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Development of Dual MQW Region LEDs for General Illumination

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ABSTRACT

Dual Multi-Quantum Well (MQW) region light emitting diodes (LEDs) for efficient pumping of multiple phosphors have been grown by Metal Organic Chemical Vapor Deposition (MOCVD), for use in broadband, white solid state light sources. Blue (460 nm) and Violet/UV (~400-420 nm) emitting MQW regions were incorporated into one device and show recombination mechanisms similar to single MQW region devices. The introduction of a decoupling region successfully separated the electroluminescent emissions, and two distinct emission peaks were observed. These devices can be used to pump a variety of phosphors designed for blue and UV sources, allowing for more design flexibility in color rendering and color temperature attributes of solid state light sources.

INTRODUCTION

Significant penetration of solid state lighting into the general illumination market depends on the development of high quality white sources retaining the efficiencies seen in current LEDs. In particular, Gallium Nitride (GaN)-based materials have become very important for many optoelectronic applications, with the development of new illumination sources based on LEDs [1]. GaN-based LEDs have fueled a revolution in the lighting industry called Solid State Lighting (SSL). SSL is prevalent in markets such as traffic signals, large area displays, signage, and backlighting. Low cost, high efficiency, high flux, and good quality white light are required attributes for a new general illumination source to become prevalent.

High quality, white solid state light sources have not been widely realized while preserving efficiency and flux seen in first generation white LED sources. White LED sources can be created by a range of methods including red-green-blue (RGB) discrete LEDs and proper color mixing, and LED pumped-phosphor sources. High quality white light should have a high color rendering capability with the ability to achieve a range of desired correlated color temperatures. First generation white LEDs employing a blue LED pump and an yttrium aluminum garnet (YAG) phosphor emitting in the yellow region of the spectrum have shown high flux but lack good color rendering and low

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correlated color temperatures. However, broadband white LED sources using different pumps and phosphors can achieve high color rendering with desired correlated color temperature by adding more colors (wavelengths) to the emission spectrum.

This work describes the development of a dual wavelength emitting LED combining blue (~460 nm) and near-ultraviolet (UV) (~400-420 nm) wavelengths. Two pump wavelengths can achieve greater efficiency and flexibility in phosphor pumping than a single wavelength. YAG:Ce phosphors are not strongly excited by 370-420 nm light[2] , as shown in Figure 1. This characteristic allows for separately pumped phosphors with a dual wavelength device. Blue LEDs provide light in the visible spectrum as well as pumping phosphors emitting at longer wavelengths. In addition, blue LEDs allow for the smallest Stokes shift for visible emitting phosphors, reducing the gap in the spectra between the pump and phosphor. On the other hand, a wider range of phosphors can be pumped by a Violet/UV LED, allowing for more tailoring of the spectrum. An LED emitting in the blue and Violet/UV regions can take advantage of the benefits of both pump wavelengths. Blue and Violet/UV LEDs are also popular sources because they are the highest flux and highest efficiency GaN-based devices.

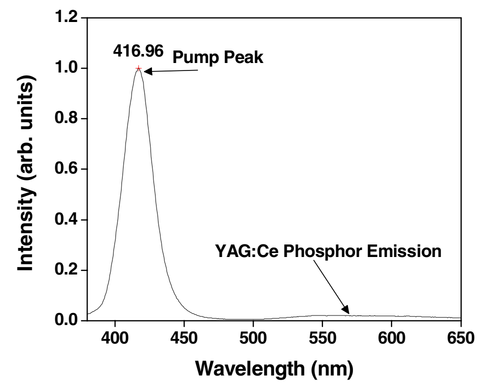

Figure 1. Excitation of YAG:Ce phosphor with LED emitting at 417 nm.

A large factor in the efficient radiative recombination in these devices is the localization of carriers by indium compositional fluctuations in the InGaN quantum wells. Photoluminescence measurements were carried out to determine the physical mechanism behind light emission in these devices. Optical recombination in low-dimensional InGaN quantum structures strongly depends on the localization of carriers in quantum dot-like structures [3, 4, 5, 6]. Inhomogeneities in the indium concentration on the nm-scale provide potential fluctuations in the band gap, and the carriers are trapped in islands that may provide 3D-quantisation up to elevated temperatures [5]. An increased overlap of hole and electron wave functions is induced by the localization of carriers in the nanoscale islands. The average localization energies were determined by an Arrhenius plot of the luminescence intensity following the approach suggested by Adelmann et al [7]. The two activation processes are necessary to describe the data in both low and high temperature regimes.

EXPERIMENTAL DETAILS

A series of LEDs were grown, fabricated and characterized by photoluminescence (PL) and electroluminescence (EL). The LEDs were grown using a Veeco Discovery series D-125 GaN MOCVD tool with a vertical injection, confined inlet design. Trimethyl-gallium, triethyl-gallium, thrimethyl-indium, and thrimethyl-aluminum were used for group III metals and ammonia for group V. P-type doping was achieved with magnesium incorporation from bis-cyclopentyldienyl magnesium (Cp_2Mg), and n-type doping with silicon incorporation from silane (SiH_4).

All the LEDs in this work consisted of InGaN/GaN quantum wells in the active region. The emission wavelength was controlled by changing the growth temperature of the wells, which affected the growth rate and the indium incorporation. The barrier was grown in two stages; the first stage was grown without hydrogen and the second stage was grown with hydrogen and at a higher temperature and rate than the first stage. Multiple growths were completed to optimize the growth rate of the well and the two stage barrier.

A series of systematic growth runs were completed at various temperatures to better understand the effects of temperature on the indium incorporation in the quantum wells. Active regions were developed specifically for 460 and 400-420 nm emission. X-ray diffraction and structure simulation were used to study changes in the indium concentration with respect to the growth temperature and the thickness of the wells against the emitted and PL wavelength.

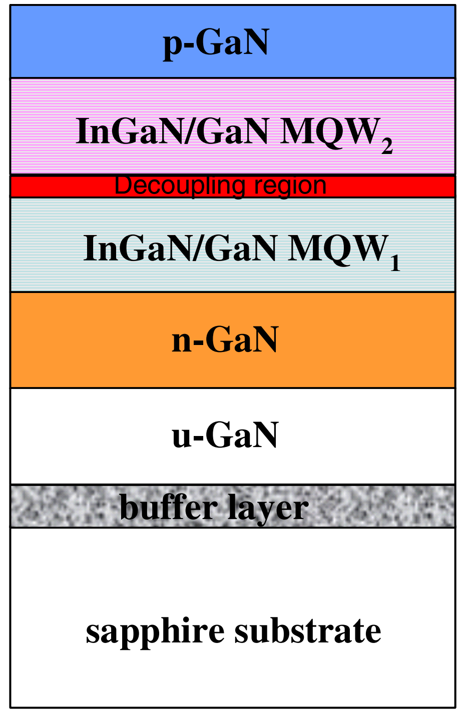

Figure 2. Schematic of dual MQW region device.

Next, a series of devices containing a 460 and a 400-420 nm set of multi-quantum well regions, a dual MQW region structure, separated by an undoped decoupling region was grown as shown schematically in Figure 2. The dual MQW region emitter incorporated the optimized MQW growth conditions for the respective emission wavelengths. The device structure development focused on the 3 layers shown below:

1. First set of MQW (460 nm)
2. Decoupling layer between the two MQWs
3. Second set of MQW (400-420 nm)

The 460 nm MQW was placed at the bottom so that it does not reabsorb the emission from the 400-420 nm MQW. A decoupling layer was introduced between the two MQWs to mitigate interaction between them. The two respective MQWs were split into three growth stages, the well and a two stage barrier. As discussed above, temperature was used to vary the indium incorporation into the well to control the desired emission wavelengths. During device optimization it was determined that varying well and barrier thickness and different growth temperatures were the best approach for the two sets of MQWs.

Thin and thick undoped GaN, n-type GaN and low aluminum concentration GaN layers were studied for the decoupling layer at both low (below 800ºC) and high (above 900ºC) temperature growths. In addition, different precursors for gallium (TMGa and TEGa) were evaluated to optimize the interface layer.

Following growth, the LEDs were annealed in a Rapid Thermal Annealer (RTA) at 800 °C for 4 minutes under N_2 ambient. Then, diodes were fabricated using photolithographic techniques, electron beam evaporated contacts, and inductively coupled plasma (ICP) etched mesas. The top of the mesa was covered with a semitransparent Ni/Au layer to support more uniform current spreading in the p-type GaN. A thicker Ni/Au layer was used as a bonding pad for the p-type contacts, and Ti/Al/Ti/Au bonding pads were deposited for the n-type contacts. Die size is ~350 μm and a typical device is shown in Figure 3.

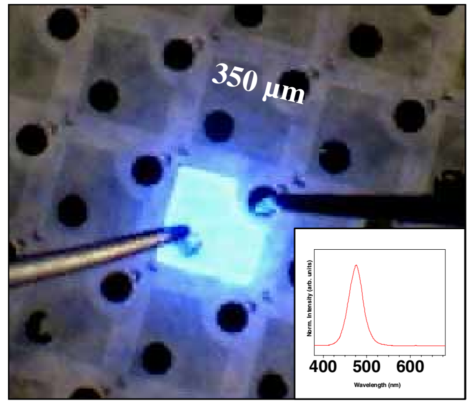

Figure 3. Photograph of EL from blue LED showing 350 μm die size.

An Optronic Laboratories OL770-LED spectroradiometer was used for all EL measurements. This work only considered the relative spectral content of the LED emission, and not the total radiant flux. EL was measured by fixing a fiber optic cable, coupled to the spectroradiometer, above the device.

Temperature dependent PL measurements were performed using a micro cryostat in a temperature range between 4 K and 293 K. The luminescence was excited by the single harmonic generation (SHG) of a Titanium sapphire laser at 354 nm. The 351 nm emission line of a XeF excimer laser was applied allowing the variation of the excitation density between 1 kW/cm^{-2} and 20 MW/cm^{-2}. The sample was kept in a liquid helium cryostat at 2 K for these measurements. The spectral resolution of the PL investigations was better than 0.05 nm.

RESULTS and DISCUSSION

A bright quantum well emission dominated the PL of all samples. Temperature dependent PL data for a blue emitter is shown in Figure 4. Similar results were obtained for the UV emitter (not shown here). A significant S-shape behavior of peak energy, which indicates the presence of QD-like potential fluctuations, is revealed by temperature dependent PL measurements for low excitation energies (Figure 4). Evaluation of MQW emission determines the activation energies to be $E_{act.}(1) = 4$ meV

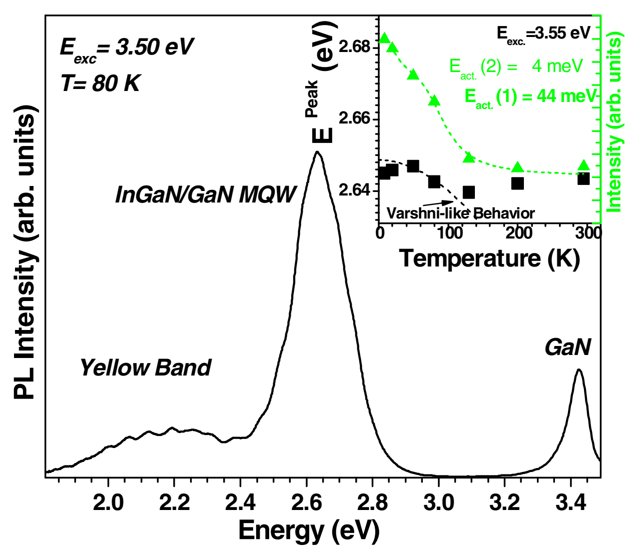

Figure 4. Temperature Dependent PL data for blue emitter. Inset shows peak position and intensity as a function of the temperature facilitating the determination of activation energies of 4 meV and 44 meV (after [6]).

and $E_{act.}(2) = 44$ meV following the approach suggested by Adelmann et al. [7] ($I = C[1+A\exp(-E_1/kT)+B\exp(E_2/kT)]^{-1}$). Here, k is the Boltzmann factor, and A and B are scaling factors. The scaling factor of the latter process is more than 200 times larger than the first. Interface roughness and/or one monolayer fluctuations of the QW thickness typically provide localization centers with localization energies below 5 meV. Therefore, the smaller energy can be attributed to imperfections of the interfaces in the MQW. A more thermally stable localization is indicated by the second $E_{act.} = 44$ meV. It is assigned to the localization of carriers in nanoscale islands caused by fluctuations in the indium concentration.

Site selective PL spectroscopy was also performed on the dual MQW device, shown in Figure 5a. For each peak a mobility edge can be determined: 2.94 for the blue emission and 3.08 for the UV emission. This indicates the existence of isolated localization sites on the low-energy side of the mobility edges, confirming the radiative recombination in the device is generated in zero dimensional centers. Hence, the dual MQW devices show the same emission mechanism as detected for each single MQW devices.

Bright electroluminescence was also observed from the devices. A blue device under the probe station is shown in Figure 3. The EL data for dual MQW region device is shown in Figure 5b. Two distinct peaks are observed in the dual MQW region device, showing separate luminescence from each of the MQWs. Similar results are observed for devices with 400 nm and 460 nm peaks.

The enabling light emission mechanism in GaN-based LEDs with a single MQW region, namely carrier localization [8], has been successfully employed in a device with dual MQW regions tailored to emit in the blue and near UV regions of the spectrum. This was important to preserve the same high brightness characteristics from standard GaN LEDs to the new device. Temperature and excitation energy dependent PL measurements confirmed the existence of carrier localization first in the single MQW region devices and then in the dual MQW region devices.

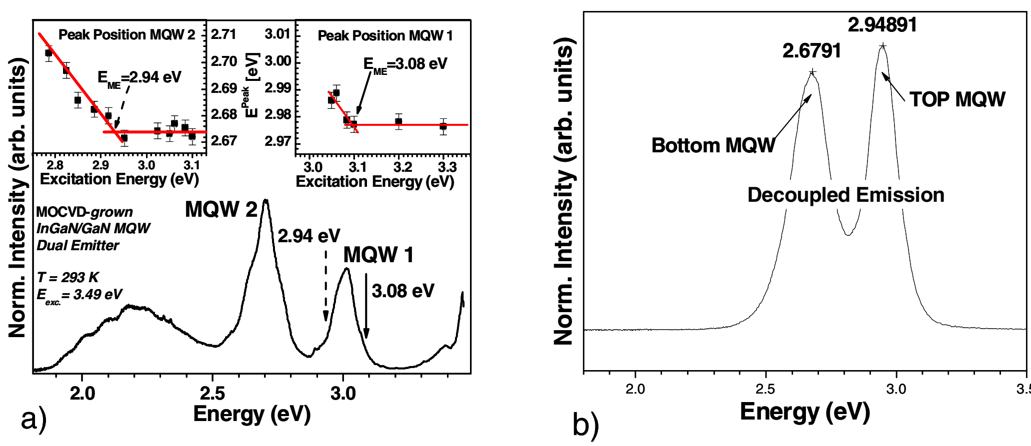

Figure 5. a) Excitation Dependent PL data for dual MQW region emitter. Insets show the peak maximum position of each MQW emission band as a function of excitation energy (site-selective spectroscopy) providing mobility edges of 2.94 eV and 3.08 eV for blue and UV peaks, respectively. b) EL data from dual MQW region device showing distinct peaks.

Bright emission derived from the carrier localization is also seen in EL. Two separate peaks appearing as superimposed LED emission spectra confirm the success of the decoupling region in the device. Decoupling of the active regions is an important factor in controlling the emission characteristics of the MQW regions.

Future work will incorporate optimized phosphors with the dual MQW region devices to achieve bright and high quality white light. Also, the addition of a tunnel junction [9] to these devices will allow for separate control of emission intensity from each MQW region and thus engineering the color temperature of white light.

CONCLUSION

The success of solid state lighting in the general illumination market depends on the development of high quality, white LED-based sources with improved flux and efficiency characteristics. LED-pumped phosphor devices can produce white light with a broad spectrum that is more similar to daylight than white light comprised of discrete LEDs. A dual MQW region device has been developed that can efficiently pump multiple phosphors using blue and Violet/UV QW emission. Such devices not only provide broadband white light but do not encounter light mixing issues faced by arrays of discrete LEDs used for white devices.

The success of new devices also depends leveraging current techniques for high performance; for example, current blue to near UV LEDs rely on compositional fluctuations to localize carriers and augment radiative recombination. PL measurements confirmed the same physical mechanisms were existent in the dual MQW region devices. In addition EL measurements showed the regions to be decoupled from each other producing independent QW emission peaks.

Dual MQW region LED devices show promise for achieving high brightness, high efficiency, and high quality broadband white light. Future work will include the development of more sophisticated dual MQW region devices. Development of new sources such as these will help solid state lighting become a viable general illumination technology.

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