LED. (At the moment, fluorescent lights and LEDs have roughly the same efficiency.)

But also interesting is the type of phosphor the typical fluorescent light uses. These phosphors are of the type that re-emits in just one or two narrow wavelengths, not in a band of colors. The specific wavelengths emitted have been very carefully chosen to make the light emitted give a good specification for the CRI. But the spiky nature of the emission spectrum (see Fig. 1.2) means that colors at wavelengths other than these are poorly reproduced by the fluorescent lamp. Of course, there is no reason (we know of) that fluorescents can't have the same spectra that LEDs do. But for the present moment at least, LEDs have the potential to give much better color rendition than do fluorescent lamps.

## INSIDE AN LED

This book is about designing lighting with LEDs, not about how to make them. Nonetheless, some aspects of their construction are worth knowing. It helps to understand some of the design aspects of different manufacturers' products. It also

helps to understand some of their claimed improvements in lifetime. We'll be talking about white LEDs made with phosphors, although much of the information is the same for other types.

The first thing to realize is that while almost all of the devices currently used by engineers—diodes, transistors, logic gates, microprocessors—are made of silicon, LEDs are not made of silicon. (There used to be some germanium devices around, but they don't work very well when they get hot, and so were abandoned.) However, it has proven difficult to get silicon to emit light. Thus, a number of different semiconductors have been put to use. While it's not important to know the details, you should realize that there are a variety of different materials being tried. Not all of the physics is understood yet, and the aging processes are unclear as well. Different types are in use for different devices from different manufacturers. What this means practically is that you should expect changes ahead. The device you buy today will probably be different from what is available tomorrow.

The fundamental semiconductor device in an LED is relatively large, a few square millimeters. This device emits blue light (for white LEDs), and two things must be done to it: the blue light has to be converted to white light with high efficiency, and the white light has to come out without being blocked. So the normal ceramic package that ICs come in won't work, because it (intentionally) doesn't let any light through.

What most manufacturers do is to add some transparent silicone (a rubbery polymer) on top of the die. This lets the light come out without much absorption or color change, bending the light as needed, and providing a degree of mechanical protection for the die. At least one manufacturer then adds a piece of glass on top of the silicone, although it's not clear to us that this offers much advantage.

To accomplish the color conversion, a phosphor is used, which is a complex molecule that absorbs the blue light that the LED is emitting and radiates it out over a band of other colors. It takes two or three different phosphors to make a reasonable white color; you should expect to see phosphor blends with even more components in the future.

Some manufacturers put the phosphor directly on top of the die, with the silicone going on top of that. Others stir it into the silicone before putting the mixture on top of the die. Putting it directly on the die increases the amount of blue light that is absorbed, but makes the phosphors sit at the same temperature as the die. Phosphors tend to degrade with high temperature. Indeed, phosphor degradation is one of the major reasons why LED light output decreases with age. Putting the phosphor in the silicone reduces the temperature the phosphors have to survive, but decreases the amount of blue light that is absorbed and converted. You could add more phosphor to compensate for this, except that phosphors are relatively expensive.

The die, phosphor, and silicone are all in a package. (And every manufacturer has its own package and footprint.) The package includes bond wires that connect the die to the leads so that you can put current through the LED. Even though it's just a single device, multiple bond wires are used in parallel to accommodate the relatively high currents (Fig. 1.3).

Now the package has an unwanted side effect. Since the LED emits light over a broad angle, some of the light is intercepted by the package. This affects efficacy

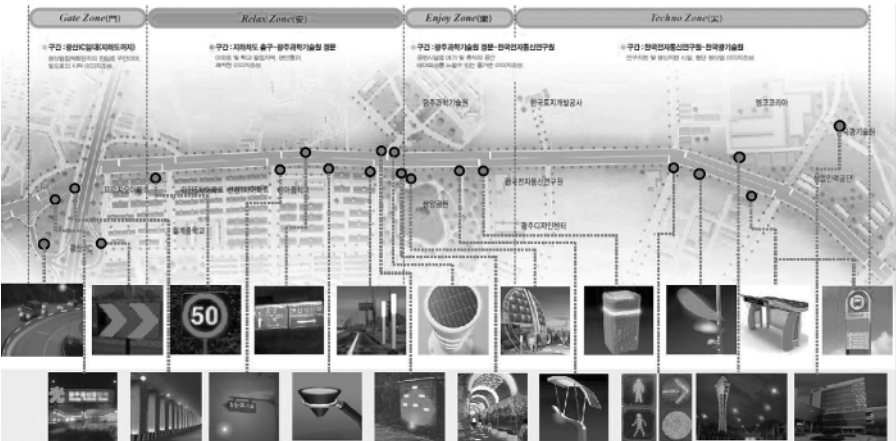


Figure 1.3 LEDs can be used everywhere. (Source: Kaist, KAPID.)

somewhat, but also some of the intercepted light is reflected and emitted. That’s okay, except that as the package ages (it’s sitting at 85 °C for 50,000 h), it yellows. As the package yellows, the absorption of light by the package increases, which decreases the efficacy. And the reflected light is also yellowed, causing the correlated color temperature (CCT) and CRI of the emitted light to shift. In some devices, this package aging is one of the major reasons why the LED time to 70% light output is 50,000 h and not longer.

Some LEDs also include some optics in their package. This may take the form of a lens and/or a mirror. The optics may be used to increase light extraction or to shape the emission direction of the light. If you don’t care about the emission direction of the light (e.g., if you’re building an omnidirectional light bulb), you should try to avoid using devices with extra optics. (Why pay for the extra cost?)

Thus, LEDs are complicated devices. It’s well worth your while to ask detailed questions of your vendor about how the devices are made and how they will stand up to high-temperature aging. You may even need to speak to people at the factory to get sufficient information.

## IS AN LED RIGHT FOR MY APPLICATION?

To listen to enthusiastic marketing, it seems that LEDs can be used everywhere. But even though this book is about LEDs, we have to acknowledge that not every application will be best served by them. As LEDs continue to increase in efficacy and drop in price, more and more applications will benefit from them. We expect that ultimately fluorescent tubes will become obsolete. But we also expect that incandescent bulbs will be around for a long, long time. Here’s a checklist of things to think about in deciding whether an LED solution is right for your application (Table 1.1).

**TABLE 1.1 Checklist of Considerations on Whether to Use LEDs for an Application**

Question	LED	Fluorescent	Incandescent
Is energy efficiency top priority?	LEDs are probably best	Fluorescents should be considered	
Is cost an important factor?			Best to use an incandescent
Is cost the <i>only</i> thing that matters?			
Does the application need long life?	LEDs, properly designed, are the best choice	Fluorescents may be good enough	
Are there lots of on/off cycles?	LEDs should definitely be used		
Are there temperature extremes?	LEDs are better than fluorescents, and usually good enough		For really extreme conditions, incandescent bulbs are even better
Is the heat generated used for other purposes?	LEDs may not dissipate enough heat, for example, to melt snow off a traffic light	Fluorescents also may not dissipate enough heat, for example, to melt snow off a traffic light	Incandescent bulbs may remain a good choice
Is good color rendition needed?	LEDs are sometimes good enough	Fluorescents almost never are	
Do colors need to be changed in operation?	LEDs are the only choice		Incandescent bulbs remain the best
Is a new form factor needed?	LEDs are the only choice		

## HAITZ'S LAW(S)

You've probably heard of Moore's law. This was the prediction by Moore in 1965 that the performance of microprocessors would double every 2 years. It was based on observations, but proved to be remarkably accurate for the next 40 years. It is only now that it has finally slowed, as ICs reach some fundamental physical limits.

A similar prediction for LEDs was made by Roland Haitz (2006). This is backed by much more historical data (see Fig. 1.4). As currently stated, it predicts that the luminous output of individual LED devices is increasing at a compound rate of 35% per year and that the cost per lumen is decreasing at 20% per year. To the extent that current manufacturers seem to have settled on 3 W as the maximum practical power in a small device, we can read this as also meaning an increase in efficacy of 35% per year.

This predicted rate of performance increase would be utterly unbelievable, except that it appears to be true. The authors began tracking the prediction a number of years ago, calculating where efficacy would be each month. Year after year, we have verified the numbers, and efficacy indeed continues to increase.

We talked to Haitz a couple of years ago about his law. His opinion was that it still had a long run ahead of it. And while he may be right that the lumens per device will continue to increase, in the next few years the efficacy will certainly start deviating, of course due to fundamental physical limitations.

To understand Haitz' law, we need to consider the meaning of "lumens" (see Chapter 3 for more detailed information). Lumens is not exactly a measure of light, but is rather a measure of how much light humans see with their eyes. As such, it very much depends on how eyes work. In particular, human eyes are most sensitive to green light. Thus, if you produce 1 W of light at 555 nm, you have 683 lumens. There's no possible way to increase this number; it is really almost a definition. The same is of course true for LEDs. If an LED gets 1 W of power, and converts it entirely

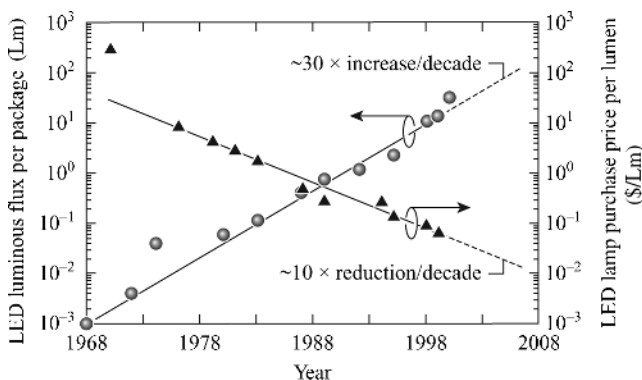


Figure 1.4 Haitz's law. (Source: <http://i.cmpnet.com/planetanalog/2007/07/C0206-Figure3.gif>. Reprinted with permission from Planet Analog/EE Times, copyright United Business Media, all rights reserved.)

to light at 555 nm, it will have no heat power dissipation at all. (Obviously, this is not really possible because of the Second Law of Thermodynamics.) All of that light then is equal to 683 lumens. So efficacy is limited to 683 Lm/W no matter what.

Now the reality is that we don't normally want intense green light. We want white light. And since white light consists of many different colors, the lumens and efficacy must be less than 683 Lm/W. What then is the real limit on efficacy?

There are two different limits, depending on how the white light is generated. Recall that white light can be made either by directly combining lights of different colors or by emitting low-wavelength light (such as blue or UV) and converting it with phosphors into white. The phosphor method is limited by the physical efficiency of phosphors. Since they absorb low-wavelength (=high energy) light, and emit higher wavelength (=lower energy) light, the difference in energy is lost as heat. This is described by Stokes' law. While the exact limit is subject to details (such as what CRI light is acceptable), phosphor conversion of white light from LEDs is limited to about 238 Lm/W. Note that since fluorescent tubes are also phosphor-converted, but starting from 235 nm rather than 435 nm, their ultimate efficacy is considerably lower than that of LEDs. While they too have room for improvement currently, ultimately LEDs will be more efficient than fluorescent lighting.

Direct emission of various color lights can be more efficient, because there is no absorption and re-emission involved. But since colors other than green are needed, the human eye response means that 683 Lm/W isn't achievable this way either. A seminal paper by Ohno (2004) shows that to get acceptable CRI, white light cannot be made at higher efficacy than about 350 Lm/W.

Haitz's law as extrapolated to efficacy thus has several more years to run. As the 200 Lm/W limit is reached, blue converted by phosphors will plateau in efficacy. To continue increasing in efficacy, red-green-blue (RGB) systems will need to be implemented. But if 35% per year is continued, only 2 years will remain before the ultimate limit in efficacy is achieved. After that, Haitz's law may still apply to the cost per lumen. Indeed, the figure shows that it is not until after 2015 that the cost per lumen of LEDs will approach that of 60 W incandescent bulbs.

Ultimately, then, LEDs can be expected to reach the theoretical limit of efficacy, and their cost can ultimately drop below that of incandescent bulbs. And what happens after that? Since efficacy can't be increased because of physics, it might be reasonable to suppose that LEDs are here to stay for the long term. Nothing can be better than LEDs, only cheaper.

## THE WILD WEST

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The LED lighting industry, and the LED industry in particular, is currently like the "Wild West": There aren't many rules, and most people aren't paying attention to them anyway. All sorts of claims are being made that are obviously wrong, and plenty more that you need special equipment to detect.

Looking first at LED device production, we should start out by saying that there are *some* reputable manufacturers. These tend to be the largest ones, although you can't assume that that's true either. They produce what they say they do, and their

datasheet contains information from measurements they've taken. The problems start rather with their marketing departments.

The biggest players are presently in a contest to demonstrate that they have higher luminous efficacy white LEDs than their competitors do. As a result, they routinely release press announcements proclaiming their progress. Now everyone in the industry measures efficacy at a temperature of 25 °C. That's just a given. But actual operation is always at elevated temperatures, since LEDs heat up in operation. And the press announcements never mention how much that wonderful efficacy rolls off at higher temperatures. Different manufacturers' processes have different roll-offs, so you don't know what you would get from this new device. What's more, it's routine to announce results from a single lab device. It's not in production, and very possibly not producible without major changes. So it's all a bit of a cheat.

Moving on, even the big manufacturers tend to have problems with efficacy roll-off with aging, which is to say, lifetime. The truth is that the various manufacturing processes appear to create LEDs that age differently. And the aging varies greatly depending on the drive current, the die temperature, and even the package temperature. The fundamental problem is that 50,000 h is 8 continuous years. There's a new LED process a couple of times a year (recall the 34% increase in efficacy per year). So there isn't time to collect data before the part is obsolete. You would think that you could extrapolate data from, say, the first 1000 h. But the truth is that this works so poorly that the committee writing the specification for LED aging gave up on it. LED lifetime? It's anybody's guess.

Further, many of the LED manufacturers have problems with data. We've seen datasheets for products that have been in production for a year that still have forward voltage copied from a competitor's datasheet. We see efficacy numbers that came from handheld meters. In some cases, the parts don't match the datasheets either in color or in efficacy. The sad story goes on and on. Thus, "Caveat emptor!" The only way to be sure of what you get is to measure it yourself. Read Chapter 14 to find out how.

Moving on now to LED bulb manufacturers, the situation is even worse, if possible. We tested a couple dozen different bulbs. Only 5% of them generated the lumens they claimed, with a majority of them being wildly off! In some cases, it was apparent that no measurement had been made at all. They calculated that each LED is rated at 60 lumens, and they put three of them in the bulb, and so the package says it is 180 lumens! No thought had been given to the drive current, the optics, the packaging, not to mention the temperature effects. The U.S. Department of Energy is making efforts to clean this up. We hope for progress in this area.

We feel that all of these problems are characteristic of an infant industry. Doubtless, all of this will improve. We just hope that consumers aren't so disappointed early on that the industry never gets to maturity.

## LEDs AND OLEDs AND . . . ?

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Incandescent bulbs replaced candles and kerosene lamps. Fluorescent tubes replaced incandescent bulbs for many purposes. It seems likely that LEDs will replace both fluorescent tubes and incandescent bulbs. What's next after LEDs?

There's been a lot of talk about OLEDs being the next big thing in lighting. The "O" in the front of the acronym OLED stands for "organic." But it's really still an LED. The difference is that this particular type uses organic rather than inorganic material. The OLEDs' claim to fame is that they are more mechanically flexible than inorganic LEDs. Perhaps they could be made directly into light bulb shapes or printed onto mechanical forms of light bulb shape.

As we indicated in the section on Haitz's law, LEDs are probably going to reach the maximum theoretical limit for efficacy of any light source. So if OLEDs are going to supplant LEDs, it can't be on the basis of efficacy, because it's impossible to be better. The same is true for any other new light source. Once the theoretical limit is reached, nothing can be better.

The way that OLEDs *could* supplant LEDs is if they were cheaper. Once there are a variety of possible ways of achieving the maximum efficacy, the market will ensure that the cheapest one is the one that dominates. In our view, OLEDs are really just another type of LED, and their progress is part of Haitz's law. So we don't know if OLEDs or LEDs will prove the eventual cost winner. But our opinion is that there probably won't be any newer technologies for lighting that end up completely replacing LEDs. LEDs will end up being so inexpensive that cheaper won't matter to consumers. We think LEDs are here to stay.

