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Blue LEDs

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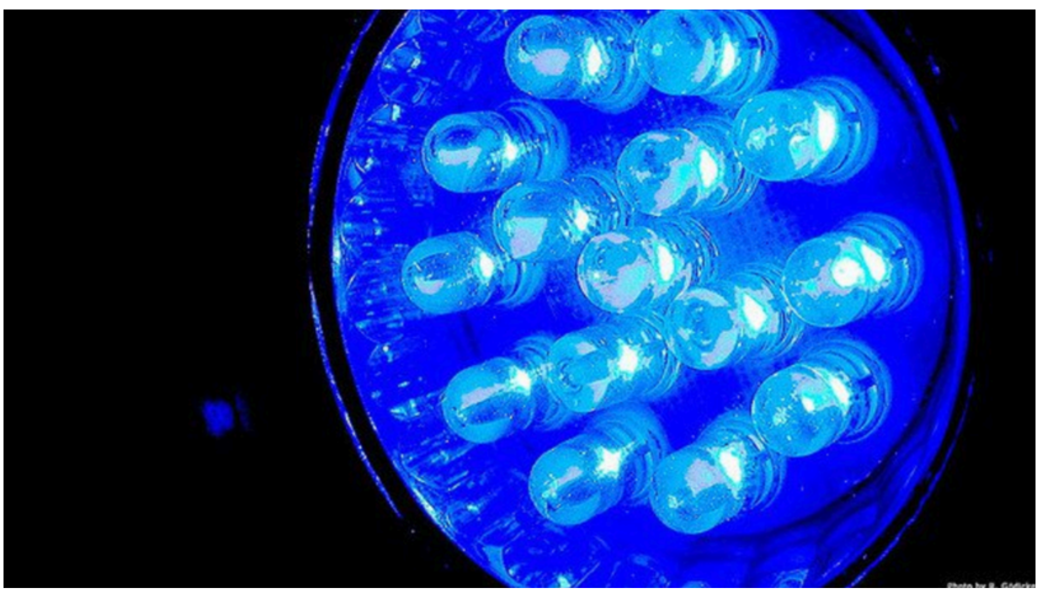
Introduction

Light-emitting diodes (LEDs) are one of the many useful products from the science of quantum mechanics. According to quantum mechanics, the electrons around atoms can be in distinct orbitals, but not in between. Electrons closer to the nucleus have the lowest energy while farther electrons have the highest energy. When electrons move from higher-energy orbitals to lower-energy orbitals, they release energy in the form of light. The energy difference between the old orbital and the new one determines the color of the emitted light. The larger the energy difference, the more blue the light is. These ideas apply to groups of atoms as well, such as those that make up solid materials, which leads to LEDs.

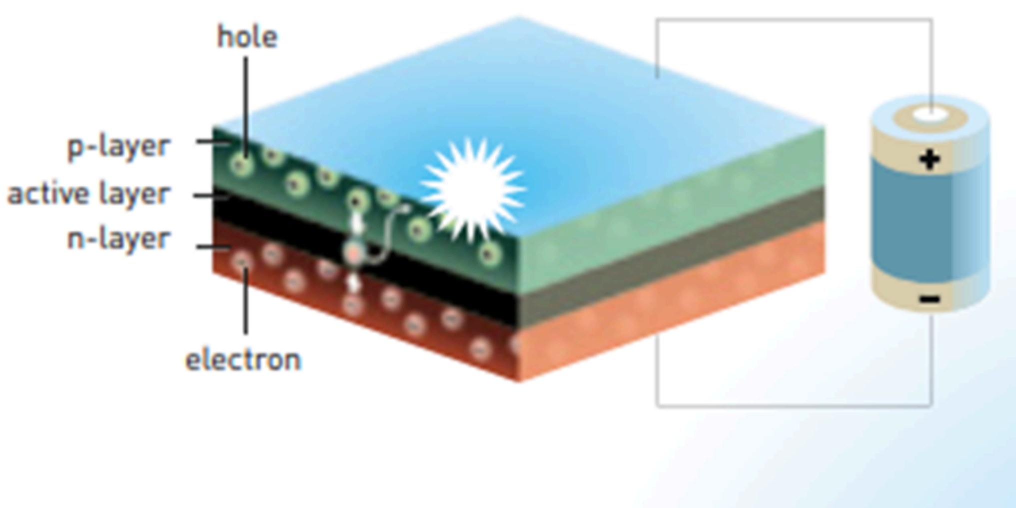
Throughout the 20th century, scientists struggled to make blue light since it needs a very high energy gap. By the early 1970s, red and green light-emitting diodes had been made successfully, but only the addition of blue light would allow white light, or any other color light to be made. It was not until 1994 when there was a breakthrough and Shuji Nakamura developed high-brightness blue LEDs, as shown in Figure 1. This success led to the use of LEDs as light sources, since they can emit much more light using much less power than fluorescent and incandescent light bulbs. Additionally, bright blue LEDs have the possibility to increase quality of life in developing countries, and other creative energy-saving uses of illumination.



[Figure 1. This image shows a blue LED lamp. Image downloaded from https://www.pbs.org/wgbh/nova/article/how-blue-leds-work-and-why-they-deserve-the-physics-nobel/ in June 2019.]

Mechanism and Significance of Blue LEDs

Semiconductors have an electrical conductivity between that of a conductor, such as copper, and an insulator, such as rubber. They are typically made from a poor conductor which is doped by adding atoms of another material to it. Light-emitting diodes are made by fusing two types of semiconductors together. One of the semiconductors must be n-type which contains a surplus of negatively charged electrons. The other semiconductor must be p-type which has a surplus of holes that hold electrons. This allows free electrons to jump from negatively charged areas to positively charged areas. Between them is an active layer, also called the p-n junction, and two electrodes are placed at either end of the setup, which is the source of electrical current. This arrangement is shown in Figure 2. When the proper voltage is applied across the diode, the negatively charged electrons move in one direction in the material and the positively charged holes move in the opposite direction. Since the holes have lower energy states, a free electron will lose energy when it falls into the hole. This energy is emitted as a photon of light. The size of the drop in energy dictates the amount of energy the photon of light contains when emitted, which therefore determines the wavelength and color of the light that the diode emits. Photons with a lower amount of energy have a longer wavelength, and photons with a higher amount of energy have a shorter wavelength. Since blue light has a shorter wavelength on the visible light spectrum compared to other colors, it requires a very high energy gap. This is the reason blue LEDs are difficult to make, and why it is easier to make LEDs of other colors such as red, green, and yellow because of their longer wavelengths, as they do not require as high of an energy gap.



[Figure 2. This image shows the setup of the heart of the LED. Image downloaded from https://www.nobelprize.org/uploads/2018/06/popular-physicsprize2014-1.pdf in June 2019.]

The development of blue LEDs is having a major impact in the illumination and electronic industries. White LED lamps are replacing incandescent and fluorescent bulbs used in the 20th and early 21st century. These lamps are made in one of two ways. The first way is to construct the lamp out of red, green, and blue LEDs, which the human eye will interpret as white light. The second way is to use blue light to excite a phosphor so that it shines in green and red. Then when all the colors come out together, white light is created. The use of such LEDs saves an incredible amount of energy and resources, can increase the quality of life for over a billion people, and makes many creative uses of light possible.

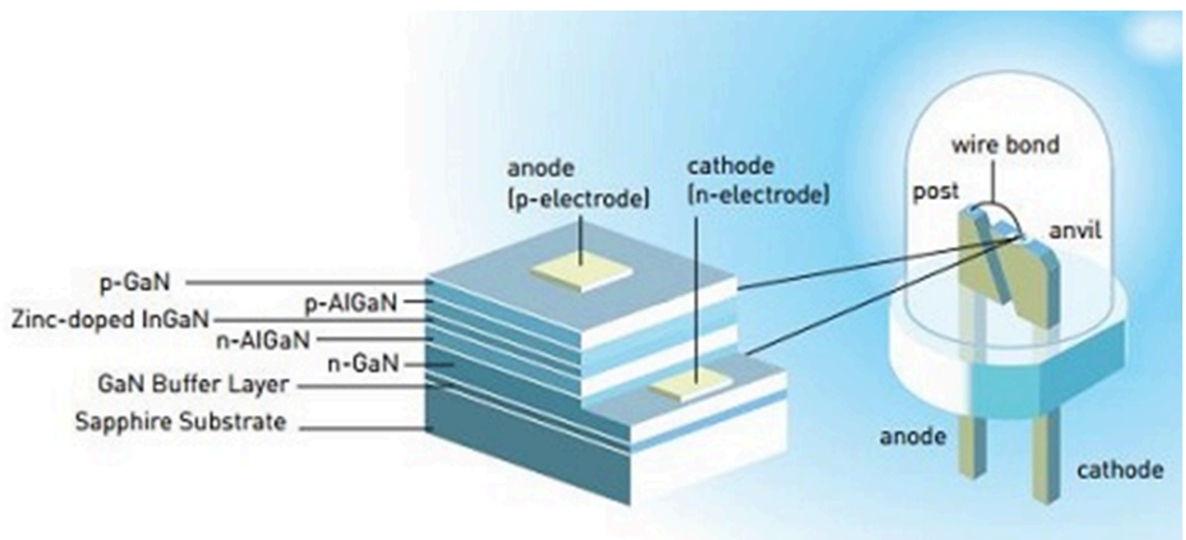
In an LED, electricity is directly converted to photons of light which leads to efficiency gains, compared to other light sources where only a small portion of electricity is converted into light and most of it converts to heat. Incandescent bulbs use electric current to heat a wire filament, causing it to glow. Fluorescent lamps have a gas discharge that creates heat and light. So, new LEDs need less energy to emit light compared to older sources. In addition, they are continually being improved so they are even more efficient with a higher luminous flux per unit electrical input power, measured in lumen/watt. LEDs can emit 300 lumen/watt, compared to 16 lumen/watt for incandescent bulbs and 70 lumen/watt for fluorescent bulbs. Further, LEDs last longer than other lamps, as they can last for 100,000 hours while incandescent bulbs tend to last 1,000 hours and fluorescent bulbs 10,000 hours. As about a quarter of the world's electricity is used to generate light, the invention of highly-energy efficient LEDs can have a considerable contribution to saving the earth's resources and economic resources by reducing material consumption, reducing energy and electricity use, and reducing greenhouse gas emissions.

Moreover, LED lamps hold promise for increasing the quality of life for close to 2 billion people who lack accessible electricity grids. Lower power requirements means that the LED lamps can be powered by inexpensive local solar power. So, LEDs can provide solar-powered and off-grid energy for hospitals, homes, and more. LEDs are also flexible light sources. They can produce millions of different colors with varying intensity and patterns all controlled by computers. Thus, there is the possibility to reproduce modifications of natural light to follow the human biological clock. Greenhouse-cultivation using artificial light is already being used. In addition, polluted water can be sterilized ultraviolet LEDs, originating from the blue LED.

Material Choice

The first attempts at blue light emission from a diode used zinc selenide and silicon carbide, which are both semiconductors with high indirect band gaps. Zinc selenide did not produce sufficient light emission, but blue LEDs can actually be made from silicon carbide. However, the external quantum efficiency and luminous efficiency are low for silicon carbide.

The primary material choice for the production of blue LEDs is gallium nitride. This material is a semiconductor with a direct bandgap of 3.4 eV, which directly correlates to the wavelength of light in the ultraviolet range, and has a Wurtzite crystal structure. Gallium nitride also has indium gallium nitride and aluminum gallium nitride for ternary compounds. Several layers of gallium nitride and aluminum gallium nitride are used with indium gallium nitride as the active layer to make the LED, as shown in Figure 3. The active layer is surrounded by n-type and p-type aluminum gallium nitride layers, with n-type and p-type gallium nitride layers used for contacts before the aluminum gallium nitride layers. There is a buffer layer of gallium nitride before other layers, and sapphire is used for the substrate. The band gap of indium gallium nitride is controlled by changing the amounts of gallium and indium. The indium and aluminum can also be mixed to increase the LED's efficiency. This combination of materials produces the most efficient bright blue LED.



[Figure 3. This image shows the design of the blue LED. Image downloaded from https://www.nobelprize.org/uploads/2018/06/popular-physicsprize2014-1.pdf in June 2019.]

Critical Material Properties

The choice material of gallium nitride has many useful attributes that contribute to its success as a semiconductor in blue LEDs. These attributes include lower resistance resulting in lower conduction losses, faster devices yielding fewer switch losses, less capacitance causing fewer losses when charging and discharging devices, and less power is needed to drive the circuit. On top of that, gallium nitride is less expensive than alternatives such as silicon, and it can be produced and used in smaller devices than such alternatives. This material is produced using the same manufacturing procedures as silicon, and the devices produced are much smaller while having the same functional performance. Gallium nitride also has the ability to conduct electrons over 1,000 times more efficiently than silicon, as well as being manufactured at a lower cost. All of these properties show why gallium nitride is a prime candidate for serving as semiconductors in tiny blue LEDs that require a high amount of efficiency.

Manufacturing Process

High-quality gallium nitride crystals used in the semiconductors of blue LEDs are difficult to grow. Bulks of such crystals cannot be produced with standard equilibrium growth methods like common semiconductor substrates can due to their exceeding decomposition temperature and high melting temperature. Gallium nitride crystals must be grown by more complicated methods, which is why they have limited availability on the market. Ammonothermal growth technology is one of the more recent and successful methods used. It is similar to hydrothermal synthesis, in which synthesis of single crystals depends on the solubility of minerals in hot water under a high pressure in a sealed vessel. Only in this case, supercritical ammonia is used instead of water, and ammonium halides are added to the reaction mixture. In this process, metallic gallium is dissolved in supercritical ammonia in a high-pressure autoclave. It is then transported to another zone of the autoclave in which the solution is supersaturated and the crystallization of gallium nitride takes place. A temperature gradient between crystallization and dissolution regions allows for mass transport of the convection. Certain mineralizers are added to the ammonia which enhances the solubility of the gallium or gallium nitride, and speeds up its dissociation. This results in growth of larger crystals of higher quality. The process is well-controlled and can be replicated at relatively low temperatures and pressures of a couple hundred megapascals. Additionally, the growth of these crystals can be performed in a variety of environments, acidic or basic. The choice of mineralizers added determines the type of environment. Ammonoacidic growth uses halide compounds as their mineralizers, while ammmonobasic growth uses alkali metals or their amides for their mineralizers.

Other Potential Applications of the Material

In addition to gallium nitride’s use in blue LEDs and the rest of the illumination industry, it can also be advantageous in other optoelectronic devices. This includes other semiconductor devices that can power more efficient cell phone screens, television screens, electronic signs, and more.

Gallium nitride can also help create high-power and high-temperature equipment. For instance, this material can be used in microwave amplifiers for wireless communication systems, which leads to improved reception on mobile devices as well as fewer transmitting stations and low-earth satellites. Greater transmitting power and better efficiencies provided by gallium nitride materials will cause fewer geostationary satellites to be able to do the same workload as more low-earth satellites. Some of the more specific equipment pieces gallium nitride can be used in for this case include amplifiers, solid-state microwave circuits and devices, microwave integrated circuits, and radio links and equipment. Another example includes aerospace components that have the ability to operate over a wide temperature range while remaining unaffected by radiation. Due to the chemical composition of gallium nitride, it could have the capability to exhibit greater radiation hardness. This could provide improved solutions for radiation effects on semiconductor devices, as well as improved aerospace facilities and techniques.

Conclusion

The invention of blue light-emitting diodes has had an enormous effect on the world of science. They led to the discovery of all the advantages and unique properties that the substance gallium nitride has to offer, bringing it to the forefront of many technological industries. Its primary contributions so far include largely improved semiconductors and more efficient electronic devices. Moreover, LEDs are also taking over the illumination industry, saving an incredible amount of the earth’s resources, and helping to improve the lives of those in need around the world. None of this would have been possible without the development of highly-efficient blue LEDs.

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