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Heterostructure for UV LEDs Based on Thick AlGaN Layers

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Thick AlGaN layers and GaN/AlGaN heterostructures were grown by low pressure MOCVD on (0001) sapphire substrates utilizing a low temperature AlGaN buffer layer. The distribution of Al in the thick AlGaN layers was observed to be non-uniform as a function of depth. The Al content gradually increases from the substrate towards the epilayer surface. Moreover, fluctuations of Al content are also noticeable. The saturation of impurity-related emission with increasing current density was observed in EL spectra of LEDs consisting of AlGaN/GaN/AlGaN DH sandwiched by a 2 µm-thick bottom layer of GaN:Si and 0.5 µm-thick layer of GaN:Mg. The dominant near-band edge emission of the GaN active layer was found to be strongly absorbed in the thick bottom layer. Utilizing a 2 µm-thick AlGaN bottom layer instead of the GaN one allowed the absorption edge to be shifted towards higher energies. A single peak at 362 nm with FWHM of 14 nm was observed in this type of LED. Luminescence properties of various types of heterostructures are also discussed.

1 Introduction

In recent years, remarkable progress in the technology of bright blue-green AlGaInN light emitting diodes (LEDs) and laser diodes has been achieved [1] [2]. The active region of these LEDs with either single- or multiple-quantum well structure are created from doped and undoped InGaN films. The visible emission from that active region does not absorb in GaN layers that promote the high-efficiency LED fabrication. However, ultra-violet (UV) LEDs are also of interest because of their potential use in white light conversion utilizing luminescent solid, in optical analysis of organic molecules, drug testing and other medical applications [3] [4]. Further advancement toward the ultraviolet spectral range can be accomplished by utilizing near-band-edge emission of GaN active layer in GaN-AlGaN heterostructures. But there is a strong absorption of the emission in a passive GaN region of the structure resulting in shifting of the peak emission to the long wavelength region. The aim of this work is to minimize the absorption of the near-band-edge emission and to fabricate UV LEDs based on thick AlGaN layers.

2 Experiment

The AlGaN layers and GaN/AlGaN double heterostructures (DH) were grown by MOCVD in a horizontal reactor with an RF heated graphite susceptor at a low pressure of 200 mbar. Ammonia, trimethylgallium (TMG) and trimethylaluminum (TMA) were applied as component precursors. Purified hydrogen was used as a carrier gas. Silane and biscyclopentadienyl magnesium were used for doping. The substrates were (0001) optical grade polished sapphire. The growth procedure involved the buffer GaN layer growth at a low temperature (520 °C) followed by annealing and the heterostructure epigrowth at a higher temperature (1040 °C). Addition of Al in the GaN buffer layer improved the structural properties of the epilayers [5]. Epitaxial structures had a specular surface. Two-dimensional growth mode seems to be dominant on the specular surfaces. Steps and terraces of ~0.3 nm height were well defined by AFM.

The structural characterization was performed by photo- and electroluminescence (PL, EL) and secondary ions mass spectroscopy (SIMS).

Mesa-type LEDs were fabricated by a standard photolithography process utilizing the dry-etch method. A sketch of the LED is given in Figure 1. Typical mesa diameters are 100 µm, and NiCr-Au and Ti-Au compositions were applied as contacts to p- and n-type materials, respectively. The EL is detected through the transparent sapphire substrate.

3 Results

The low temperature (77K) PL spectra of a structure consisting of a 0.1 µm $Al_{0.04}Ga_{0.96}N$ / 0.2 µm GaN / 0.1 µm $Al_{0.08}Ga_{0.92}N$ DH grown on a 2.5 µm-thick undoped GaN bottom layer are given in Figure 2. PL emission was detected both from the surface and through the sapphire substrate. Due to strong absorption of near-band-edge emission from the GaN active layer in the thick bottom layer, there is a remarkable reduction of PL intensity and shifting peak position to longer wavelength region for emission detected from the substrate side. In order to reduce the absorption, a thick AlGaN bottom layer instead of the one of GaN have to be grown.

A thick AlGaN layer with intended Al content of ~4% was grown with constant TMA/(TMA+TMG) mole fraction using a low temperature AlGaN buffer layer. A non-uniform Al distribution in depth of the thick AlGaN layers was observed. SIMS profiling of Al in the single thick layer is given in Figure 3. Here, Al content gradually increases from the substrate towards the epilayer surface. Moreover, fluctuations of Al content are also noticeable. Thus, we can consider thick AlGaN layers (more than 0.6 µm) as a multi-layer structure. Each layer differs slightly in composition from the others. The whole structure seems to suffer from deformations and strains which influence the nonuniform incorporation of Al with depth during the layer growth. Moreover, strain seems to influence the non-linear behavior of the Al incorporation. A feature of the Al distribution is its low concentration in the region near the substrate. In this region absorption of near-band-edge emission is also observed. PL spectra excited and detected both from the surface and from the sapphire substrate sides for AlGaN thick layer are given in Figure 4. A typical PL spectrum of band-edge emission from undoped GaN layer is also shown.

Figure 5 shows the EL spectra of the conventional LED structure (sample a328) consisting of GaN/AlGaN DH sandwiched by 2 µm-thick bottom layer of GaN:Si and 0.5 µm-thick layer of GaN:Mg. The saturation of impurity-related emission with increasing current density was observed in this structure. Under higher current, the high energy edge of the EL spectrum was determined by absorption in the thick GaN:Si bottom layer (see Figure 5). Figure 6 depicts the EL spectra obtained from different types of LED. Samples a467 and a469 had a similar structure. They consisted of a 2.5 µm-thick n-type AlGaN bottom layer, a 0.2 µm-thick undoped GaN active layer, a 0.1 µm-thick p-type AlGaN:Mg barrier layer, and a 0.5 µm-thick p-type GaN:Mg contact layer.

The main difference between these structures (a467, a469) was the TMA/(TMA+TMG) mole ratio during the AlGaN bottom layer growth. TMA/(TMA+TMG) mole ratio was kept constant for the sample a467. This mole fraction for the sample a469 was kept at a higher value but only at initial growth of the AlGaN bottom layer and then the magnitude of the mole ratio was decreased to the previous value as for sample a467. SIMS measurements reveal an increase in the Al content in the region near the substrate for the sample of A469 as compared to one for the sample a467, whereas Al content in the region near the active layer was the same in the both cases. It should be noted that attempts to grow thick (more than 0.6 µm) AlGaN layers with Al content more than 8% resulted in formation of defect structures with cracked surfaces, which was not suitable for LED fabrication.

The EL peak position of these samples in Figure 6 indicates these growth peculiarities. Increasing the TMA/(TMA+TMG) mole ratio during the first stage of AlGaN bottom layer growth shifts the EL peak position for higher energies for sample a469 due to reduction of absorption from the GaN active layer in the bottom layer. EL spectra of this type of LEDs with forward currents are given in Figure 7. A single peak at 362 nm with FWHM of 14 nm was observed. To the best of our knowledge, it is the shortest wavelength observed in III-N LEDs

It should be noted that EL spectra of ordinary GaN p-n junctions demonstrated a broad emission band at around 2.8 eV. With an increase in the forward current, this band tends to saturate and near-band-edge emission at 3.2-3.4 eV can be detected. On the other hand, the broad emission at around 2.8 eV was observed in PL spectra of p-type GaN layers doped with Mg. Thus, we attribute the band at around 2.8 eV in EL spectra of the GaN p-n junctions to donor-acceptor pair recombination in the GaN:Mg layers. The similar evolution of EL spectra as the forward current increase was inherent in LEDs based on GaN-AlGaN DH. Thus, the shoulder in the EL spectra at 3.0-3.2 eV appears to be connected with electron injection in the p-type AlGaN:Mg barrier layer. There is almost no wavelength shift with increasing forward current. The I-V characteristic of the UV LED is given in Figure 8. The turn-off voltage is of 3.5 V. The value of the series resistance of 177 Ω is reasonable for this structure, given the small diameter of the mesa (100 µm).

4 Conclusions

Non-uniformity of the Al distribution as a function of depth was observed in thick AlGaN layers. Al content gradually increased from the substrate towards the epilayer surface. Moreover, fluctuations of Al content were also noticeable. The saturation of impurity-related emission with increasing current density was observed in LEDs consisting of GaN/AlGaN DH sandwiched between 2 µm-thick bottom layer of GaN:Si and 0.5 µm-thick layer of GaN:Mg. In this case, the dominant near-band-edge emission of the GaN active layer was strongly absorbed in the thick bottom layer. Utilizing a 2 µm-thick AlGaN bottom layer instead of the one of GaN shifts the absorption edge towards higher energies. EL spectra of this type of LED consisted of single peak at 362 nm with FWHM of 14 nm.

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FIGURES

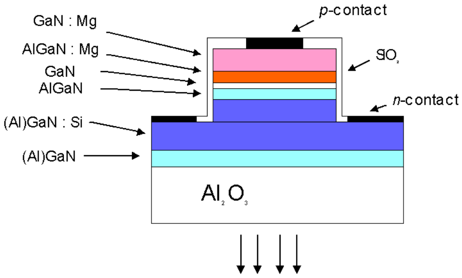

Figure 1. Scheme of light-emitting diode.

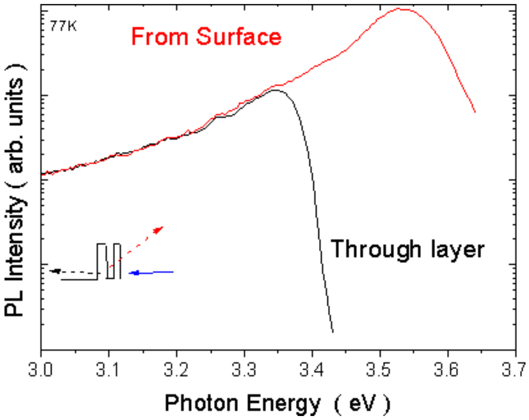

Figure 2. Photoluminescence spectra of AlGaN/GaN/AlGaN DH grown on a 2.5 µm-thick undoped GaN layer.

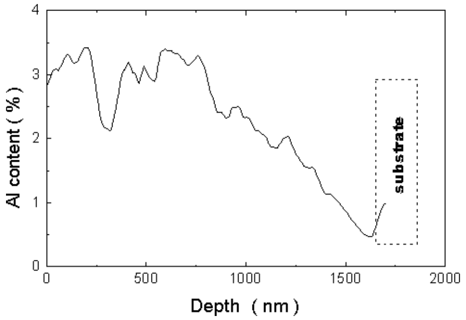

Figure 3. SIMS profile of Al in a thick AlGaN layer grown directly on a sapphire substrate.

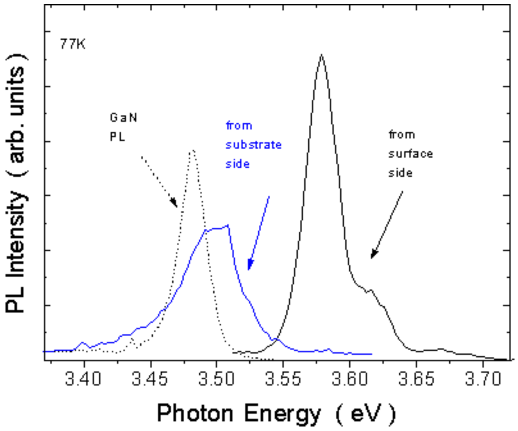

Figure 4. Photoluminescence spectra excited and detected both from the surface and from the sapphire substrate side for 2.5 µm - thick AlGaN layer. A typical PL spectrum for undoped GaN layer is also shown.

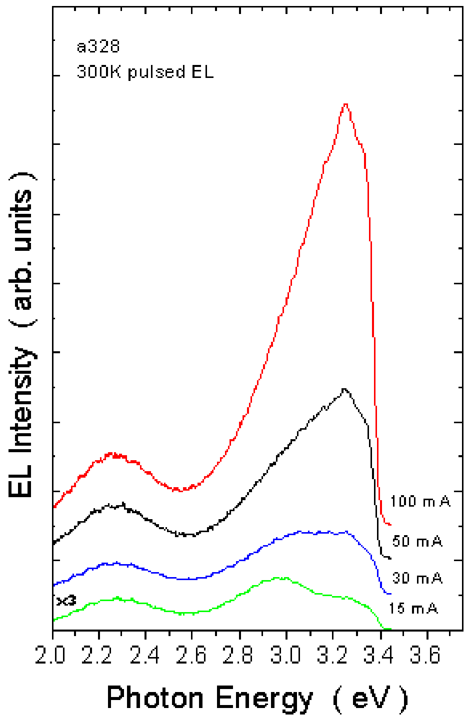

Figure 5. Electroluminescense spectra of sample a328 (a 0.1 μm $Al_{0.04}Ga_{0.96}N$ / 0.2 μm GaN / 0.1 μm $Al_{0.08}Ga_{0.92}N$ DH grown on 2.5 μm - thick GaN layer).

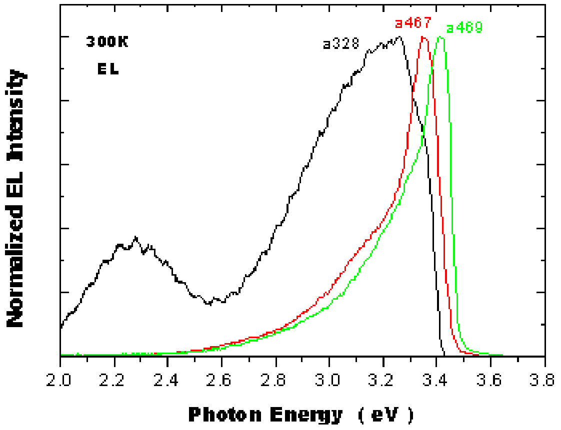

Figure 6. Electroluminescence spectra of LEDs with different bottom layers.

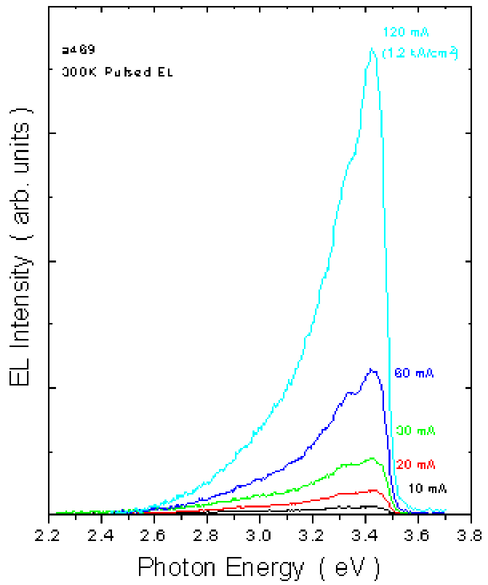

Figure 7. Electroluminescense spectra of structure a469 under different forward currents.

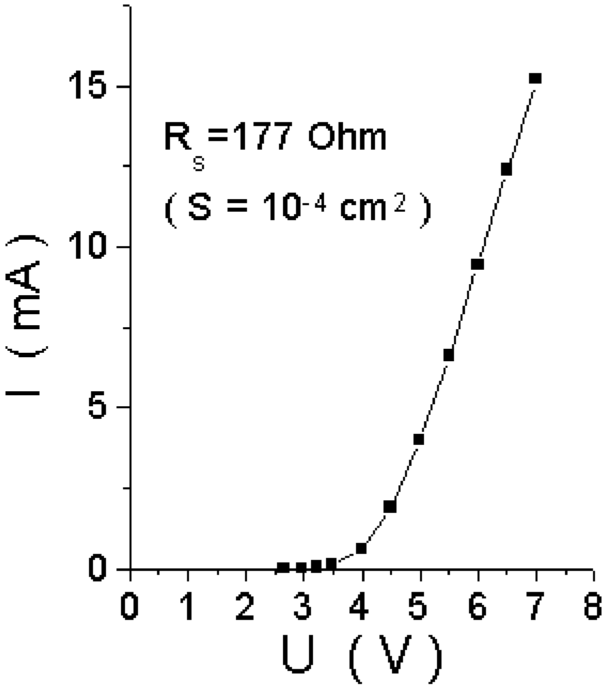

Figure 8. I-V characteristic of structure of a UV LED (a469).