BY **MIKE WOOD**

How do LEDs work?

A little physics; a little basic semiconductor theory

CHATTING WITH SOME COLLEAGUES at the USITT show in Cincinnati last week it occurred to me that, although we've dug into many LED topics in this column, one thing we've never talked about is how the darn things actually work. Most of the light sources we use in entertainment luminaires produce light using techniques we are familiar with from experience and natural phenomena. We understand that if you heat an object to a high enough temperature then it starts to glow red and emit light, so the light output from a filament in an incandescent lamp isn't at all surprising. Similarly we've all seen lightning streak across the sky and can make the mental connection between that and a discharge lamp. Fluorescent lamps are a little harder to explain, but again they rely upon effects seen in nature—a plasma discharge and fluorescence converting the ultra-violet emissions from that discharge into visible wavelengths. Similar fluorescence is seen in many natural organisms both in plants and in animals, being particularly common in ocean dwelling life forms. You don't have to go scuba diving to see examples of natural fluorescence though, many butterflies have fluorescent pigments and I'm sure everyone has noticed their finger nails glowing under UV or black light on stage or at Halloween. Although not quite as bright as finger nails, other keratin based substances such as wool and hair exhibit the effect as well.

All of those are readily understandable but what on earth is going on inside an LED to make it emit light? It isn't any of the phenomena we've just mentioned and doesn't involve heat (except as a by-product), an electric arc or fluorescence. Instead it's a very low level sub-atomic effect produced by the movement of electrons within energy bands inside the device. I'm not going to dig too deeply into the physics of this (even if I knew it) but it's worth taking a closer look at what's going on.

LEDs are more properly known as Light Emitting Diodes and, as the name suggests, normally consist of a single p-n junction diode. But, hang on a minute, what's a diode and what's it got to do with emitting light? A diode is the basic building block of solid state electronics and is the simplest possible semiconductor device. The fundamental electrical property of a semiconductor diode is that it only allows electric current to flow in one direction, but how does it do that? Most semiconductors are made of a poor conductor such as silicon and germanium that has had atoms of another material deliberately added to it. This process of adding these impurities is often called doping. The original pure material is electrically neutral and has exactly the right number of electrons associated with each atom, meaning there are neither too many nor too few electrons and so there are no free electrons available to carry electric current. However the doping process of adding extra atoms moves some of the electrons in the material and can leave a material with either more free electrons than it needs in some parts or with too few, thus leaving positively charged holes where electrons can fit. Both these changes make the material more able to conduct an electric current. In normal terminology the material with extra electrons is called N-type, since those extra electrons are negatively charged particles, and the material with a deficit of electrons (or surfeit of holes) is called P-type. Because of the electrostatic attraction between positive and negative particles free electrons are attracted towards the positively charged holes.

A diode is a very simple device which uses one piece of N-type material (with an excess of electrons) connected to another piece of P-type material (with an excess of holes). The area where the two materials meet is known as the junction. **Figure 1** shows a

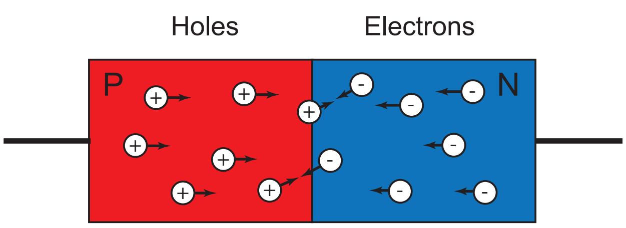

Figure 1 – Initial diode formation

schematic illustration of what this assembly might look like at the moment the junction is formed.

Initially the N-type material (shown in blue) on the right has too many electrons and the P-type material (shown in red) on the left has too few, this causes an imbalance and the electrons and holes will tend to move towards each other across the junction attracted by their opposing electrostatic charges. Where a hole and electron meet they will cancel out forming a neutral area of paired holes and electrons. This will continue until the situation shown in **Figure 2** is achieved with the formation of an area called the depletion zone (shown in yellow) on either side of the junction where everything is nicely balanced out and all the surplus holes and electrons are used up.

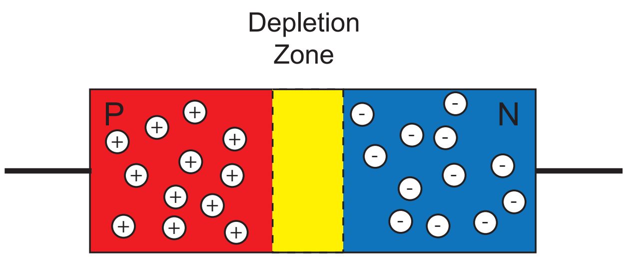

Figure 2 – Depletion zone

In the depletion zone the semiconductor material is essentially restored to its original, pre-doping, state where there are no free electrons to carry current so it behaves, once again, as an insulator. In this state, with no externally applied voltage, the diode is an insulator which would allow no current to pass. To get current flowing through the device you have to encourage the free electrons on the right in the N-type material to move towards the P-type material on the left and vice-versa and overcome the yellow depletion zone. By connecting the P-type material to the positive terminal of a power source and the N-type material to the negative terminal as shown in **Figure 3** an electric field can be created across the diode so that the free electrons will be attracted towards the positive electrode and repelled from the negative one. Similarly the holes will be attracted towards the negative electrode and repelled by the positive one. Get the applied voltage high enough and the electrons that are happily sitting in holes in the depletion zone will be shoved out, the depletion zone will be eliminated, and everything will start moving again.

> **“. . . what on earth is going on inside an LED to make it emit light?”**

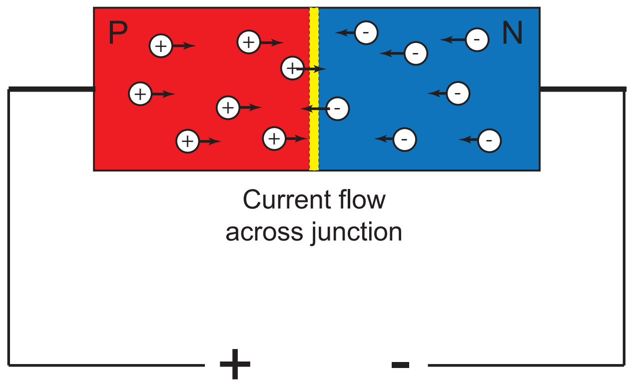

Figure 3 – Current flowing

If you connect the voltage the other way around with the positive terminal connected to the N-type material and the negative terminal to the P-type material then just the opposite happens—the electrons retreat even further towards the positive electrode and the holes towards the negative making the depletion zone even larger. In this state the diode becomes an even better insulator and won't conduct electricity at all.

Okay, you might say, this is all very interesting, but I'm not that interested in the physics. When do we get to the light emitting part of this particular diode? Don't worry. This is just about all the theory we need to understand the principles of the process but there's no avoiding a little delving in the bowels of basic semiconductor theory.

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In a light emitting diode everything behaves exactly the same as in the diode illustrated here and, in fact, most diodes are *light emitting* to some extent, but the light might be invisible. LEDs are operated in the connection shown in **Figure 3** *(known as forward biased)* where the diode is connected such that current flows through the device and electrons and holes are continually moving and meeting at the junction and being replenished from the applied electric voltage. It's what happens when those electrons and holes meet up that actually generates the light.

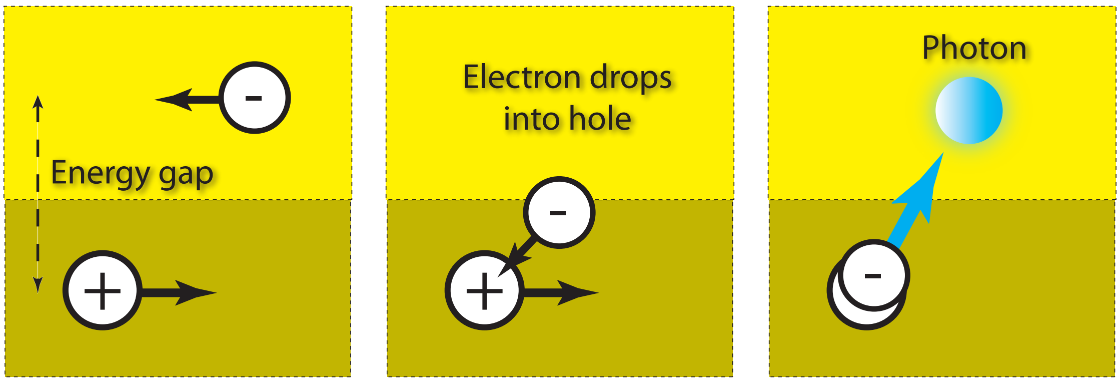

Figure 4 – Electron and hole combine

As shown diagrammatically in **Figure 4** a free electron in the conduction band of the semiconductor has an energy level higher than the energy level of the hole. When the high energy electron drops into a low energy orbital in the hole it has to lose that excess energy somehow and, in this case, the energy is emitted as a photon, the basic unit of light. The difference in the energy levels, or the height of the fall, will determine the energy of the photon and the higher the energy of that photon the higher the frequency of the light. As mentioned earlier many semiconductor diodes exhibit this effect, it's just that the band gap energy level in most materials is fairly low so the light emitted is of very low frequency, outside of the visible range down in the infra red. The fundamental difference with LEDs is that the semiconductor materials are chosen such that the energy drop is much higher and the photon emitted is high enough in frequency to be visible. The key again is that the higher the energy of the photon, the bluer the emitted light. Most semiconductor materials tend to exhibit a single size energy band gap, which means that all the photons are emitted with approximately the same energy level. This results in the narrow band of almost monochromatic light that we are all familiar with from LEDs.

When you look at an LED chip it looks like the whole thing is glowing and emitting light. However, from the description above you can see that actually photons are only emitted from the area where electrons and holes combine near to the junction of the LED where the two materials, the N-type and the P-type, join. In other words, it's the meat in the sandwich that produces the light. Unfortunately, this is not ideal, as for the light to exit and be useful it now has to pass through one or the other layers as well as whatever is used for an electrical connection. The photons also may hit another electron on the way out and be absorbed in the process of knocking it out of an orbital into a higher energy level. In non-LED diodes even if photons are produced most of them are absorbed by the semiconductor material in this way and end up as heat. However, in an LED the materials used for the semiconductor layers, connection layers, and packaging are carefully selected to be transparent and thin enough that many of the photons escape as usable light. The choice of these semiconductor materials is critical. To be a good LED material they have to possess the right energy gap for the light color you want and be transparent to that particular color of light. In the early days of LED research it proved relatively simple to find materials that moved the frequency up from the infra red into the visible red, so red LEDs appeared first with gallium arsenide (GaAs) based devices in the fifties. Research into complex materials with a high enough energy gap to produce greens and blues took a lot of research, and, as we know, it wasn't until the early nineties that Shuji Nakamura of Nichia (now on the Materials Department faculty at the University of California at Santa Barbara) demonstrated a gallium nitride (GaN) material that was capable of producing high output blue light. Strangely enough, although we now have materials that have the right height band gaps to generate long wavelength light in the reds and deep ambers, and others with larger band gaps that generate short wavelength light in blues and ultra violet, there is still a big gap in the middle around the yellows and greens where no efficient materials

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have yet been developed. Ironically, this is right in the region around 555 nm where the human eye is most sensitive and LEDs would be really useful. This gap extends to around 625 nm as, although amber LEDS are available, their performance and stability is poor. Considerable fame and fortune awaits the researcher who manages to plug this hole and patent the process! In the meantime developments in phosphor assisted LEDs where amber or yellow phosphors are excited by a deep blue or UV LED are helping fill the visible gap.

Next time I’ll continue this tale and talk about how the semiconductor materials are packaged to control and maximize light output and the innovation that is going in to that and heat management. Strangely enough as we journey through photonic lattices we will end up back with a natural phenomena; butterfly wings. ■

Mike Wood is President of Mike Wood Consulting LLC which provides consulting support to companies within the entertainment industry on technology strategy, R&D, standards, and Intellectual Property. A 30-year veteran of the entertainment technology industry, Mike is the Treasurer and Immediate Past President of ESTA. Mike can be reached at 512.288.4916.