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HIGH-BRIGHTNESS VISIBLE LEDS

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18.1 INTRODUCTION

Over the past decade a transformation in light emitting diode (LED) application has occurred from indicator use to the more demanding solid-state lighting and illumination markets. This includes areas such as backlighting in consumer hand-held products, outdoor displays, traffic signals, and general room lighting through the replacement of incandescent and fluorescent light sources. This transformation has been driven directly by the significant increases in LED efficiency that has enabled LEDs to penetrate into such markets. These new high-efficiency LEDs are typically referred to as high-brightness LEDs (HB-LEDs), and utilize quantum well active regions to achieve their high efficiency and lumen output.

Quantum well-active regions can have either a single quantum well (SQW) or multiple quantum well (MQW) structure, reducing internal reabsorption and increasing the radiative recombination rate of the device through greater spatial overlap of electrons and holes. A discussion of quantum wells can be found in Chap. 19, "Semiconductor Lasers." Figure 1 provides a basic structure for a modern HB-LED. It is similar to the DH structure, but utilizes a MQW active region between the *n* and *p*-type layers of the device, composed of quantum wells (QWs) that are on the order of a few nanometers in thickness. By adjusting either the composition or width of the QW, the emission wavelength of the LED can be tuned. The use of QW active regions in LEDs has not only allowed for an increase in the efficiency of the devices, it has also resulted in the ability to obtain new wavelength emissions that were not previously available due to epitaxial strain and lattice matching constraints.

18.2 THE MATERIALS SYSTEMS

There are two main semiconductor material systems currently exploited for visible HB-LEDs. These are the AlInGaP and AlInGaN systems. A detailed discussion of the AlInGaP system is in Chap. 17, "Light-Emitting Diodes." AlInGaP is used for amber and red LEDs that fall within the 590- to 650-nm wavelength region. It is limited to this wavelength range because the AlInGaP quaternary shifts to an indirect band gap as wavelengths below 590 nm are targeted. This left a void in the blue and green spectral regions for visible HB-LEDs.

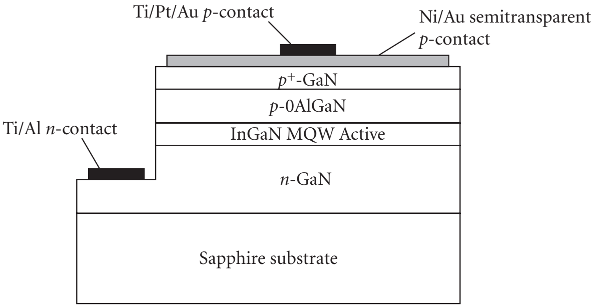

FIGURE 1 Typical structure for a modern InGaN HB-LED showing associated epitaxial layers, including the multiquantum well (MQW) active region.

In the past decade, this void has been quickly filled with MQW LEDs made from the AlInGaN material system. GaN has a wurtzite crystal structure and band gap at room temperature of about 3.2 eV (385 nm). By alloying with Al or In, the band gap can be shifted to shorter or longer wavelengths, respectively. This has led to the realization of InGaN QW active regions in HB-LEDs offering light output in the blue to green spectral regions. Although InN has a direct energy gap of 0.7 eV, phase segregation in InGaN alloys limits the ability to obtain active regions emitting at wavelengths above 530 nm. Despite this, InGaN QW active regions have successfully been used to create blue and green HB-LEDs with complete wavelength tunability across the visible 400- to 530-nm range.

18.3 SUBSTRATES AND EPITAXIAL GROWTH

Current AlInGaN HB-LEDs use one of two substrates: sapphire or silicon carbide (SiC). Despite considerable lattice mismatch between these and GaN (roughly 16 percent for sapphire and 3.5 percent for SiC), low-temperature buffer layer technologies have been developed to allow for nucleation and growth of high-quality AlInGaN HB-LEDs. Low-temperature AlN buffer layers on sapphire substrates are directly formed by MOCVD that result in dislocation entanglement just above the nucleation interface. As depicted in Fig. 2, many of the dislocations interact and annihilate. The subsequent growth of a thick (typically 3 to 4 μm) *n*-GaN buffer layer further reduces dislocation density below 10^9 per cm^2. The use of 6H-SiC substrates offers closer lattice matching and lower defect densities, although this comes with a higher cost that has kept sapphire as a more popular substrate solution. Recent research has aimed to produce native or lattice-matched substrate solutions for GaN growth. Native GaN substrates have been produced, although the diameter of such substrates and cost remain a challenge. A sister wide band gap compound, ZnO, has strikingly similar properties

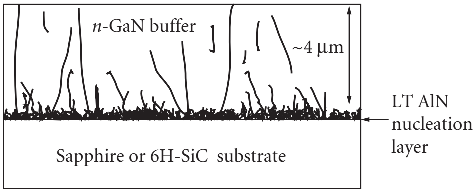

FIGURE 2 Cross-section schematic of the dislocation reduction that occurs due to use of a low temperature (LT) AlN nucleation layer. Dislocations originate from the large lattice mismatch of the nitrides with SiC or sapphire substrates, but can be reduced well below $10^9/cm^2$ when a LT-AlN nucleation layer and thick GaN buffer layer are used.

to GaN and is currently considered a good candidate for a lattice matched substrate for AlInGaN HB-LED growth. ZnO has the same wurtzite crystal structure as GaN, is nearly lattice matched to GaN, and can be easily doped *n*-type to form a conductive substrate. Lattice matched substrates made from ZnO have just become commercially available through hydrothermal growth.

Growth of AlInGaN HB-LEDs is accomplished commercially with MOCVD (a short discussion of MOCVD was provided in Sec. 17.8 in Chap. 17). While high quality growth of AlInGaN epitaxial films has been demonstrated by MBE, typical HB-LED structures require 4- to 5-μm-thick films that are not economically realizable in MBE systems due to the slow growth rate and limited number of substrates per growth. MOCVD reactors are able to accommodate multiple 2″ substrates per growth (as many as 40 in larger systems) with the necessary uniformity and control of film thickness. One of the initial challenges in AlInGaN HB-LED growth was *p*-type doping of GaN. The metal-organic precursor sources of MOCVD introduce a considerable amount of hydrogen into the films that directly compensates *p*-type acceptors. This issue was resolved through post-growth annealing at temperatures above 800°C in which the excess hydrogen is driven out of the epitaxial films. Upon out-diffusion of the hydrogen, the *p*-type acceptors become active and the necessary hole injection into the structures is then possible.

18.4 PROCESSING

Many of the steps covered in Sec. 17.9 of Chap. 17 are used in the fabrication of HB-LED epitaxial wafers. Sapphire substrates are electrically insulating, imposing the need for creating both *n*- and *p*-type contacts on the front of the HB-LED surface as was shown in Fig. 1. As a result, the epitaxial structure must be etched down to the *n*-GaN layer in order to make electrical contact to the *n*-side of the HB-LED structure. AlInGaN is relatively resistant to wet chemical etching and must be dry etched using reactive ion etching (RIE) or inductively coupled plasma (ICP) methods. RIE/ICP is capable of high etch rates that are anisotropic, meaning that they are capable of etching vertically down into the structure with little to no lateral etching. SiC substrates are electrically conductive and thus allow for the *n*-contact to be formed on the back side of the substrate without the need for etching of the front surface.

The typical fabrication process for AlInGaN HB-LEDs utilizes four lithographic steps. These include the mesa etch, SiO_2 passivation, *n*-contact, and *p*-contact layers. A top view and associated cross section of a standard HB-LED device are given in Fig. 3, indicating these layers. Prior to the

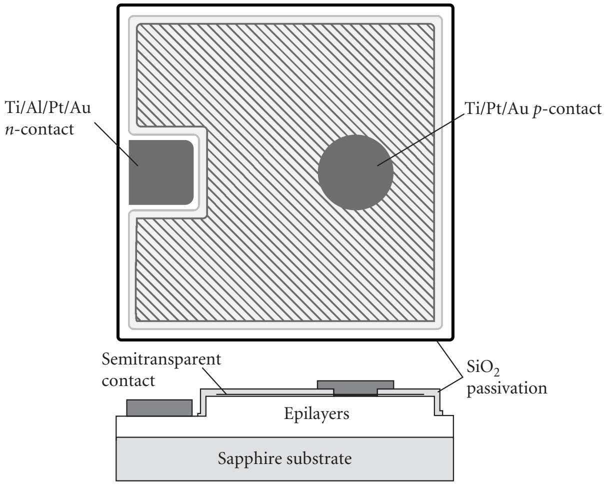

FIGURE 3 Top view and cross-section schematic of a standard nitride HB-LED. A mesa is etched to allow for contact to the *n*-type underlayer. A semitransparent contact on top of the mesa is used to promote uniform hole injection due to poor hole mobility in the *p*-GaN.

first lithographic step a semitransparent top contact is deposited on the surface (*p*-side) of the entire epi wafer. This is necessary in order to achieve uniform current injection across the device due to the higher resistivity of the *p*-GaN in comparison to the *n*-GaN. The most common semitransparent contacts are Ni/Au and indium tin oxide (ITO), with Ni/Au being the most widely used. Once the semitransparent contact is formed the lithographic steps are then carried out. The mesa etch is a dry etch step to access the *n*-GaN layers for the *n*-type contact as required when using sapphire substrates. The SiO_2 passivation step covers the side walls of the mesa and protects its lateral edges. Once the passivation is in place, the last two lithographic steps define the *n*- and *p*-type contacts to the device through a lift-off process. Common metallizations are Ti/Al/Pt/Au for the *n*-contact and Ti/Pt/Au for the *p*-contact to the semitransparent contact underlayer. To separate the individual LEDs on the fabricated wafer, the substrate must first be thinned from its typical 400 µm thickness to on the order of 80 to 100 µm using a multiple step wafer polishing method on automated multiwafer polishers. Once thinned, singulation of the individual die is accomplished either by a scribe and break method or by using laser separation. The sawing method typically employed for other III–V LEDs is not possible due to the substantial hardness of sapphire and SiC that greatly limits their ability to be cut using a dicing saw.

18.5 SOLID-STATE LIGHTING

The current push towards energy conservation has created a considerable interest in the replacement of conventional lighting by solid-state LED fixtures. LEDs offer the potential to considerably reduce power consumption while maintaining the necessary lumen output for lighting. Generating white light from HB-LEDs is typically accomplished by one of two methods as depicted in Fig. 4. The first method, shown in Figs. 4*a* and *b*, utilizes an AlInGaN-LED in conjunction with one or more phosphors. When a UV-LED is used, the UV light emission is absorbed and re-emitted by a mixture of red, green, and blue phosphors. As indicated in Fig. 4*a* the phosphors down-convert the UV light (dashed line) to visible light (solid line), and when the appropriate ratio of phosphors is used, white light is emitted. A more common LED/phosphor combination used for general illumination is the combination of a blue (~465 nm) AlInGaN-LED and a yttrium aluminum garnet (YAG) phosphor such as cerium doped $Y_3Al_5O_{12}$. In this approach (Fig. 4*b*) a portion of the blue LED emission is absorbed by the YAG phosphor and down-converted to the yellow spectral region. When the proper ratio of YAG phosphor is used, the resulting binary complimentary output of the blue LED and yellow YAG phosphor creates white light as perceived by observers. The second method for white light emission is preferred when color tuning is necessary, such as in outdoor displays. As indicated in Fig. 4*c*, by using red, green, and blue LEDs, one can create white light when the appropriate ratio of each is selected. This RGB approach has the added benefit of allowing the user to create any color within the associated color gamut by balancing the ratio of the individual LEDs.

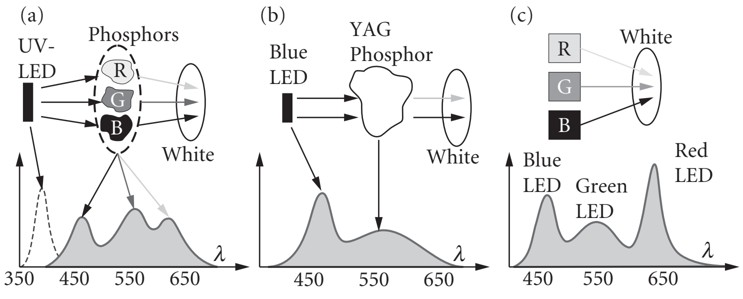

FIGURE 4 Methods for white light generation using HB-LEDs. White light is achieved by using a HB-LED and phosphors (*a* and *b*), or the combination of a red, green, and blue HB-LED (*c*).

This method also allows for active adjustment of the color temperature of white light emission which is not possible using the LED/phosphor approach.

The primary figure of merit for solid-state lighting is the luminous efficacy of the fixture. Luminous efficacy refers to the ratio of lumen output from the source to the power input, and has the units of lumens per Watt (lm/W). Conventional incandescent and fluorescent lights have typical luminous efficacies of 15 lm/W and 70 lm/W, respectively, varying somewhat depending on manufacturer. As of early 2008, currently available LED-based replacements have luminous efficacies as high as 80 lm/W, exceeding compact fluorescents. By comparison, lab demonstrations of white LEDs are commonly breaking 120 lm/W, with the expectation of reaching 150 lm/W in the near future. Despite these accomplishments the added cost of solid-state white lighting has slowed the market acceptance. A common cost comparison is the first cost of a light source, typically measured in terms of the cost per kilolumen (klm). Incandescent and fluorescent light sources fall in the $0.5 to $3.00 per klm, while current light emitting diode sources fall easily in the $20 to $30 per klm range. Considerable progress in efficiency continues to climb and it is expected that as the luminous efficacy and lifetime of solid-state white LEDs continues to rise that the cost per kilolumen will decrease while market acceptance increases.

18.6 PACKAGING

HB-LEDs chips for standard current use (20 to 70 mA) have lateral geometries on the order of $350 \times 350\ \mu m^2$. Such LED chips are commonly packaged similarly to IR-LEDs in a 5-mm T1-3/4 format, as shown in Figs. 21 and 22 in Chap. 17. For AlInGaP HB-LEDs the substrate is conductive and silver filled epoxy is used for attaching the die to the lead frame to form one of the contacts. The other contact is formed using standard ball wire bonding to the top of the LED chip. For AlInGaN HB-LEDs, commonly grown on insulating sapphire substrates, two wire bonds are required to make the electrical connections to the lead frame. Silver-filled epoxy is still used for such LEDs since the sapphire is transparent and emission can be effectively redirected upward from the epoxy surface below the chip. In addition to the 5-mm T1-3/4 package, a considerable number of new surface mount device (SMD) packages have become available to support the introduction of HB-LEDs into the consumer hand-held device market. A schematic of a typical SMD package is provided in Fig. 5. The LED is placed on a metal lead frame that is encased in a plastic outer shell. Once the HB-LED has been die bonded into the package with silver-filled epoxy, it is then wire bonded and encapsulated with transparent epoxy for protection. Such SMD packages are typically several millimeters on a side; however, smaller versions with formats nearly identical to chip resistors are available that have

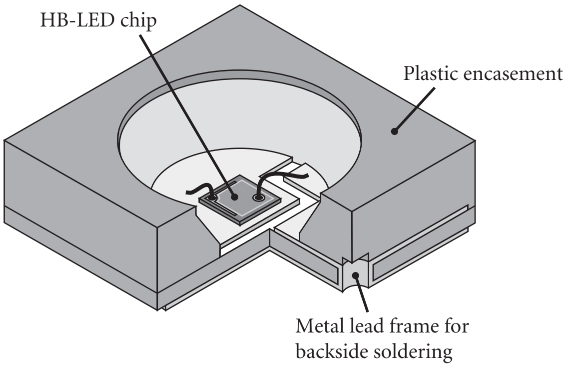

FIGURE 5 Schematic of a standard surface mount device (SMD) package for HB-LEDs.

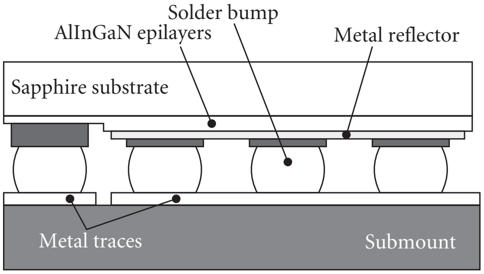

FIGURE 6 Cross-section schematic of the flip chip geometry used for high-power nitride LEDs. Flip chip packaging allows for increased heat dissipation from the LED junction, enabling them to be driven at much higher current densities.

very small form factors providing the low profile necessary for applications such as cell phone key pad backlighting.

In recent years the push for solid-state white lighting has resulted in a transition to larger HB-LED chip sizes and an increase in the operating current densities. The latter brings new constraints to packaging due to the increased need for thermal management in an effort to keep the junction temperature of the HB-LED as low as possible. While the traditional packaging formats have proven very effective for standard drive current use, they are not suitable for high drive current applications using large area HB-LEDs since they do not provide adequate thermal management. This has forced a significant change in not only the design of packaging for high drive current, large area HB-LEDs, but also the devices themselves. Most HB-LEDs use sapphire substrates that provide very poor heat dissipation from the LED junction due to the low thermal conductivity of sapphire. This has been overcome by using a flip chip approach, where the LED chip is flipped over onto a carrier and attached using solder bump methods similar to the silicon IC industry. A rough schematic of a flip chip geometry is shown in Fig. 6. The HB-LED chip is designed to support multiple solder bump attachments to the submount. A highly reflective metal layer is formed on the *p*-side of the device to redirect light emission through the backside of the device. The solder bumps affix the LED die firmly to the submount and create the electrical connections to the metal traces below, allowing for subsequent wire bonding between the submount and the external leads of the package. The solder bumps also serve as a route for efficient heat transfer from the LED junction to the submount enabling the junction temperature of the LED chip to remain low under high drive current conditions. There are a variety of external package geometries that have been developed to support flip chip HB-LEDs with no specific convention between manufacturers. Among the main considerations in the package design has been the encapsulant around the LED and providing a low thermal resistance path to the external housing. Standard clear epoxies that are used in conventional packages typically cannot withstand temperatures much above 100°C. In flip chip high drive packages this can be easily exceeded and would cause thermal damage to conventional epoxies. This has led many companies to develop a variety of new high-index encapsulants, such as silicones, that are able to withstand the higher temperature demands of high drive solid-state lighting. Low thermal resistance packaging has also followed many new routes such as packages with copper tungsten metal bases, metal core board, and high thermal conducting insulating materials (e.g., BeO and AlN).