LED Lighting Notes

By George Wiseman, Version 110617

Pictures:
LED light made from Ikea under-cabinet lights (top, bottom, box of transformers, wiring schematic)
Test light output with solar cell, find out how many watts needed to get the same voltage. Use killAwatt meter.
LED bulb in desk lamp. (capacitor, weights)
Maglight LED conversion kit (a year on a charge)
0.7 watt LED bulb in fridge.
LED bulb with bad connections
Ikea solar bed-side lamp
If no dimmer, then 'double bulb' string switched lamp
LED night lights (reactor flashlight)
Button LEDs for tight spaces
LED bulb in fridge
Incandesent bulb in oven
LED fish wire
LED 'hole vision' light
LED crank powered flashlight / solar flashlight
LED camping lanterns (dimmable best) Red light version would be a good idea.

Videos:
Dimmable LED, light is still on when dimmer is at most dim. Get dimmers that actually shut off.
Test light output of home-built Ikea lamp (vs wattage).
Test light output of halogen bulb /transformer desk lamp (vs wattage)

LED clamp-style work light:
Convert OEM LED light fixture to true CAL (remove resistors).
Test wattage and light before and after conversion.

Incandescent bulbs are becoming illegal; a 'politically correct' move by ignorant politicians looking for votes. People, (politicians and public alike) have not yet realized that changes such as 'energy efficiency' cannot be effectively legislated. There are too many variables and the technologies change too fast. You just end up with a lot of useless laws on the books; worse than useless actually because they may prevent or impede the best solutions from naturally occurring.
The market always has, and always will, ultimately determine what succeeds and fails. If laws are made against what people want or need, people will just do it anyway. What is REALLY needed is:

1. A stop to Free Energy suppression and an education program to teach people the truth about all the options that have already been invented, proven and locked away in Government vaults.
2. A public release of all the Free Energy innovations from Government vaults. Those inventions BELONG to the people whom the Government represents. The Government does not own them, the people do. These days Government has forgotten that it is the servant to the people.

Back to light bulbs…

People are now starting to understand that florescent bulbs are not a good option, regardless of Oprah's recommending them, because they contain mercury and they are NOT the most efficient or practical option available. LEDs are the clear winner for efficiency and practicality; they are also coming down in price and up in 'wattage'.

I started working with LED lights when I self-learned electronics in the 1980's. They are a really convenient way to 'see' the status of an electronic circuit.

When people started to promote florescent lights, I had already done the experiments and math that proved LEDs were a far superior option. The big problem was the price (and some colors weren't available then).

For me, LEDs are a no-brainer… even if a single white LED bulb, capable of the same light as a 40 watt incandescent costs $50. It is still less expensive when considering the WHOLE energy picture. **I'll explain**.

I'm an alternative energy researcher and proponent; for both off-the-shelf and still-developing technologies. I want my home to be entirely energy self-sufficient (plus extra energy to sell to the utility).

Alternative energy systems are NOT cheap. Anyone considering making their own power system MUST find ways to reduce the energy required for any particular task. By **reducing** the energy required to make light **by 85%** of incandescent requirements, I reduce the need for a larger power system and THAT saves hundreds of dollars.

For example: off-the-shelf systems for solar or wind currently run about $10 per installed watt. For every 40 watt light I reduce to 6 watt, I reduce the NEED of 34 watts of power system (while retaining full comfort). That's a power system savings of $340 with an 'investment' of $50… so $290 net savings… per bulb. *This does not include the (much advertised) direct savings in electrical energy, reduced cost of bulb replacements (LEDs should last at least 50,000 hours), energy to do the bulb replacements (go to store etc.), energy to MAKE, store and transport the incandescent bulbs and the energy required to acquire the materials to manufacture the bulbs.*

BTW, President George W. Bush was incorrect when he said "Energy conservation means freezing in the dark." If all the money that was (and is) being spent on 'energy' wars in just Iraq and Afghanistan (http://costofwar.com/en/) was instead spent on true energy conservation, there would be NO NEED for war. Put the industrial/military complex to work making America energy self-sufficient instead of killing hundreds of thousands of people who's only 'crime' is owning oil that we want. THAT is what makes them hate us.

Just the technologies I have developed, PROVEN to work and implemented in my own life would immediately reduce the energy needs of the USA by 25%. These technologies would cost no more than $1000 per person. Since 2001 the USA has already spent over 1.2 Trillion dollars in just Iraq and Afghanistan. That's close to $4000 per person in the USA. When is enough enough? How much blood are we going to trade for oil? What is needed is less legislation and more education… Most people WILL make the right choices if they understand the facts and consequences.

For lighting, at this time, I see LEDs as the best choice. They use 1/6 of the energy of incandescent (to make the same visible light). Last "up to 35 times longer" (US DOE) and produce less heat (reducing cooling costs). Fluorescents use 1/3 the energy of incandescent, so LEDs are twice as efficient as florescent. BTW fluorescents are also not dimmable. In our home, to decrease energy usage, we use dimmers on quite a few of our lights.

I'm part way through changing out all the lighting in our home and vehicles (including my RV) to LED. I'm usually using an 'attrition' approach, replacing bulbs that burn out with suitable LED alternatives.

So far, the only place I've found that I cannot switch to LED is the oven light (LEDs would melt in the heat and incandescent bulbs actually make sense because any heat they generate just helps the oven get hot). Our fridge just got its 0.7 watt LED light bulb (replaces a 40 watt incandescent bulb) from here. I also found dimmable LED bulbs there.

I didn't know that most commercially available 'household' LED bulbs are NOT dimmable, which was a shock because I've been experimenting with 5mm LEDs for years, installing them in electronic projects and my own home-retrofitted lamps, and I could dim them whenever I wished. I just started buying 'commercial' LED bulbs because I'm currently too busy to build my own; so far I'm not really impressed.

If I wish to use commercial dimmers on my home-built LED lights, I simply use a CAL power supply, then as voltage is reduced to the bulb, the current is also reduced. (less current = less light... see my Capacitive Battery Charger and Brown's Gas books to understand CAL). I'll be publishing my LED experiments soon.

Note: If buying a dimmer, make sure it is designed to actually SHUT OFF! Most designs shut the power down to about 1%, which makes incandescent lights look like they are shut off (they no longer glow) but they are still bleeding power. I discovered this when my LED bulbs did not shut off.

If I'm building my own dimming switches, I use a high frequency PWM circuit. Using resistors to limit current in an AC circuit is wasteful (and un-needed if you use CAL), because resistors turn the 'excess' energy into heat, which just brings you back into the inefficiency of using incandescent bulbs (90% of energy is wasted as heat). My home-built LED lights do not need heat sinks.

If you see heat sinks on LED bulbs, then you can be fairly certain that they are using resistors inside and are not optimally efficient (though they are still MUCH more efficient than incandescent).

The LED lights I build myself, by using multiple 5mm LEDs, do not need a heat sink. When I build them myself I can also spread the LEDs out and direct them to optimize where the light goes (no sense having the light go up when you only need it to go down).

Another issue to watch is amperage. The 5mm LEDs (which I generally experiment with) are designed to last 100,000 hours at a maximum amperage of about 20 mA (I design for 15 mA).

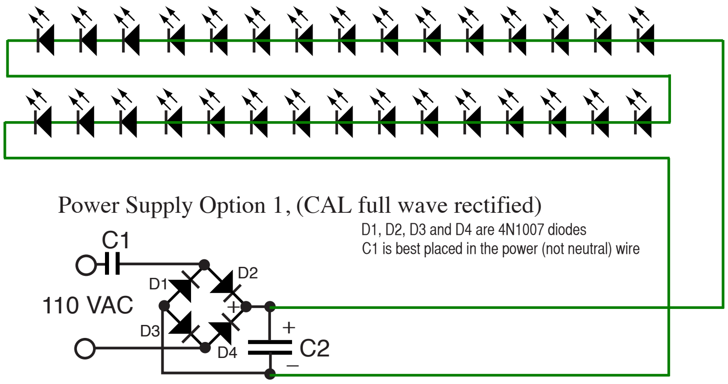
Household LED bulb designers, in an effort to increase light output and decrease cost, push the amperage up; which gives a marginal increase in light at a substantial cost of hours (hoping the customer will be unaware of the tradeoff). I REALLY disagree with this strategy (they should educate the public instead). If you see bulbs rated for less than 100,000 hours, you can be sure it's because they are using higher amperage (remember that higher amperage also increases the need for heat sinks).

Florescent Lights NOT a good idea
http://www.forbiddenknowledgetv.com/videos/the-law/toxic-green-light-bulbs.html

Home-Build LED lighting
from 5mm LEDs powered by 110 VAC
Using Capacitive Power Supply (CPS),
specifically Capacitive Amperage Limiting (CAL)

by George Wiseman Eagle-Research.com

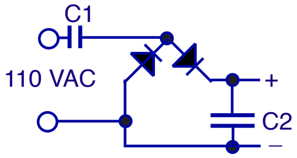
30 LEDs in series, can be any color or mixture of colors



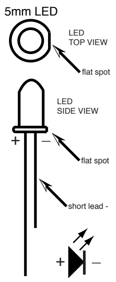
Power Supply Option 1, (CAL full wave rectified)

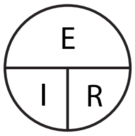
D1, D2, D3 and D4 are 4N1007 diodes
C1 is best placed in the power (not neutral) wire

Power Supply Option 2, (CAL 1/2 wave rectified)



This 1/2 wave rectified circuit option demonstrates how to discharge C1, if you want to ‘dim’ the LEDs by 50%.





E = Voltage in Volts
I = Current in Amperage
R = Resistance in Ohms
We know the voltage (110 VAC) and the amperage (0.02 A) so E/I= 6300 Ohms to achieve 20 milliamps (mA)
We need 6300 (or greater) ohms to keep the amperage under 20 mA (also have to assume up to 130 VAC).

Now that we know the resistance we want (6300 ohms), we’ll choose to use a *capacitor* instead of a resistor.
Capacitors can be used to limit current in nearly any AC circuit ***without wasting energy as heat***!
In this case capacitive reactance is the same as capacitive resistance.
This is a totally forgotten use of capacitors and NOT using this technique has resulted in the waste of Quads of Megawatts since the 1800s.
Capacitive reactance = capacitive resistance = XC = 1/(2*π*f*C)
π = 3.14
f = frequency of AC in Hz
C = capacitance in Farads
1 microfarad (uF) = 0.000001 Farad

XC = 1/(2*3.14*60*0.00000047) = 6636 ohms.
So a 0.47 uF ceramic capacitor, with a minimum 200 VAC rating, should work perfectly.
π and Hz were givens, so I just substituted common capacitor values for C until the XC (resistive) answer was in the range I needed.

For people with 50 Hz and 220 VAC, just make the appropriate changes to the formulas to find your capacitive resistance and to size your capacitors.

Bright White 5mm LED’s have about a 3.5 VDC forward voltage drop.
So it is possible to put 30 of them in series if you have a minimum of 110 VAC

LEDs are polarity sensitive, you will burn them out if you connect them wrong or voltage goes in reverse through them... be careful. See the polarity drawing.

You can make your own breadboard, to solder the LEDs to, or buy premade ones from any electronics supply store, like Radio Shack.
You can also drill #8 holes through material (like wood or plastic) and glue the LEDs into the holes; then solder the leads together on the backside of the material.

You can put as may strings (of 30 or less) LEDs as you like in parrallel (one string is shown). You just have to add 0.47 uF (in parrallel, to increase the amperage) to the amperage limiting capacitor (C1) for each string.

C2 is not ‘needed’ in the circuit. It is an option added to make the light a purer DC (take away the 100 to 120 Hz pulse of the full wave rectified 50 to 60 Hz input).
The value of C2 is about 4 times the value of C1, larger will make a ‘smoother’ light but will also cause a delay in the startup of the LED (you may notice up to a second delay in the startup of commercial LED lightbulbs) and a delay in the shutdown.
On the otherhand, my wife likes the ‘soft-start’ feature; it allows her eyes to adjust.
C2 can be an electrilytic capacitor, make sure it is rated for (at least) the highest voltage you expect the ‘load’ (your string of LEDs in this case) to be.

BTW, if making a night light, make it RED! Red LEDs the least expensive and red light does not significantly degrade night vision. It‘s a night light, you do not have to see true colors, you just need to negotiate without hurting yourself or disturbing anyone.

The disadvantage to wiring anything in series is that if there is one bad connection or one blown bulb, the whole string won’t work.
The advantage of the CAL version of the CPS is that you can safely, quickly and easily test to find the bad spot. *In fact, this technique (putting a capacitor in series) can be used to find a short circuit or a bad connection in any AC circuit.*

The CAL is never damaged by a ‘short circuit’, so you just connect one side of a test lead to the positive of the full wave bridge rectifier, then using the other end of the test lead, touch each LED connection in turn (starting at the negative of the full wave bridge rectifier). The rest of the lights will come on when you bypass the bad connection.
Of course you could also use this testing technique with a multimeter set on the appropriate voltage scale.

So again, with CAL circuits, the amperage is locked and the load voltage varies with the load resistance. One LED would be a 3.5 VDC load. Ten LED, in series, is a 35 VDC load. 30 LED, in series, is a 105 VDC load... all at 20 mA no matter the number of LEDs in series (up to the limit of the source voltage). This makes a simple, inexpensive and extremely efficient power supply.

This power supply will also be compatible with most commercial switches and dimmers.

Figuring the value of the capacitors to use:

Do not use electrolytic capacitors for CAL. Use only oil filled or ceramic capacitors (as applicable).

Always make sure the voltage rating of your capacitors is above the highest possible peak voltage of the circuit.

Capacitive reactance (or shall we say the ability of a capacitor to resist the flow of ac power or capacitive ohms) is equal to the equation:

$XC = 1 / (2*\pi*f*C)$

XC = capacitive reactance (capacitive ohms)
$\pi = 3.14$
f = frequency, Hertz (Hz)
C = capacitance in Farads

It is difficult to find high uF values in oil filled capacitors, so you can wire the capacitors in parallel to achieve any uF rating you desire.
The formula to do this is: $CT = C1 + C2 + \ldots CN$
So if you put a 10 uF capacitor in parallel with a 25 uF capacitor, you now have a 30uF capacitor. There is no limit to how many capacitors you can put in parallel. Just be sure the voltage rating of each is ABOVE the circuit operating voltage. So if you have a 110VAC input power, your capacitors need to be rated above 110 VAC. There is no upper voltage limit; for example it's fine if you use a capacitor rated for 1000 VAC in a 110 VAC circuit.

The amount of AC current that can flow through a capacitor is dependent on frequency and voltage. Using higher frequency and/or higher voltage lowers the capacitance needed. In most cases, it isn't practical to raise the frequency or voltage, we just use what's readily available (like 110 VAC and 60 Hz).

The simplest way to limit amperage in a CAL circuit is to change (reduce) the capacitance. This can be done manually or with switches. Just disconnect or shut off some capacitors that are wired in parallel. I cover amperage limiting using PWM or Hall-Effect amperage limiting elsewhere.

Calculating the wattage of a CAL circuit.

Circuit wattage should always be calculated from current (amperage) and voltage OF THE LOAD.

The most common error of 'educated' people, when calculating the true wattage of a CAL circuit is to assume the INPUT voltage and amperage are the measurements to use. Because this is usually true in 'conventional' circuits that do not use CAL… engineers have gotten sloppy by just assuming that input amperage and voltage are the same as load amperage and voltage.

Using input voltage and amperage to calculate wattage with CAL circuits is incorrect because the capacitor RETURNS all unused power back to the source, reducing the 'actual' power draw and wattage. This is quickly and easily seen to be true if you hook the circuit up to an actual wattmeter.

The TRUE wattage is the amperage and voltage measured across the load (NOT the input amperage and voltage). CAL circuits ‘lock’ the amperage, so the voltage at the load will vary with the resistance of the load. Higher resistance = higher voltage. This is because the CAL inherently allows the voltage to rise until there is enough voltage to push the desired current across the load… then locks the current.

If the load resistance drops during operation (like electrolyzers do) then the load operating voltage will DROP and the wattage efficiency will increase (the wattmeter will slow down). This drop in load voltage does not change the input voltage and the CAL circuit does not short (from the reduced resistance).

Notes on charging batteries.

Battery quirks.
When to charge a battery.
Matching battery capacities and charge levels.

Frequencies the eye sees best:

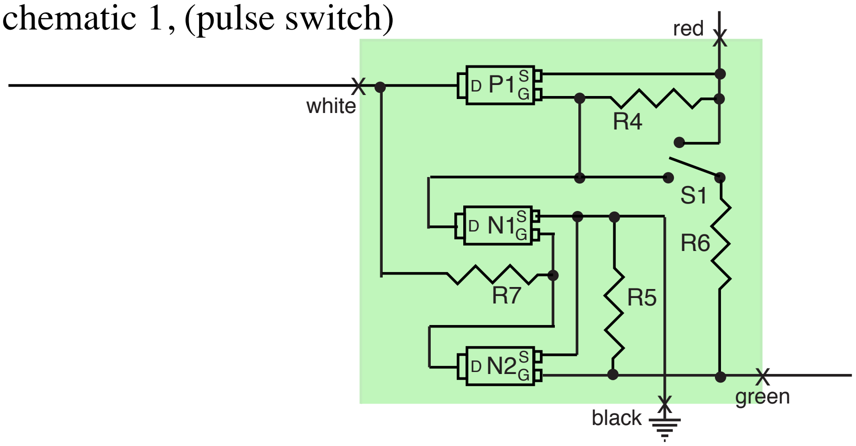
http://encarta.msn.com/encyclopedia_761579230_2/light.html
The electromagnetic spectrum refers to the entire range of frequencies or wavelengths of electromagnetic waves (see Electromagnetic Radiation). Light traditionally refers to the range of frequencies that can be seen by humans. The frequencies of these waves are very high, about one-half to three-quarters of a million billion (5×10^{14} to 7.5×10^{14}) Hz. Their wavelengths range from 400 to 700 nm. X rays have wavelengths ranging from several thousandths of a nanometer to several nanometers, and radio waves have wavelengths ranging from several meters to several thousand meters.

Waves with frequencies a little lower than the range of human vision (and with wavelengths correspondingly longer) are called infrared. Waves with frequencies a little higher and wavelengths shorter than human eyes can see are called ultraviolet. About half the energy of sunlight at Earth’s surface is visible electromagnetic waves, about 3 percent is ultraviolet, and the rest is infrared.

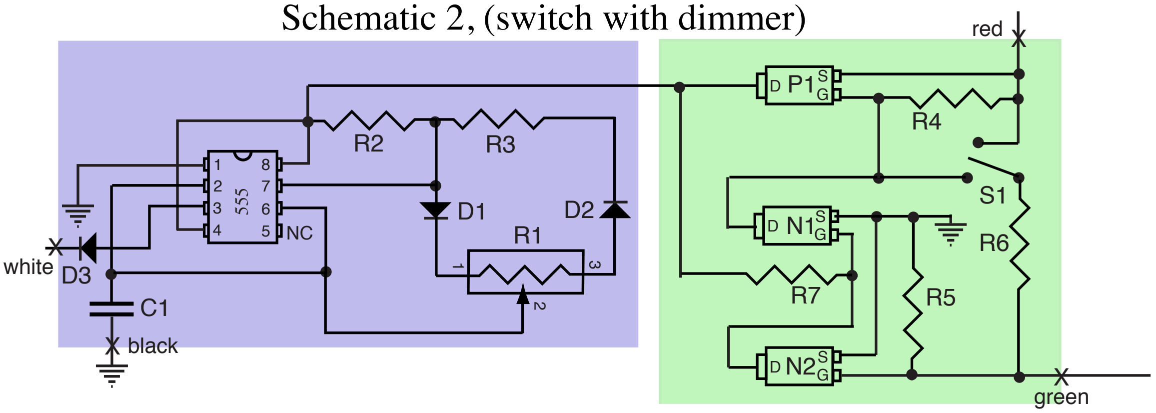
Each different frequency or wavelength of visible light causes our eye to see a slightly different color. The longest wavelength we can see is deep red at about 700 nm. The shortest wavelength humans can detect is deep blue or violet at about 400 nm. Most light sources do not radiate monochromatic light. What we call white light, such as light from the Sun, is a mixture of all the colors in the visible spectrum, with some represented more strongly than others. Human eyes respond best to green light at 550 nm, which is also approximately the brightest color in sunlight at Earth’s surface.
http://spectrum.ieee.org/image/520290

LED Lighting circuits

Schematic 1, (pulse switch)



Schematic 2, (switch with dimmer)



555 is a standard timing IC, frequency varied by R1 and C1;
(set at Hz that human eye sees best, using least light)
(NC = not connected)
P1, is a board mounted p-channel mosfet, IRFD9014
(turns on power to '555 'dimer' and N1 gate for tail biting latch on P1)
N1 and N2, are board mounted n-channel mosfets, IRFD014
(N1 latches P1 into the ON position; N2 shuts OFF latch)
D1 and D2 are 1 amp, 1000 volt diode IN4007
(directs current to/from 555 through variable resistance R1 to allow PWM)
D3 is a 1 amp, 1000 volt diode IN4007
(prevents feedback from other switches)
R1 is a ??K potentiometer, mounted with a dimmer knob or slide
R2 and R3 are 1K
(voltage pullup resistors)
R4, R5 and R7 are 1 meg ohm.
(R4 keeps P1 shut off if not grounded < 3VDC applied)
(R5 holds all N2 gates at ground)
(R7 prevents short from P1 to N2 during shutoff pulse)
R6 is 1K ohm.
(R6 prevents possible short circuit if shutoff signal is grounded)
C1 is ??uF
(controls the PWM frequency. Larger = lower Hz)
S1 is SPDT momentary, both ways, with center off. (Wired so up = on, down = off)
(negative pulse (up) turns on only current switch)
(positive pulse (down) turns off all switches)
X are places wires enter/exit the board

Need to find standardized wiring color codes. RV? Household? CAT5?
* signal to light (controls mosfet or relay)
* power to dimmer
* ground for dimmer
* signal to shut off all other switches

About LEDs

LED Architecture

At the heart of every white LED is a semiconductor chip made from nitride-based materials. The chip is traditionally positioned on top of the cathode lead. Applying several volts across this device makes the chip emit blue light. Passing the light through a yellow phosphor yields white light. Modern, high-power LEDs are variants of this architecture, featuring more complex packages for superior thermal management. Click on image for a larger view.

(Image)

The first-ever report of light emission from a semiconductor was by the British radio engineer Henry Joseph Round, who noted a yellowish glow emanating from silicon carbide in 1907. However, the first devices at all similar to today's LEDs arrived only in the 1950s, at Signal Corps Engineering Laboratories, at Fort Monmouth, in New Jersey. Researchers there fabricated orange-emitting devices; green, red, and yellow equivalents followed in the '60s and '70s, all of them quite inefficient.

The great leap toward general lighting came in the mid-1990s, when Shuji Nakamura, then at Nichia Corp., in Tokushima, Japan, developed the first practical bright-blue LED using nitride-based compound semiconductors. (Nakamura's achievement won him the 2006 Millennium Technology Prize, the approximate equivalent in engineering of a Nobel Prize.) Once you've got blue light, you can get white by passing the blue rays through a yellow phosphor. The phosphor absorbs some of the blue and reradiates it as yellow; the combination of blue and yellow makes white.

All LEDs are fabricated as aggregated sections, or regions, of different semiconductor materials. Each of these regions plays a specific role. One region serves as a source of electrons; it consists of a crystal of a compound semiconductor into which tiny amounts of an impurity, such as silicon, have been introduced. Each such atom of impurity, or dopant, has four electrons in its outer shell, compared with the three in an atom of gallium, aluminum, or indium. When a dopant takes a place that one of these other atoms would normally occupy, it adds an electron to the crystalline lattice. The extra electron moves easily though the crystal, acting as a carrier of negative charge. With this surfeit of negative charges, such a material is called n -type.

At the opposite end of the LED is a region of p-type material, so called because it has excess positive-charge carriers, created by doping with an element such as zinc or magnesium. These metals are made up of atoms with only two electrons in their outer shell. When such an atom sits in place of an atom of aluminum, gallium, or a chemically similar element (from group III in the periodic table), the lattice ends up an electron short. That vacancy behaves as a positive charge, moving throughout the crystal like the missing tile in a sort-the-number puzzle. That mobile vacancy is called a hole.

In the middle of the sandwich are several extraordinarily thin layers. These constitute the active region, where light is produced. Some layers made of one semiconducting material surround a central layer made of another, creating a ”well” just a few atoms thick—a trench so confined that the laws of quantum mechanics rule supreme. When you inject electrons and holes into the well by applying a voltage to the n - and p -type regions, the two kinds of charge carriers will be trapped, maximizing the likelihood that they will recombine. When they do, a photon pops out.

To make an LED, you must grow a series of highly defined semiconductor layers on a thin wafer of a crystalline material, called a substrate. The substrate for red, orange, and yellow LEDs is gallium arsenide, which works wonderfully because its atoms are spaced out identically to those of the layers built on top of it. Hardly any mechanical strain develops in the semiconductor's crystalline lattice during fabrication, so there are very few defects, which would quench light generation.

Unfortunately, blue and green LEDs lack such a good platform. They're called nitride LEDs because their fundamental semiconductor is gallium nitride. The n -type gallium nitride is doped with silicon, the p -type with magnesium. The quantum wells in between are gallium indium nitride. To alter the light color emitted from green to violet, researchers vary the gallium-to-indium ratio in the quantum wells. A little indium produces a violet LED; a little more of it produces green.

Such LEDs would ideally be manufactured on gallium nitride substrates. But it has proved impossible to grow the large, perfect crystals of gallium nitride that would be necessary to make such wafers. Unipress, of Warsaw, the world leader in this field, cannot make crystals bigger than a few centimeters, and then only by keeping the growth chamber at a temperature of 2200 C and a pressure of almost 20 000 atmospheres.

So the makers of blue LEDs instead typically build their devices on wafers of sapphire, whose crystalline structure does not quite match that of the nitrides. And that discrepancy gives rise to many defects—billions of them per square centimeter.

(Illustration: Bryan Christie Design)

Combatting Droop

Droop—the loss of efficiency at high power—afflicts conventional nitride LED structures. These feature an active region with gallium indium nitride quantum wells and GaN barriers, and an electron-blocking layer to keep electrons in this region. Researchers at Rensselaer Polytechnic Institute have reduced droop with new active regions, made first by combining GaInN wells and aluminum gallium indium nitride barriers and, more recently, by pairing GaInN wells with GaInN barriers. Meanwhile, Philips Lumileds has also developed a structure that is less prone to droop, thanks to a far thicker quantum well. Click on image for a larger view.

It is amazing that such LEDs work at all. Any arsenide-based red, orange, or yellow LED that contained as many defects would emit absolutely no light. To this day, researchers, including Nakamura himself—who moved to the University of California, Santa Barbara (UCSB) in 1999—can't agree on the cause of the phenomenon. Perhaps the solution to this problem may also explain droop.

The explanation won't come easily. When researchers set out to find the cause of droop in nitride LEDs, one of their first suspects was heat, which they knew could cause droop in arsenide LEDs. There, heat imparts so much energy to the electrons and holes that the quantum well can no longer trap them. Instead of recombining, some of them escape, only to be swept away by the electric fields in the device. But researchers dismissed this possibility after noting that nitride LEDs suffered from droop even when driven by short, pulsed voltages spaced far enough apart to let the devices cool down.

Another theory was proposed as far back as 1996 by Nakamura. He argued that everything could be explained by the structure of the quantum well. Nakamura and his colleagues looked at LEDs with a transmission electron microscope and were surprised to find light and dark areas within the quantum well, suggesting that the material there was not uniform. They then investigated the crystalline structure more closely, using X-ray diffraction, and found that the quantum well had indium-rich clusters (bright) next to indium-poor areas (dark).

Nakamura conjectured that because the indium clusters were free from defects, the electrons and holes would be trapped in them, making bright emission possible, at least at low currents. Continuing with this line of reasoning, Nakamura's team argued that LEDs' high efficiency at low currents stemmed from a very high proportion of electron-hole recombination in defect-free clusters. At higher currents, however, these clusters would become saturated, and any additional charge carriers would spill over into regions having defects dense enough to kill light emission. The saturation at high current, they suggested, accounted for the observed droop.

This theory has fallen out of favor in recent years. ”To start with, we saw indium-rich clusters in InGaN quantum wells, just as the rest of the world did,” explains Colin Humphreys, the head of the Cambridge Centre for Gallium Nitride at the University of Cambridge, in England. But then he and his team began to suspect that their electron microscope was causing the very thing it was detecting. So the group carried out low-dose electron microscopy. ”We looked at the first few frames—a very low exposure—and saw no indium clustering at all. But as we exposed the material to the beam, these clusters developed,” he says. They concluded that the clustering was merely an artifact of measurement.

In 2003, Humphreys presented that jaw-dropping finding at the Fifth International Conference on Nitride Semiconductors, in Nara, Japan. It wasn't well received. Many delegates contended that something must have gone wrong with the Cambridge samples. So Humphreys's group went back and studied a wider variety of specimens, including LEDs supplied by Nichia. Their work only reinforced their view that the clusters were formed by electron-beam damage.

In 2007, Humphreys's Cambridge team, together with researchers at the University of Oxford, described how they had attacked the problem with what's known as a three-dimensional atom probe. This device applies a high voltage that evaporates atoms on a surface, then sends them individually through a mass spectroscope, which identifies each one by its charge-to-mass ratio. By evaporating one layer after the other and putting all the data together, you can render a 3-D image of the surface with atomic precision.

The resulting images confirmed, again, what the electron microscope had shown: There is no clustering. Discrediting the cluster theory was an important step, even though it left the research community without an alternative explanation for droop.

Then, on 13 February 2007, the California-based LED manufacturing giant Philips Lumileds Lighting Co. made the stunning claim that it had ”fundamentally solved” the problem of droop. It even said that it would soon include its droop-abating technology in samples of its flagship Luxeon LEDs.

Lumileds kept the cause of droop under wraps for several months. Then, at the meeting of the International Conference of Nitride Semiconductors, held September 2007 in Las Vegas, it presented a paper putting the blame on Auger recombination—a process, named after the 20th-century French physicist Pierre-Victor Auger, that involves the interaction of an electron and a hole with another carrier, all without the emission of light.

The idea was pretty radical, and it has had a mixed reception. Applied Physics Letters published Lumileds' paper only after repeated rejections and revisions. ”In my experience, it was one of the most difficult papers to get out there,” says Mike Krames, director of the company's Advanced Laboratories.

Krames's team used a laser to probe a layer of gallium indium nitride, the semiconductor used for quantum wells in a nitride LED. They tuned the laser to a wavelength that only the gallium indium nitride layer would absorb, so that each zap created pairs of electrons and holes that then recombined to produce photons. When the researchers graphed the resulting photoluminescence against different intensities impinging on the sample, they produced curves that closely fit an equation that described the effects of Auger recombination.

The bad news is that you can't eliminate this kind of recombination, which is proportional to the cube of the density of carriers. So in a nutshell, if you've got carriers—which of course you need to generate light—you've also got Auger recombination. The good news, though, is that Lumileds has shown that you can push the peak of your efficiency to far higher currents by cutting carrier density—that is, by spreading the carriers over more material. The company does so with what's known as a double heterostructure (DH), essentially a quantum well that's 13 nanometers wide, rather than the usual 3 or 4 nm. It still shows quantum effects, although they are not so pronounced, and the design is less efficient than the standard one at low currents. Still, it excels at higher currents. The Lumileds team has created a test version that delivers a peak efficiency slightly higher than that of a conventional LED.

Promising though this new crystalline structure may be, it is difficult to grow. Perhaps this is why Lumileds has yet to incorporate the design into its Luxeon LEDs. ”There are multiple paths to dealing with droop, and we've investigated most of these paths,” says Krames. ”We have new structures in the pipeline, DH as well as non-DH, and we will move forward with the best structure.”

Not everyone is convinced that Auger recombination is the cause of droop. One such skeptic is Jörg Hader, a University of Arizona theorist, who works with former colleagues in Germany at Philipps-Universität Marburg and at one of the world’s biggest LED manufacturers, Osram Opto Semiconductors, in Regensburg.

”All [Lumileds] showed was that they can fit the results with a dependence that is like Auger,” claims Hader. ”It’s a fairly weak argument to see a fit that fits, and see what might correspond to that fitting.” In his view, there’s a good chance that the Lumileds data could also be fitted with other density dependencies, as well as the cubed dependence that is classically associated with Auger recombination.

Hader has calculated the magnitude of direct Auger recombination for a typical blue LED. The equations that describe this interaction of an electron and a hole with a third carrier date back to the 1950s, but that doesn’t mean that they are easy to solve. Hader says he took no shortcuts. Instead, he accounted for all physical interactions in a program tens of thousands of lines long, a program that in its initial form would have taken several years to run. However, Hader says he’s learned what he can omit safely in order to get the running time down to just 1 minute. He says the model shows that Auger losses are too small to account for LED droop, although he does allow that droop might be caused by other processes related to Auger recombination. These processors are more complicated because they also involve defects in the material or thermal vibrations (phonons, in quantum terms) of the semiconductor crystal.

Krames criticizes Hader’s calculations for leaving out the possibility that electrons might occupy higher energy levels, known as higher conduction bands. But Hader believes that including these bands would hardly affect his conclusions.

This May, computer scientists at UCSB brought new evidence to bear on this debate. Chris Van de Walle’s team included a second conduction band in their calculations of Auger recombination in nitrides and concluded that Auger contributes strongly to droop. However, they modeled only the bulk materials, not realistic quantum wells, for which Van de Walle admits his methods cannot handle the calculations, at least not on today’s computers.

Hader does not doubt the general shape of the UCSB results. However, he points out that the value Van de Walle’s team has taken for the second conduction band substantially differs from that given in certain academic papers. Using these published values would have profound effects on any estimate of the magnitude of Auger recombination. The conclusions of Hader and Van de Walle highlight the lack of consensus among theorists over the cause of droop.

http://spectrum.ieee.org/image/520319
(Illustration: Bryan Christie Design)

Less Leakage

POLARIZATION FIELDS may cause LED droop. Such fields are claimed to drive electrons out of the active region and into the p -type layer, where some recombine without emitting light [top]. A ”polarization matched” structure [bottom] has a far weaker internal field and therefore suffers less electron leakage, leaving more electrons to recombine with holes. Click on image for a larger view.

Meanwhile, a group headed by E. Fred Schubert at the Rensselaer Polytechnic Institute, in Troy, N.Y., has proposed yet another theory. His team, in collaboration with Samsung, blames droop on the leakage of too many electrons from the quantum well.

Interestingly, Schubert’s team, like the researchers at Lumileds, drew its conclusions by pumping light into the nitride structures and observing the light that those structures emitted in response. But Schubert and company investigated full LED structures, and they compared the results they’d obtained from optical pumping with light output generated when a voltage was applied, as it is in normal operation. As expected, droop kicked in when the device was pumped electrically. But the researchers saw no sign of droop in the photoluminescence data.

They then brought in Joachim Piprek, a theorist from the NUSOD Institute, a device simulation consultancy in Newark, Del. He used a computer model to simulate the behavior of a blue LED and found that the strong internal fields characteristic of nitrides must be causing electrons to leak out of the wells.

Now Schubert and his colleagues have produced direct evidence to back up their argument for leakage. They took an LED unconnected to any circuit and hit it with light at a wavelength of 405 nm, which is absorbed only in the quantum wells. The researchers detected a voltage across the diode, implying that carriers must leave the wells, contradicting Lumileds’ theory.

Schubert’s team has tried to control electron leakage by redesigning the LED. By carefully selecting the materials for the active region—switching from the conventional gallium nitride barrier to an aluminum gallium indium nitride version—they have been able to eliminate the charges that tend to form wherever distinct crystalline layers meet. They say such ”polarization matching” consistently cuts droop, raising power output by 25 percent at high currents.

Schubert believes that the electrons that leak out of the wells recombine with holes in the p -type region. If he could detect this recombination, it would certainly add weight to his explanation. ”We’ve looked for that luminescence,” says Schubert, ”but we have not seen it.” He’s not surprised, though, because p -type gallium nitride is a very inefficient light emitter, and the LED’s surface is nearby, so surface recombination at the top contact is also likely.

However, it is possible to detect electrons in the p -type region by modifying the standard LED structure, and researchers at UCSB have done just this. This team, led by Steven DenBaars and Nakamura, did the job of fitting the p -type region with an additional quantum well, one that emits light of a color different from that of the main LED. At a workshop in Montreux, Switzerland, in the fall of 2008, the group reported that they had found just this sort of emission.

Although this experiment proved that electrons do flow into the p -type region, it can’t tell us where they came from. And while Schubert's theory of electron leakage could explain the results, there may well be other things that can also account for them. We can't even rule out Auger recombination as the dominant mechanism, because the proportion of electrons flowing into the p -type region is still to be quantified.

Each theory has its champions. Theoreticians at Philipps-Universität Marburg support Auger recombination, mainly the phonon-assisted form, as the main cause of droop. So does Semiconductor Technology Research, a device-modeling company based in Richmond, Va. Meanwhile, Hadis Morkoç's group at Virginia Commonwealth University seconds Schubert's support of electron leakage, which they attribute to the poor efficiency with which holes are injected into the quantum well.

Confused? Join the club—and realize that this controversy is precisely what you'd expect to find in a field that has suddenly begun to make great progress. Even if we don't have a universally agreed-upon theory to account for droop, we do have a growing arsenal of proven weapons to fight it—Schubert's polarization-matched devices, Lumileds' wide quantum well structures, as well as designs that improve hole injection, among others. Too bad that we still can't agree on how they work.

The industry will move forward. LEDs are just starting to supplant fluorescent as well as incandescent lighting. Someday, in our lifetimes, incandescent filaments will finally stop turning tens of gigawatts into unwanted heat. Smokestacks will spew less carbon into the global greenhouse. And we won't have to get up on stepladders to change burned-out bulbs nearly so often as we do today.

And around that time, when you're reading this magazine by the light of an LED, perhaps the theorists will have watertight explanations for the experimentalists, and we'll know the answer to the burning question that remains: What causes droop?

About the Author

Richard Stevenson, author of "The LED's Dark Secret" [p. 22], got a Ph.D. at the University of Cambridge, where he studied compound semiconductors. Then he went into industry and made the things. Now, as a freelance journalist based in Wales, he writes about them. Between assignments, he builds traditional class A hi-fi amplifiers, as opposed to the class D type favored by IEEE Spectrum's Glenn Zorpette. "If we were to share an office," Stevenson says, "many hours would be lost to discussions of the path to hi-fi nirvana."

To Probe Further

The Philips Lumileds papers are “Auger Recombination in InGaN Measured by Photoluminescence,” by Y. C. Shen, G. O. Mueller, S. Watanabe, N. F. Gardner, A. Munkholm, and M. R. Krames, Applied Physics Letters 91 141101, 1 October 2007, and “Blue-Emitting InGaN–GaN Double-Heterostructure Light-Emitting Diodes Reaching Maximum Quantum Efficiency Above 200 A/cm^2,” by N. F. Gardner, G. O. Müller, Y. C. Shen, G. Chen, S. Watanabe, W. Götz, and M. R. Krames, APL 91 243506, 12 December 2007.

The papers from Rensselaer Polytechnic Institute are “Origin of Efficiency Droop in GaN-Based Light-Emitting Diodes,” by M.-H. Kim, M. F. Schubert, Q. Dai, J. K. Kim, and E. Fred Schubert, J. Piprek, APL 91 183507, 30 October 2007; “Effect of Dislocation Density on Efficiency Droop in GaInN/GaN Light-Emitting Diodes,” by M. F. Schubert, S. Chhajed, J. K. Kim, and E. Fred Schubert, D. D. Koleske, M. H. Crawford, S. R. Lee, A. J. Fischer, G. Thaler, and M. A. Banas, APL 91 231114, 7 December 2007; and “Polarization-Matched GaInN/AlGaInN Multi-Quantum-Well Light-Emitting Diodes With Reduced Efficiency Droop,” by M. F. Schubert, J. Xu, J. K. Kim, E. F. Schubert, M.-H. Kim, S. Yoon, S. M. Lee, C. Sone, T. Sakong, and Y. Park, APL 93 041102, 28 July 2008.

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The paper from Virginia Commonwealth University is “On the Efficiency Droop in InGaN Multiple-Quantum-Well Blue-Light-Emitting Diodes and Its Reduction with p-Doped Quantum-Well Barriers,” by J. Xie, X. Ni, Q. Fan, R. Shimada, Ü. Özgür, and H. Morkoç, APL 93 121107, 23 September 2008.