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An Enhanced Blue Light Emitting Diode

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Abstract : This research produces a highly efficient energy saving electroluminescent enhanced blue light emitting diode.
The fabrication of this enhanced blue LED involves the growth of a complex semiconductor crystal with advanced heterostructure bandgap design and absolute optimization of the light out-coupling to maximize efficiency.
This research discusses innovative ideas which enhance the efficiency of the white light source by critically analyzing the processes involved. It covers the fabrication of blue GaN LED chip, channeled at improving the efficacy of each building block stage from Substrates, Buffers and Epitaxy, to Physics, Processing and Devices, to Lamps, Luminaires and Systems.
Keywords: Light Emitting Diodes; Electroluminescence; Semiconductor Bandgap; Light source; LED fabrication

1. Introduction

The conventional light sources such as arc lamps, high pressure sodium lamps, and other metal halide lamps are not very efficient and generate high radiant heat. The desirable factors considered in choosing light sources for illumination are their savings in energy consumption, reduced pollution, substantial cost savings to consumers, durability, reliability, availability, compactness, digital controllability, output color rendering index, and output spectrum. LED's are preferred as light sources compared to the incandescent lights because they are simpler to drive, more economic, have a longer lifetime, and provides the necessary output power. They are therefore suitable for optical communication although their output spectrum is much wider than that of a laser diode [1]. Light Emitting Diodes are semiconductor photon source which provides highly efficient electronic-to-photonic transducers. They show superiority by virtue of their small size, high brightness, high efficiency, high reliability, ruggedness, and durability [2].

Historically, electrically generated light by emission from a solid-state device came from H.J. Round while working at Marconi Electronics in 1907. He applied voltage across two contacts on a carborundum (SiC) crystal. Also electroluminescence was 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 [3]. These developments took place prior to the formulation of the modern theory of electronic structure of solid-state materials.

Part of the foundation of solid state lighting technology was through the understanding of physics of semiconductors and p-n junctions. This study progressed in the 1940s, and led to the invention of the transistor at Bell Telephone Laboratories in the USA in 1947 [4]. The discovery guided further research on the application of a p-n junction as a device for light emission. K. Lehovec and his research team in the Signal Corps Engineering Laboratory in the USA, leveraged on the previous discoveries to explain the electroluminescence in SiC in 1951. According to K. Lehovec, electroluminescence in SiC occurs as a result of the injection of carriers across a junction followed by radiative recombination of electrons and holes. The observed photon energy was less than the energy gap of SiC, so they suggested that radiative recombination was likely to occur due to impurities or lattice defects [5]. Further investigation in 1955, reveals that injection electroluminescence was shown in a number of III –V binary, ternary, and quaternary compounds such as GaAs, InP, InGaAs, InGaAsP, and InAlGaAs. Although recombination of electron-hole pairs in the elementary semiconductors such as Germanium and Silicon normally leads to the emission of phonons due to lattice vibrations, the bandgap can be modified through the addition of isoelectronic impurities e.g. Nitrogen atoms such that photons are emitted. Consequently 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].

Semiconductors can be classified based on their band gap into two categories namely Direct and Indirect band gap semiconductors as shown in figure 1. In the indirect bandgap semiconductors, the minimum of the conduction band and the maximum of the valence band occur at different crystal momentum termed k values in the Brillouin zone. The elementary semiconductors are examples of indirect bandgap materials. However, in the direct bandgap semiconductor, the minimum of the conduction band and the maximum of the valence band lie at the same k value. A wide range of direct bandgap materials with different absorption/emission wavelengths can be obtained from III-V ternary and quaternary compounds [7].

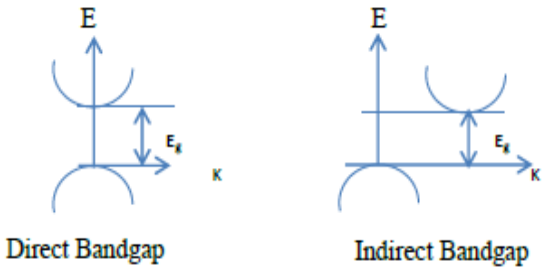

Figure 1. Direct Bandgap and Indirect Bandgap Semiconductors

In 1962, the observation of light emission from p-n junctions was reported. It was discovered that semiconductors with direct bandgap emit photons during electron-hole pair recombination [8]. But for semiconductors with indirect bandgap, the electron-hole pair recombination leads to lattice vibrations with the emission of phonon. Later on, laser emission in GaAs at liquid nitrogen temperature (77K), was experimented by IBM, General Electric

and MIT Lincoln Laboratory [9].

The GaN-based light emitting diode is the best choice for efficient light source. GaN is a semiconductor of the III-V class, with Wurtzite crystal structure. Usually, it is grown on a substrate of sapphire (Al_2O_3) or SiC. Although the substrates have different lattice constants, the Nitrogen acts as isoelectronic impurity. GaN can be doped to p-type with magnesium and can be doped to n-type with silicon. The introduction of impurities by doping GaN creates defects which enhances the electron conductivity. Furthermore, GaN has a direct bandgap of 3.4eV which corresponds to the wavelength of light in the ultraviolet region. The III-nitride (III-N) offers spectra in the ultraviolet region. It has been observed that AIN, GaN, and InN have direct bandgap energies of 6.2, 3.4, and 0.7eV respectively at room temperature [10].

The technology for the fabrication of GaN-based light emitting diodes have evolved and improved since 1950s. At Philips Research Laboratories, H.G. Grimmeiss and H. Koelmans obtained efficient photoluminescence from GaN over a wide spectral range using different activators. In 1960, Hydride Vapour Phase Epitaxy (HVPE) technique was used by growing GaN on a substrate [11].

2. Materials and Methods

One of the major considerations is the fabrication of the p-n junction particularly the active region. The challenge is to p-dope GaN in a relatively controlled process. It was observed that Zn-doped GaN emitted more light and results to a better p-doping. Also Mg-doped GaN when irradiated with low energy electrons emitted more light. It was demonstrated by Nakamura that a simple thermal treatment leads to efficient activation of Mg acceptors [12]. Pankove and G.F. Neumark Rothschild further investigated the effect of hydrogen on the neutralization of dopants. The development of the blue LEDs involves the growth and p-doping of alloys which are used to create heterojunctions such as the ternary AlGaN and InGaN explained previously.

The structure of the Blue LED is as shown in Figure 2 below.

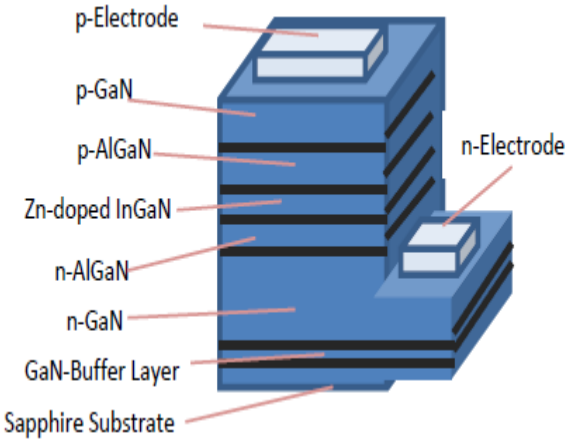

Figure 2. Structure of Blue LED

An injected DC current denoted by *i*, leads to an increase in the steady-state carrier concentrations Δn, which in turn result in radiative recombination in the active-region volume V. The total number of carriers per second passing through the junction region is given by:

i/e, where *e* is the magnitude of the electronic charge. The Rate of carrier injection R representing carriers per second per cm^3 is given by:

$$R = \frac{i/e}{V}$$

Efforts were made to increase the fraction of the electron-hole pair recombination that occurs radiatively by increasing the active region volume [13]. So, the injection of carrier pairs per second leads to the generation of an internal photon flux

denoted by Φ.

$$\Phi = \eta_i \frac{i}{e}$$

Where η_i is the Internal Quantum Efficiency representing the ratio of the generated photon flux to the injected electron flux.

The internal photon flux is enhanced by the multiquantum-well active regions created which engenders higher carrier concentration thus enhances radiative recombination through the reduction of radiative lifetime. Consequently, the internal quantum efficiency η_i is increased. Also in order to maximize the internal quantum efficiency, the heterostructure confinement layers was lattice matched to the active region. Since narrow quantum wells confine carriers more tightly, this idea was deployed to further enhance the internal quantum efficiency [14].

Another very important step applied to maximize efficiency is to control the process by which internal photons can be extracted from the LED structure termed Extraction Efficiency. The photon flux generated in the active junction is radiated uniformly in all directions. Consequently, the flux that emerges from the device depends on the direction of emission. The photon flux traveling in a given direction of ray is attenuated by the factor expressed mathematically as:

$$\eta_1 = \exp(-\alpha l_1)$$

Where α = the absorption coefficient of the n-type material. l_1 = the distance from the junction to the surface of the device [15].

There are other techniques applied to enhance the extraction efficiency of the LED such as selecting a geometry that allows a greater fraction of the light to escape. This is achieved using a spherical dome surrounding a point source at its centre [16]. There are various construction geometries such as hemispherical domes, cylindrical structures, inverted cones, and truncated inverted pyramids. Also extraction efficiency was further enhanced by roughening the planar surface and by imparting a texture to it. The idea is to permit rays beyond the critical angle to escape via scattering rather than reflecting back. As described in figure 2, the extraction efficiency was improved by guiding light to the surface of the device via a 2D photonic crystal comprising a regular array of 100-250-nm diameter holes formed in the current-spreading layer.

The principles guiding the design of the device is based on the relationship between the output photon flux Φ_o which is the external photon flux and the internal photon flux Φ_i expressed as:

$$\Phi_o = \eta_e \Phi_i = \eta_e \eta_i \frac{i}{e}$$

Where η_e and η_i are extraction efficiency and internal efficiency respectively [17:18].

The external efficiency η_{ex} of the LED is the ratio of the external photon flux to the injected electron flux and is related to the output photon flux Φ_o as shown below:

$$\Phi_o = \eta_{ex} \frac{i}{e}$$

Another major consideration in the design of the LED is the Power conversion efficiency η_c or sometimes referred to as Wall-plug efficiency. This is the ratio of the emitted optical power P_o to the applied electrical power. It can be expressed mathematically as:

$$\eta_c \equiv \frac{P_o}{iV} = \eta_{ex} \frac{h\nu}{eV}$$

Where h= Planck's constant, ν is the frequency of

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the photon, energy of photon is *hv*, V is the voltage drop across the device [19].

The Responsivity (R) describing the ratio of the emitted optical power P_o to the injected current *i*, is given as:

$$R = \frac{P_o}{i} = \frac{h\nu\, \Phi_o}{i} = \eta_{ex} \frac{h\nu}{e}$$

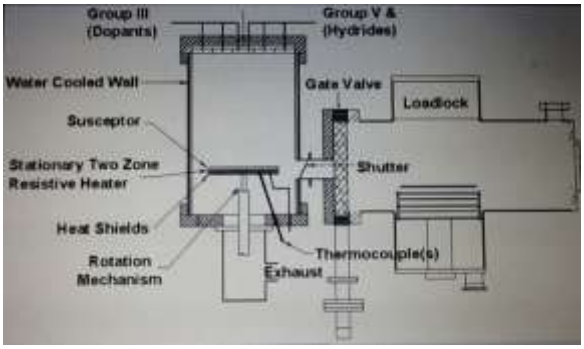

Figure 3. Showing Schematic diagram of Emcore D125 Metal Organic Chemical Vapor Deposition (MOCVD) reactor

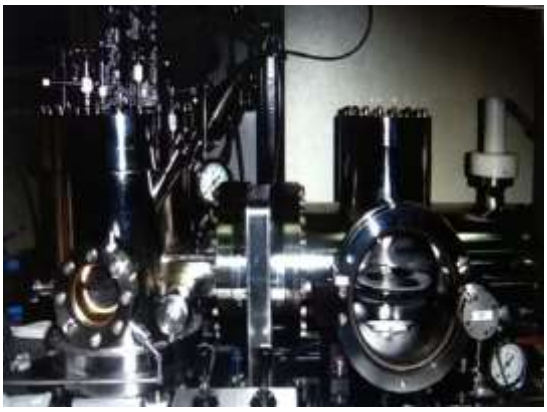

Figure 4. Emcore D125 Metal Organic Chemical Vapor Deposition Growth Chamber

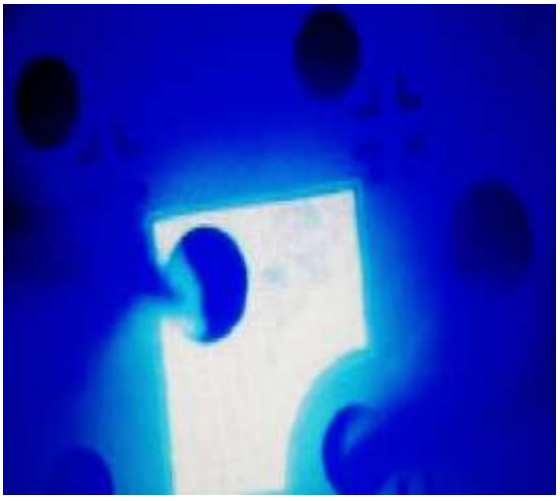

Figure 5. Measurement of the I-V characteristics of the blue light emitted from the fabricated LED

The next consideration of the LED is its apparent color when viewed directly or when illuminating a perfectly white object. This attribute was quantified through use of chromaticity coordinates (x,y) on the Commission Internationale de L'Eclairage (CIE) 1931 [20]. The correlated color temperature is the temperature of the blackbody whose perceived color most resembles that of the light source in reference. In principle the CCT was deduced by constructing "iso-CCT" lines, which intersect the Planckian locus. The correlated color temperature (CCT) together with the color-rendering index (CRI) defines the overall color quality of the light. Color rendering ability of the fabricated Blue LED demonstrated the ability to faithfully render the colors of non-white objects that it illuminates. The quantitative measure of the faithfulness of color rendering is the Color Rendering Index [21].

Furthermore, the higher the input power density the more lumens can be created per cm^2 of semiconductor chip. Consequently the limits on input power density depend on the ability to extract heat from the chip and phosphor, and on the ability of chip and phosphor to maintain their conversion efficiencies at high operating temperatures [22].

In this research, all the samples were grown by MOCVD using the EMCORE D125 vertical geometry as shown in figure 4. This rotating disc reactor offers enhanced capabilities by using 6 hydride sources for group V and dopant precursors and 10 metal-organic sources for group III and dopant precursors [23]. Also it has in-situ optical

reflectance monitoring, a non-contact optical thin film thickness measurement. The MOCVD EMCORE D125 is an optimization tool in the growth of GaN-based structures. The growth of the samples was done in stages for proper monitoring of the crystallographic orientation. First, the samples used were grown on quarters of 2-inch diameter (0001)- orientation (c-plane) sapphire substrates. The chamber pressure was controlled at 100-300 Torr. Aluminum, gallium, indium and nitrogen sources were substituted with Trimethylaluminum (TMAI), trimethylgallium (TMGa), trimethylindium (TMIn) and ammonia (NH_3) respectively, for enhanced performance. The p-type doping source consists of Biscyclopentadienyl magnesium (CP_2Mg) while the n-type doping source consists of disilane (Si_2H_6). In order to remove impurities, the substrates were cleaned by a H_2SO_4:H_2O_2 (3:1) solution for 15mins, then etched in 2% HF solution and rinsed in deionized water, followed by N_2 blow-drying. Next after loading, an in-situ thermal cleaning procedure was applied to the sapphire substrates for 12mins at 1080^{o}C under H_2 ambient to remove native oxide from the substrate surfaces. The samples are allowed to cool down from the thermal cleaning step and then a GaN buffer layer of 35nm was deposited at 525^{o}C. Then the temperature was elevated to 1025^{o}C to grow a 1µm thick Si-doped, n-type GaN layer. After that, the substrate temperature was ramped down to grow the InGaN well layer at 717^{o}C and grow the GaN barrier layer at 845^{o}C.

In the active region of the InGaN/GaN Multi-Quantum well, are three pairs of 5nm thick $In_{0.4}Ga_{0.6}N$-well layers and 10nm thick GaN-barrier layers all in the structure. A 30nm GaN cap layer was then grown on the multi-quantum wells and the substrate temperature was elevated to 730^{o}C to grow a 250nm thick Mg-doped p-type GaN layer. The LED structure was then grown on the sapphire substrate as shown on Figure 2. During the growth phase, nitrogen was used as a carrier gas while growing the InGaN multiple Quantum well to increase the indium incorporation rate [24]. Next, the samples were annealed at 735^{o}C for 40mins in N_2 ambient to activate the Mg-doped p type GaN layers. With the aid of a reflectometer the growth was controlled in-situ at a laser wavelength of 635nm [25].

The fabrication of the InGaN/GaN multi-quantum well was achieved using an inductively coupled plasma (ICP) of Unanix SLR-7701-8R system for etching mesa for n-contact and E-beam Evaporator of Auto 306 system for metallization of the p-n electrode. The surface of the as-grown samples was partially etched by this ICP system until the n-type GaN layer was exposed for n-type ohmic contact after the annealing process. The target ideal depth etch was 700nm within 160s [26:27:28].

Ni/Au (5nm/5nm) contacts were subsequently evaporated onto the p-type GaN layer to serve as the semi-transparent metal ohmic contact to enhance the holes carrier migration rate. A p-layer was made by depositing a 205nm Au contact on top of the semi-transparent layer [29]. Also the n-type electrode was made by depositing Ti/Al/Ni/Au (10nm/200nm/30nm/100nm) contacts onto the exposed n-type GaN layer. The electrodes are shown in figure 2.

3. RESULT AND DISCUSSIONS

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Measurements of the current-voltage (I-V) characteristics, luminous intensity and wavelength of the fabricated blue LED chip were measured with an LED chip tester. The LED was coated with suitable Phosphor chemicals to produce white light. It was challenging to find phosphors with high quantum efficiencies and long lives at high temperatures. Therefore, some degree of thermal management was done to keep the phosphor somewhat cooler than the chip.

The Room temperature electroluminescence measurement of the fabricated LED chips is as shown in figure 6.

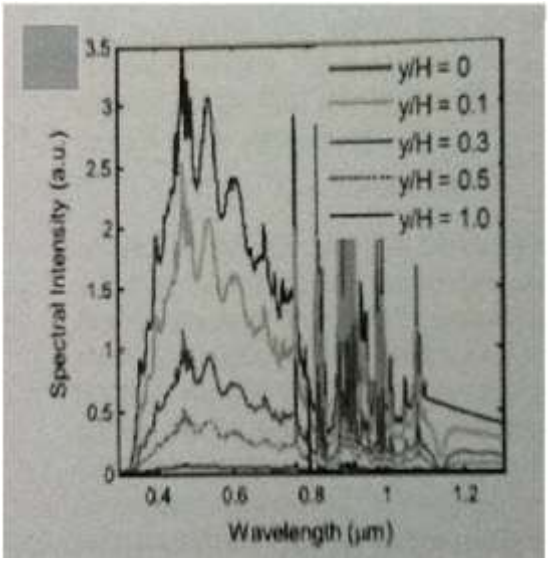

Figure 6. Graph plot of Electroluminescence

4. CONCLUSION

A highly efficient energy saving electroluminescent white light using enhanced blue light emitting diode has been fabricated. The efficiency was improved using MOCVD to grow multilayers of nanometer thickness Nitride films on a Sapphire substrate. The emphasis is on the photolithographic technic applied to achieve LED device that emitted blue light with a luminous intensity of 85mcd when measured with a current of 20mA.

Nanocrystalline phosphors were used to minimize optical scattering associated with Mie Scattering. Hermetic packages with very high index of refraction and excellent stability in presence of high intensity light, humidity and high temperature were used to enhance the efficiency of this device.

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