AND WHITE LIGHT WAS CREATED

Y SE HIZO LA LUZ BLANCA

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The 2014 Nobel Prize for Physics has been awarded to Isamu Akasaki; Hiroshi Amano; and Shuji Nakamura, "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources". This article contains a brief summary of the history of the obtention of blue and white light diodes, as well as an analysis of the problems that still has this technology.

El premio Nobel de Física 2014 fue otorgado a Isamu Akasaki, Hiroshi Amano y Shuji Nakamura, "por la invención de diodos emisores de luz eficientes, que hicieron posible la fabricación de fuentes de luz blanca brillantes de alta eficiencia". En este artículo se presenta un breve resumen de la historia de la obtención de diodos azules y blancos, analizando los problemas que aun presenta esta tecnología.

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INTRODUCTION

This year the Royal Swedish Academy of Sciences announced that the Nobel prize in physics had been awarded to Professor Isamu Akasaki at Meijo University, Nagoya, and Nagoya University, Japan; Professor Hiroshi Amano at Nagoya University, Japan; and Professor Shuji Nakamura at University of California, Santa Barbara [1]. The winners (see Figure 1) are rewarded for the invention of the blue light-emitting diode (LED).

Light-emitting diodes are part of our everyday life; they are used in application ranging from traffic lights, remote-control transmitters, and mobile phones, to TV screens. Thanks to the blue LEDs, today we have efficient white solid-sate lamps for general illumination. Compared with incandescent and fluorescent sources, LEDs have higher reliability, longer lifetime, and lower power consumption.

The first commercial LEDs were fabricated in the 1960s and emitted red light. Through the 1970's, additional colors became available and the most common materials used were GaP for green and red, and GaAsP for orange and yellow. In the 80's, red an infrared LEDs based on AlGaAs were developed and a rapid growth in their use started.

In the 1990s AlInGaP based LEDs with life times over 100,000 hours appeared in the market. By changing the ratio of the component materials one can get a range of colors from red to yellow.

Researchers struggled to create blue LEDs, but despite the great efforts carried out in the research community as well as in the industry, blue light remained a challenge for more than two decades.

Figure 1: The three Japanese Nobel Prizers in Physics 2014. From left to right: Isamu Akasaki, Hiroshi Amano and Shuji Nakamura (image taken from http://www.nobelprize.org/nobel_prizes/physics/)

Gallium nitride (GaN) was always assumed as a good candidate for fabricating ultraviolet and blue LEDs because its band-gap energy of 3.4 eV. In 1971 Pankove [2] conceived a metal-insulator-semiconductor LED based on GaN, but he did not succeed in obtaining the p-doping necessary to fabricate a p-n junction LED, and it was not until 1993 that the first GaN based blue LED was released.

WHAT IS A LED?

In incandescent bulbs, electric current is used to heat a wire filament, making it shine. In fluorescent lamps, a gas discharge is produced, creating the light.

A light-emitting diode functions in an entirely different way: it is a *semiconductor* device that converts electrical energy into light. A LED is no larger than a flea and is basically a p-n junction diode, in which under forward bias, electrons and holes recombine emitting a monochromatic (single color) light (see Fig. 2). The emitted wavelength depends on the semiconducting material used.

THE BATTLE TO OBTAIN BLUE LIGHT

After Haase et al. [3] reported the first ZnSe based laser diode emitting at 490 nm at 77K, the hopes of obtaining blue light were focused on II-VI semiconductors and most of researchers had given up gallium nitride as a hopeless material. ZnSe emerged as a promising candidate to fabricate blue emitting devices because it has a bandgap of 2.7 eV and is easily grown onto GaAs substrates given the similarity between their lattice constants. However, despite the large number of theoretical and experimental work aimed at the subject, the expected results were not obtained and devices based on ZnSe still have severe stability problems and rapid degradation, making commercial applications impossible.

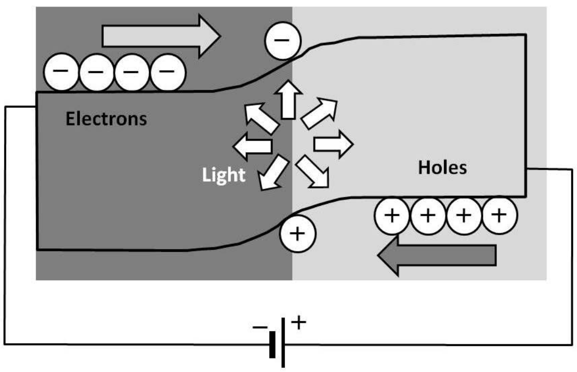

Figure 2: Illustration of a LED, showing its operating principle.

Meanwhile Akasaki and Amano at Nagoya University, and Nakamura, working alone at Nichia Chemicals in Tokushima continued systematic work on gallium nitride, GaN.

THE GaN MYSTERY

There were two major obstacles preventing the fabrication of GaN based LEDs. One was the poor crystalline quality of the GaN layers and the other the difficulty to achieve p-type doping in that material.

The difficulty of growing good quality GaN films is due to the lack of high quality crystalline substrates with the same lattice parameter as GaN. This problem was overcome by Akasaki and his doctoral student Hiroshi Amano. They succeeded in obtaining high-quality GaN layers growing a thin AlN buffer layer [4] onto sapphire substrates by metalorganic vapour phase epitaxy (MOVPE) technique.

Later, Nakamura used GaAlN and GaN buffer layers with a different growth sequence from that used by Akasaki and developed a new 'two-flow' MOCVD system which allowed him to growth high quality GaN layers [5].

The problem of the p-doping was solved when Akasaki and Amano discovered that a p-type conducting GaN layers can be obtained using Mg and irradiation with low energy electrons. This led to the first demonstration of a GaN based blue LED in 1989 [6]. This process was later explained and improved by Nakamura who achieved p-type GaN materials with very high conductivity [7] by thermal annealing in a nitrogen atmosphere, a process much faster and reliable as compared to the irradiation technique. Nakamura was then able to create the first high-brightness blue GaN based LED and in November 1993 *Nichia* announced commercial blue InGaN LEDs.

Next year, Nakamura defended his PhD thesis at the University of Tokushima

THE WHITE LIGHT

There are two ways to generate white light: by mixing red, green and blue LEDs (known as Red-Green-Blue, RGB process) or by using a blue LED to pump a phosphor.

The majority of today's white LEDs solid-state lamps use an InGaN blue LED, covered by phosphor. In this process, the blue photons are absorbed by the phosphor and re-emitted in the yellow part of the spectrum. The idea is similar to that of the fluorescent lamps where a narrow band UV light is down-converted in phosphor to a rather broad emission spectrum of visible light (a little red, some green, and a lot of yellow). The mix of the residual blue photons and yellow light provides a good approximation of white light to the eye. The specific composition of the phosphor determines the spectrum.

Usually, phosphor is doped with rare earth elements, whose existence is limited, and the extraction process is expensive and polluting. Even though the combination of blue LED and phosphor is an established technology with a good performance, it is not perfect.

One critical aspect in illumination is "the quality" of the light emitted, which is measured by the color rendering indices (CRI). The higher the CRI value, the closer a light source is able to reproduce the colors of an object illuminated by a sunlight (which has a CRI of 100). For example, incandescent bulbs, despite their other obvious disadvantages, have a CRI around 95. In comparison, white phosphor LEDs lamps have lowers CRI, of about 70 to 80. This is because phosphor produces white light with little red component in the system's output.

Improvements in the CRI of LEDs white lamps using phosphor can be achieved by mixing the different types of phosphor that add red wavelengths. Also, substituting a blue LED for an ultraviolet one we can make further improvements to the CRI. However this goes against the device efficiency.

The RGB process produces white light with much improved CRI values. In this process the white light is replicated by direct emitting LEDs. However, to date, RGB lamps have not produced high quality white light because of a lack of efficient green LEDs. This is known as the "Green Gap," referring to the incapacity to produce efficient green devices (wavelength bigger than 500 nm). To obtain green emission with InGaN it is necessary to add too much indium, and it reduces the radiative recombination rate.

Another general problem is that InGaN-based LEDs exhibit a significant efficiency loss when operating at high injected current densities, the origin of which remains as an open issue [8].

Despite these problems *Cree* announced this year a white high-power LED with 300 lumens per watt, which increases the potential for the solid-state-lighting industry.

InGaN LASERS

Not only the fabrication of blue LEDs has had a huge technological impact: the creation of blue lasers diodes (LDs) has been of great importance too. For example, the storage density in digital video disks (DVDs) is bigger for shorter wavelengths of the laser used to write and read the information, since the focused light diameter decreases (more precisely, the storage density is inversely proportional to the square of the wavelength). So, blue-based InGaN lasers allow to increases the data-storage density in modern digital video disks (DVDs). Previous DVDs, used red AlInGaP semiconductor lasers and had a data capacity of about 4.7 gigabytes.

The first nitride based violet LDs with an emission wavelength of around 400 nm at room temperature were developed by Nakamura in 1996 [9]. Finally, in January 1999 the first commercial violet laser entered the market. More details can be found in ref. [10].

A FINAL REMARK

As has been said, Alfred Nobel would have been quite pleased with the 2015 Physics prize. The invention of the blue LED means a great benefit to mankind, and there are good reasons to think that we are just contemplating the tip of the iceberg. That is definitively in the spirit of Nobel's legacy.

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