Scientific Background on the Nobel Prize in Physics 2014

EFFICIENT BLUE LIGHT-EMITTING DIODES LEADING TO BRIGHT AND ENERGY-SAVING WHITE LIGHT SOURCES

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

Efficient blue light-emitting diodes leading to bright and energy-saving white light sources

Light-emitting diodes (LEDs) are narrow-band light sources based on semiconductor components, with wavelengths ranging from the infrared to the ultraviolet. The first LEDs were studied and constructed during the 1950s and 1960s in several laboratories. They emitted light at different wavelengths, from the infrared to the green. However, emitting blue light proved to be a difficult task, which took three more decades to achieve. It required the development of techniques for the growth of high-quality crystals as well as the ability to control p-doping of semiconductors with high bandgap, which was achieved with gallium-nitride (GaN) only at the end of the 1980s. The development of efficient blue LEDs also required the production of GaN-based alloys with different compositions and their integration into multilayer structures such as heterojunctions and quantum wells.

The invention of efficient blue LEDs has led to white light sources for illumination. When exciting a phosphor material with a blue LED, light is emitted in the green and red spectral ranges, which, combined with the blue light, appears as white. Alternatively, multiple LEDs of complementary colours (red, green and blue) can be used together. Both of these technologies are used in today's high-efficiency white electroluminescent light sources. These light sources, with very long lifetimes, have begun to replace incandescent and fluorescent lamps for general lighting purposes. Since lighting represents 20-30% of our electrical energy consumption, and since these new white light sources require ten times less energy than ordinary light bulbs, the use of efficient blue LEDs leads to significant energy savings, of great benefit to mankind.

This year’s Nobel Prize in Physics honours the inventors of efficient blue LEDs: I. Akasaki, H. Amano and S. Nakamura.

Early history

The first report of electrically generated light by emission from a solid-state device came from H.J. Round working at Marconi Electronics in 1907 [1]. He applied voltage across two contacts on a carborundum (SiC) crystal. At low voltages yellow light was observed, but more colours were emitted at higher voltages. Electroluminescence was also studied by O. Losev (1903-1942), a device physicist in the Soviet Union, who in the 1920s and 1930s published several articles in international journals on electroluminescence from carborundum [2]. These developments took place prior to the formulation of the modern theory of electronic structure of solid-state materials.

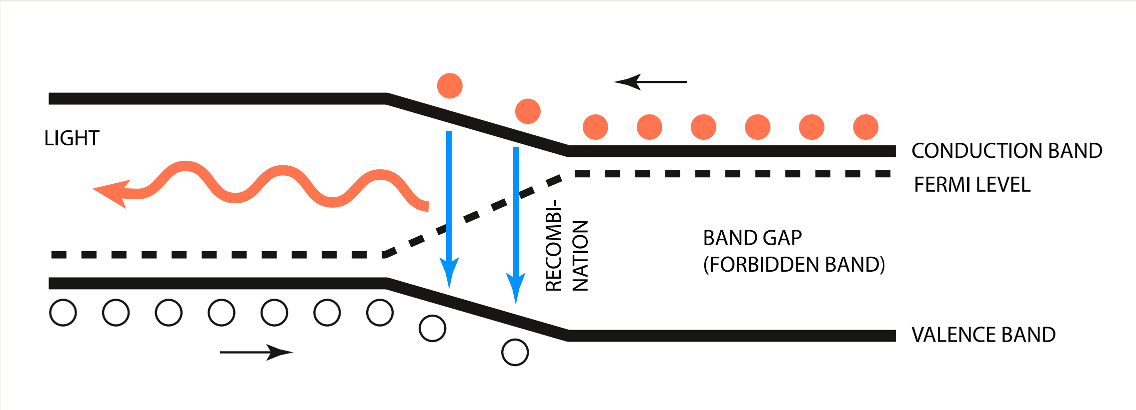

Fig. 1. Principle for light emission in a p-n junction. In a p-n junction biased with a forward voltage, electrons are injected from the n- to the p-side, and holes are injected in the opposite direction. Electrons recombine with holes and light is emitted (spontaneous emission). For efficient diodes it is important that the semi-conductors have direct bandgaps. LEDs with indirect bandgaps require phonon-assisted recombination, which limits the efficiency. The quantum efficiency of a LED is the ratio of the number of emitted photons to the number of electrons passing through the contact in a given time.

The understanding of the physics of semiconductors and p-n junctions progressed during the 1940s, leading to the invention of the transistor at Bell Telephone Laboratories in the USA in 1947 (Nobel Prize 1956 to Shockley, Bardeen and Brattain). It became clear that a p-n junction could be an interesting device for light emission. In 1951, K. Lehovec and co-workers of the Signal Corps Engineering Laboratory in the USA [3] used these ideas to explain the electroluminescence in SiC as resulting from the injection of carriers across a junction followed by radiative recombination of electrons and holes. However, the observed photon energy was less than the energy gap of SiC, and they suggested that radiative recombination was likely to occur due to impurities or lattice defects. In 1955, injection electroluminescence was shown in a number of III-V compounds [4, 5]. In 1955 and 1956, J.R. Haynes at Bell Telephone Laboratories demonstrated that electroluminescence observed in germanium and silicon was due to recombination of holes and electrons in a p-n junction [6] (see Fig. 1).

Infrared LEDs

Techniques to make efficient p-n junctions with GaAs were rapidly developed during the following years. GaAs was attractive because of its direct bandgap, enabling recombination of electrons and holes without involvement of phonons. The bandgap is 1.4 eV corresponding to light in the infrared. In the summer of 1962, the observation of light emission from p-n-junctions was reported [7]. A few months later, laser emission in GaAs at liquid nitrogen temperature (77 K), was demonstrated independently and almost simultaneously by three research groups at General Electric, IBM and the MIT

Lincoln Laboratory, in the U.S. [8-10]. It would be a few years, however, before laser diodes became widely used. Thanks to the development of heterostructures (Nobel Prize 2000 to Z.I. Alferov and H. Kroemer), and later quantum wells, allowing for a better confinement of the carriers while reducing the losses, laser diodes could operate continuously at room temperature, with applications in a large variety of areas.

Visible LEDs

Following early experiments at the end of the 1950s [11], progress in making efficient LEDs using GaP (indirect bandgap equal to 2.2 eV) was made in parallel by three research groups from Philips Central Laboratory in Germany (H.G. Grimmeiss), the Services Electronics Laboratories (SERL) in the UK (J.W. Allen) and Bell telephone laboratories in the USA (M. Gershenzon) [12-14]. They had different objectives, ranging from communication, lighting and television to indicator lamps for electronics and telephones. Using different dopants (*e.g.* Zn-O or N) at various concentrations, different wavelengths were generated ranging from red to green. By the late 1960s a number of manufacturers in different countries were making red and green LEDs based on GaP.

Mixed crystals including Ga, As, and P (GaP_xAs_{1-x}) are interesting since the emission wavelength can be shorter than for GaAs, reaching the visible range while the bandgap is direct for x below 0.45. N. Holonyak Jr. and co-workers at the General Electric laboratory in the USA, began to work with GaP_xAs_{1-x} in the late 1950s, and succeeded in making p-n junctions and observing LED emission. Laser diode emission at 710 nm (red) was reported in 1962 [15].

Early work on blue LEDs

The step to the emission of blue light proved to be considerably more difficult. Early attempts with ZnSe and SiC, with high indirect bandgaps, did not lead to efficient light emission. The material that enabled the development of blue LEDs was GaN (Gallium Nitride).

Gallium Nitride

GaN is a semiconductor of the III-V class, with Wurtzite crystal structure. It can be grown on a substrate of sapphire (Al_2O_3) or SiC, despite the difference in lattice constants. GaN can be doped, *e.g.* with silicon to n-type and with magnesium to p-type. Unfortunately, doping interferes with the growth process so that the GaN becomes fragile. In general, defects in GaN crystals lead to good electron conductivity, *i.e.* the material is naturally of n-type. GaN has a direct bandgap of 3.4 eV, corresponding to a wavelength in the ultraviolet.

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