BY **MIKE WOOD**

How do LEDs work? – Quantum dots

MANY OF MY ARTICLES here in *Protocol* concern LEDs and the rapidly changing technology surrounding them. I continue to be enthusiastic, as those of you who know me will realize, about how lucky we are to be around when such a dramatic change has happened in how we produce light. It's not happened before since the switch from candles to electric light, and I can't think that it will ever happen again. Once LEDs achieve the very high levels of efficacy that we will see in the next few years there's no room for another such leap. Yes, different alternative light sources will come along, but they can never be any more efficient than 100%. Perhaps cheaper, perhaps more convenient, perhaps other advantages; but never again the totally disruptive change we've seen in the last ten years or so.

In this issue, I want to talk about a technology that is very closely related to LEDs and that will, I'm sure, become more important to us in entertainment lighting. That topic is quantum dots. I'm sure you've heard of them in relation to their use in high-end video displays, but may not yet have come across them in a lighting context.

> "A quantum dot is small; very small; very, very, small."

At the very base level, a quantum dot is a semiconductor, the same kind of material that LEDs, transistors, and integrated circuits are made from. One fully descriptive name I've seen for quantum dots is "fluorescent semiconductor nanocrystal." Just trips off the tongue, doesn't it? Quantum dot is more of a slang name, but it seems to have stuck. Another name sometimes seen for these devices is "artificial atoms" but we need to dig a bit deeper to find out why.

To understand what makes a quantum dot special, you have to get right down to the subatomic level and see what's going on inside. We don't need to get into the details (if I even fully understood them) but a basic understanding is essential. **Figure 1** shows three examples of what's going on inside different semiconductor materials.

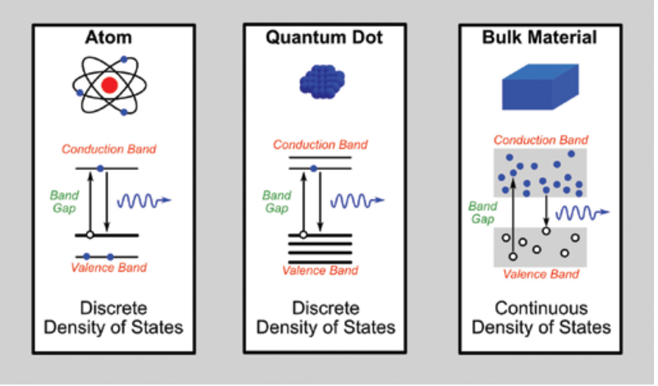

Figure 1 – Electron states in fluorescence

On the left, we see the situation within a single atom of a semiconductor material. Electrons can be enticed to break free from a lower energy valence band up to a higher energy conduction band through some external influence, perhaps through an electric current, or perhaps through excitation by a light source. With a single atom these electron bands are well defined and exist at specific values related to the particular atom we are looking at. When that displaced electron falls back again from the conduction band to the valence band it emits energy as an electromagnetic wave. This electromagnetic wave can be within the range we call light. The difference in energy levels between the two bands is called the band gap, and it's the size of the band gap that determines the wavelength of the electromagnetic wave, and thus the color of the light emitted. The important takeaway here is that the color of the light is solely driven by the width of the band gap and, if the electron bands are discrete, so too will be the colors emitted.

This is in contrast with a bulk material as shown on the right. This is typically what we will see in the type of semiconductor used in LEDs and transistors. There are vast numbers of atoms present which allows much more freedom for the movement of electrons and there are many more allowed energy levels close to each other. The net result is that the valence and conduction bands don't just occupy discrete energy levels. Instead, they each form a band encompassing a range of energy levels. The wavelength of light emitted is controlled by the material itself, which atoms are present, and how they are arranged. In order to change the wavelength of the light emitted by a conventional semiconductor you have to change the material. This is precisely what we see with conventional LEDs. That material mix in a red LED is different from that in a blue LED. The material controls the color.

Now let's take a look at a quantum dot, the middle diagram in **Figure 1**. A quantum dot is small; very small; very, very, small. So small that there are relatively few atoms present. This means that the electron-hole pairs are constrained to a much smaller space. The quantum dot is of the same order of size as the radius that the electron-hole pair would occupy if left unchecked. In other words, the size of the quantum dot is such that it acts as a box for the electrons and constrains their movement to a very defined space. This drastically reduces the number of possible energy bands and we end up with a situation very similar to that of a single atom, where there are a few discrete energy bands and thus a single possible wavelength of light emitted when the electron drops from a discrete conduction band back to a discrete valence band. Most importantly it's the *size* of the quantum dot that controls the size of that band gap, not just the material. For the exact same material, changing the size of the quantum dot, and thus changing the band gap, will change the wavelength of the light emitted. The larger the bandgap, the greater the energy and shorter (bluer) the light wavelength, and conversely, the narrower the bandgap, the lower the energy and the longer (redder) the light wavelength.

Another way to think about this that might make it clearer what's going on is to consider the electrons as wave functions, rather than thinking about them as particles. The confinement of movement restricts the possible wave functions to those that have a shorter wavelength than the physical confines of the material. Our dot is really, really small—and has dimensions that are comparable with the wavelength of the wave function. The smaller the box, the shorter the wavelength of the wave function, thus the higher the energy and the wider the band gap. It's akin to resonance—once we get our box small enough then the wave function wavelength must fit in the space from node to node (or multiples thereof). Quantum theory is often counter-intuitive and I don't pretend to fully understand what precisely is going on here!

That's incredibly significant. Now you have a material where, just by changing its size or shape, you can tune in the wavelength of the light you want to produce. No new chemistry to make a blue emitter instead of a red emitter. Same chemistry, but with a different size or shape of quantum dot.

What do I mean by small?

In *The Hitchhiker's Guide to the Galaxy*, Douglas Adams described space in this manner. "Space is big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the road to the chemist's, but that's just peanuts to space." A quantum dot needs the same kind of definition, just in the opposite direction. For all this to work the quantum dot has to be tiny, so tiny as to be almost treatable as dimensionless. Real quantum dots range in size from around 1 nanometers to 10 nanometers. **Figure 2** tries to put that size in perspective.

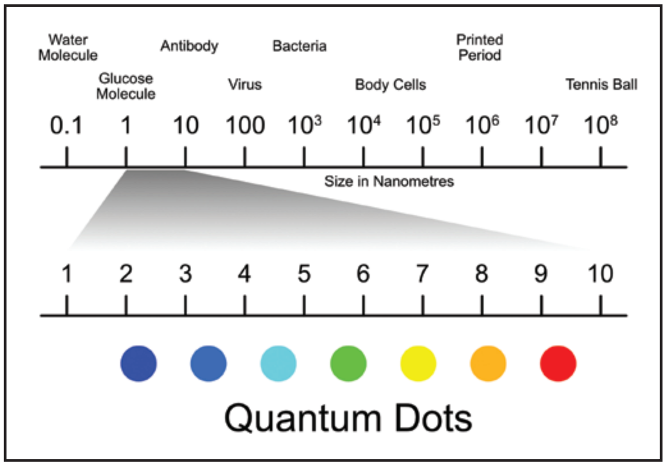

Figure 2 – Relative size of quantum dots

A single water molecule, one atom of oxygen and two of hydrogen, is around 0.1 nm in size. A glucose molecule (six carbon, six oxygen, and 12 hydrogen) is about 1 nm. Our quantum dots start at about that size. Smaller than antibodies, smaller than viruses and bacteria. About the size of 10 to 50 atoms in diameter. (Note: The relationship between quantum dot size and wavelength isn't linear, but the actual relationship is calculable. It varies from material to material.)

Figure 3 shows how this might work in practice with a single semiconductor material fashioned into differing sizes of quantum dots.

In this diagram, I've shown the quantum dots being excited by

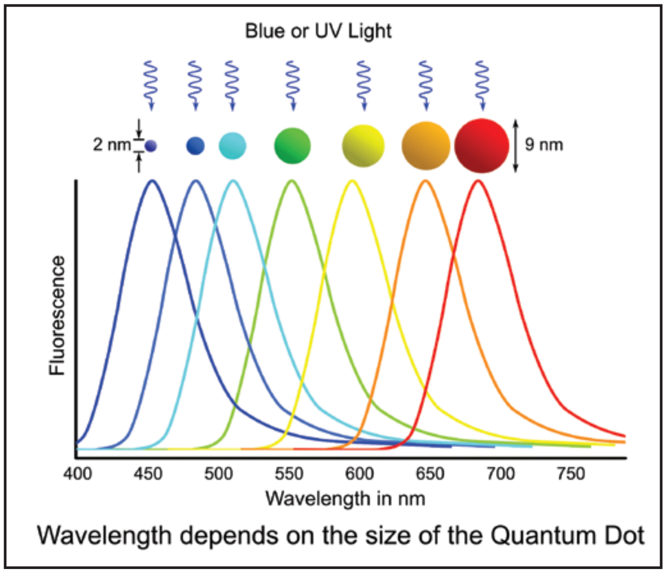

Figure 3 – Wavelength versus size of a quantum dot

short wavelength (high energy) blue or UV light, however you can manufacture Quantum Dot LEDs (QLEDs) where the excitation comes directly from electric current. The light from a quantum dot is characterized as a single, tightly constrained, wavelength with a narrow half-power bandwidth. That center wavelength can be tuned across the entire visible range of light wavelengths (and outside that if desired) with a single semiconductor material. It's extremely efficient at all wavelengths. Mixtures of quantum dots can be used to produce broad band and mixed colors. For example, a controlled mix of dot sizes could produce a quantum dot device which emitted in red, green, and blue light to produce a mixed white light result.

> **"Those colors are defined by industries other than our own and we are stuck with them."**

More colors for all

In real products quantum dots are first being used as a replacement for phosphors with a conventional blue or UV LED as the pump. You've likely already seen them in high-end video screens where the white LEDs behind the LCD panel are being replaced with RGB QLEDs. This leads to improved color saturation and an extended color gamut. Now being used in new 4K displays, the technology will likely trickle down, the CES show in January was full of them. As to lighting, again I think we'll see first use of quantum dots as replacements for phosphors. (Note: a quantum dot works through fluorescence rather than phosphorescence, but the result in this application is the same.) Osram has already shown a hybrid device using quantum dots to make a green emitting device. This makes good sense, the most efficient LEDs we can make at the moment are the blue. Those are used as the sources in the common white LEDs used in domestic LED lamps. In entertainment lighting however we want all the colors and, at the moment, red is the weak link. Red LEDs are inefficient and heat sensitive, and conventional red phosphors are poor. However, a blue or UV pump LED with a red emitting quantum dot converter can fill that gap. Prices are higher at the moment, but heading downwards all the time.

The range and tuneability of colors is compelling. **Figure 4** shows a small part of the range of quantum dots made by one manufacturer. They offer a complete range of colors all the way from deep red to violet with 10 nm spacing along the spectrum.

Up to this point our choices in LED colors for entertainment lighting have been limited to the same standard six or seven colors all manufacturers produce, driven by the few chemistries in production, and the phosphors available. Unfortunately, those colors are defined by industries other than our own and we are stuck with them. The cyan we use for example is actually the FAA approved color for airport taxiway lighting, not necessarily the same as we might choose for our application. The current range of colors has a large gap between cyan and blue, an even larger one in yellow between green and amber, and no decent deep red. Quantum dot technology offers us a way to fill those gaps with highly saturated alternatives. That means better colors, better color rendering, and more lifelike lighting. I'm all for it. ■

Mike Wood runs Mike Wood Consulting LLC, which provides consulting support to companies within the entertainment industry on product design, technology strategy, R&D, standards, and Intellectual Property. A 40-year veteran of the entertainment technology industry, Mike is a past President of ESTA and Co-Chair of the Technical Standards Council. Mike can be reached at mike@mikewoodconsulting.com.

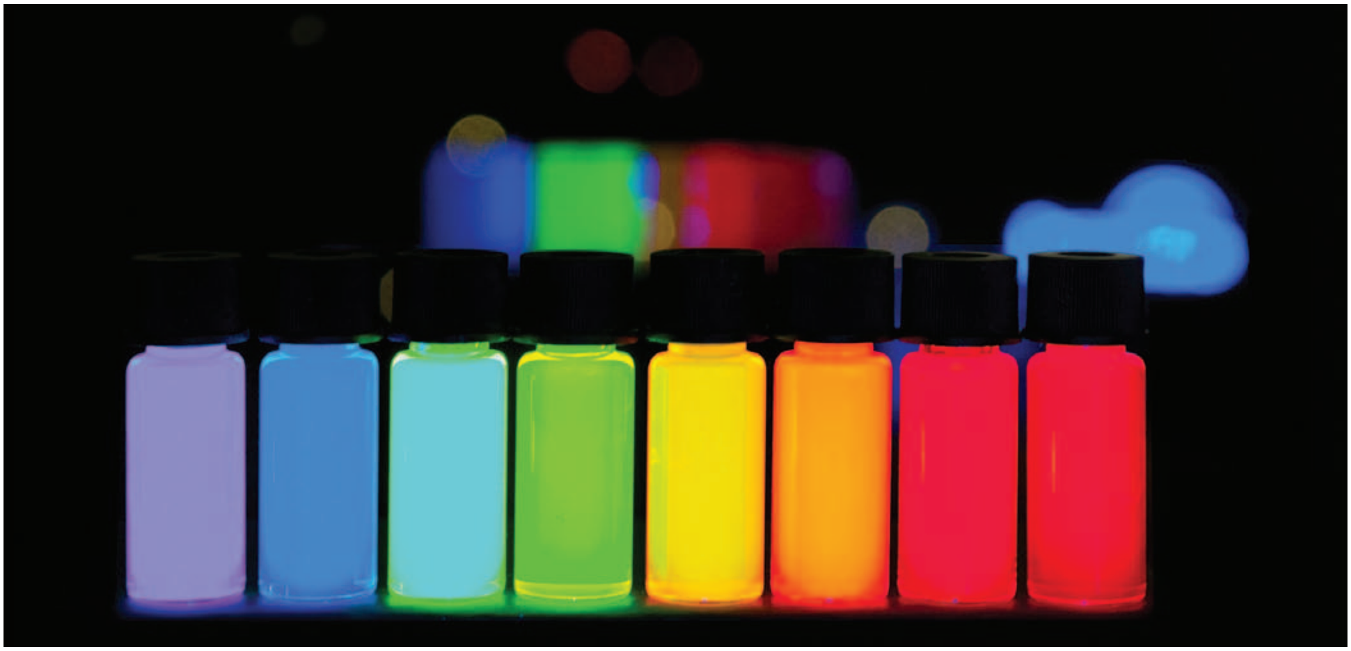

Figure 4 – Quantum dot range of colors