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Low-temperature operation of AlGaN single-quantum-well light-emitting diodes with deep ultraviolet emission at 285 nm

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We present a study of the electrical and optical characteristics of 285 nm emission deep ultraviolet light-emitting diodes (LED) at temperatures from 10 to 300 K. At low bias, our data show the tunneling carrier transport to be the dominant conduction mechanism. The room-temperature performance is shown to be limited mostly by poor electron confinement in the active region and a pronounced deep level assisted recombination but not by the hole injection into the active region. At temperatures below 100 K, the electroluminescence peak intensity increases by more than one order of magnitude indicating that with a proper device design and improved material quality, milliwatt power 285 nm LED are viable. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1516631]

For nitride-based deep sub-300 nm emission light-emitting diodes (LEDs) the use of AlGaN layers with high Al-mole fraction ($x>30\%$) is required. From our previous studies, we found that the major factors controlling the internal quantum efficiency are a proper design of the active layer that provides a proper carrier confinement [in the quantum wells (QW)], the defect density which determines the nonradiative recombination and the p doping of the AlGaN layers which limits the hole injection into the active region. In order to reduce the defects density and the nonradiative recombination, we recently proposed an AlN/AlGaN superlattice (SL) strain relief approach.[1] The SL insertion allowed us to significantly reduce the biaxial tensile strain and grow a 2 μm thick, crack free AlGaN layers with an Al content up to 40%.[1] These buffer layers were then used for deep ultraviolet (UV) LEDs allowing for submilliwatt and milliwatt power levels at 285 nm and 325 nm, respectively.[2,3]

To improve the hole injection, we have also proposed the use of hole accumulation layers that can be created at an AlGaN/GaN interface by using large band gap offsets and the effect of piezodoping in nitride-based materials.[4] Recently depositing AlGaN/GaN heterostructures with large band gap offsets over the low defect density AlGaN buffer layers, we clearly established the existence of the hole accumulation layer. This formed the basis of our report on the nitride-based p-channel heterostructure junction field-effect transistor.[5] We now present a study of the role that the active region design plays in the carrier confinement and the hole injection for a 285 nm emission deep UV LEDs. The studied LEDs employed both the reduced defect density AlGaN buffers and the p-AlGaN/p-GaN heterostructure-based hole accumulation layers.

The epilayer structure of the 285 nm LED consisted of a 0.2 μm thick $Al_{0.4}Ga_{0.6}N$ layer that is deposited over basal plane sapphire using conventional low-pressure metalorganic chemical vapor deposition.[2] This is followed by a ten period AlN (20 Å)/$Al_{0.4}Ga_{0.6}N$ (300 Å) SL for strain relief and dislocation filtering and a 1.8 μm thick Si-doped n^+-$Al_{0.4}Ga_{0.6}N$ buffer layer. This approach reduces the threading dislocation density by a factor of 5 and thus enables the deposition of the 1.8 μm thick n^+-$A_{0.4}Ga_{0.6}N$ layers without cracking.[1] In addition, it improves the emission characteristics of the active layers by a reduction of the nonradiative recombination. The device active region consisted of an $Al_xGa_{1-x}N$ ($x=0.36$, 100 Å)/$Al_xGa_{1-x}N$ ($x=0.32$, 30 Å)/$Al_xGa_{1-x}N$ (x=0.36, 100 Å) single QW (SQW) which was capped with a Mg-doped p-$Al_{0.4}Ga_{0.8}N$ (200 Å) and a p^+-GaN (500 Å) layer. All layers of the structure were deposited at 1050 °C and 76 Torr.

For the experimental study, square geometry p-n junction devices were fabricated using a reactive ion etched mesa to access the bottom n^+-$Al_{0.4}Ga_{0.8}N$ layer. As before, Ti(20 Å)/Al(100 Å)/Ti(200 Å)/Au(2000 Å) and Ni(20 Å)/Au(200 Å) were used for the n- and p-contact metals.[6] The contact anneal procedures were identical to our earlier reports.[2,3,6] For the temperature dependent measurements, the sample was mounted in the closed-cycle He cryostat. The electrical characteristics were measured in the temperature range of 10–300 K using the Agilent 4155C semiconductor parametric analyzer. A single-pass TRIAX-550 spectrometer with UV enhanced cooled charge coupled device detector was used for the electroluminescence (EL) spectra measurements.

In Fig. 1, we plotted the simulated band diagrams for this LED structure at 4.3 V of forward bias. Simulation were done using a commercial simulator software APSYS.[7] Even though the Mg doping for p-$Al_{0.4}Ga_{0.6}N$ and p-GaN layers was around 1×10^{20} cm^{-3}, in simulations, we assumed the ionized acceptor concentration to be 1×10^{17} cm^{-3} in both p-AlGaN and p-GaN layers. Due to a large Al-composition difference, a pronounced surface charge of 1.7×10^{13} cm^{-2} is induced at the p-AlGaN/p-GaN interface by spontaneous polarization field.[8] This interface charge creates a considerable hole accumulation and band bending at p-AlGaN/p-GaN interface depleting the p-AlGaN layer by an electric field. As seen from Fig. 1 under forward bias, the holes are injected first into a two-dimensional potential well created at the p-AlGaN/p-GaN interface and then into the LED QW. This process may lead to some increase of the

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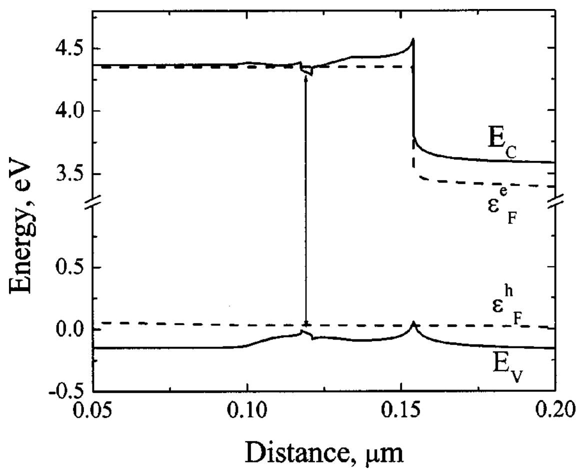

FIG. 1. Simulated band diagram of LED structure under 4.3 V forward bias.

device turn-on voltage since some additional voltage is required to fill up the potential well and then inject holes into QW. However, the gain in the device differential resistance due to improved p doping of p GaN is much more important compared to slight increase of the turn-on voltage.

In Fig. 2, we plotted the current versus voltage ($I-V$) characteristics of the LED in the temperature range of 10–300 K. As seen at 10 mA of forward current, the LED operating voltage increases from 5.2 V at room temperature to 6.7 V at 10 K. The turn-on voltage of about 4.9 V at 300 K is somewhat larger than that expected from the active layer band gap of 4.35 eV showing additional voltage drop at the heterointerfaces. The increase of turn-on and operating voltages is much larger than that expected from the active layer band gap change with temperature. We believe it could be associated with n-contact temperature degradation. At low currents, the $I-V$ characteristics can be described by tunneling current associated with tunneling of high-energy electrons from the active layer into the p-barrier layers followed by nonradiative and radiative recombination with deep impurity-related levels.[9–11] From the $I-V$ curves of Fig. 2 plotted in semilogarithmic scale, the characteristics energy of tunneling process was found to be about 151 meV at 10 K increasing up to 194 meV at room temperature. This weak dependence of the $I-V$ slope on the temperature is typical for the tunneling related excess current at low bias levels.

The device differential resistance was measured at 50

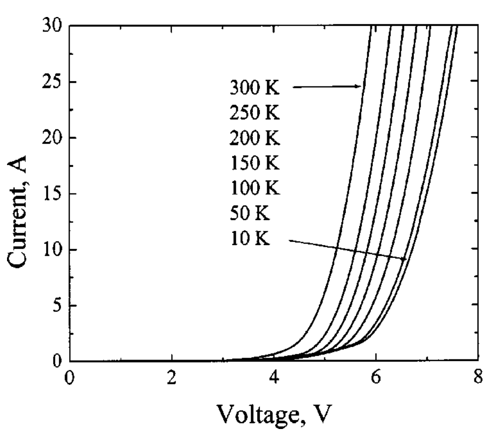

FIG. 2. The LED $I-V$ curves at different temperatures.

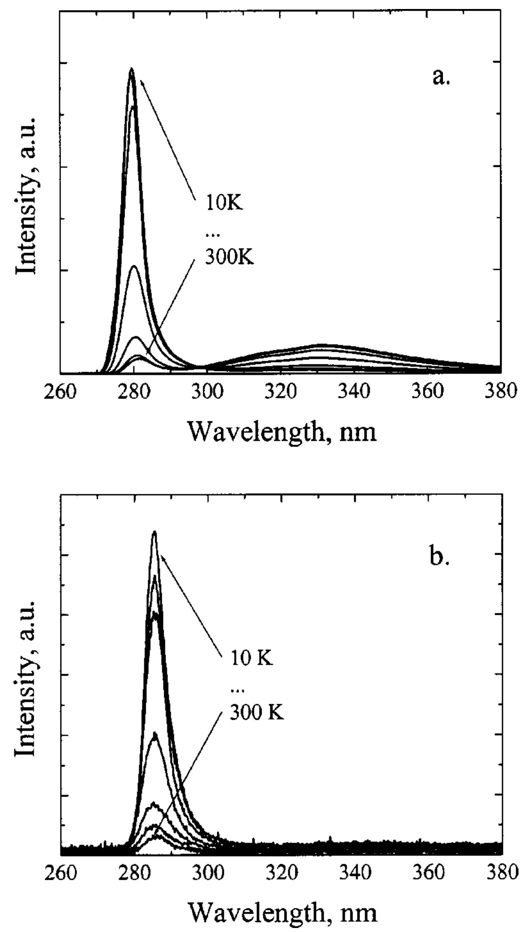

FIG. 3. (a) The LED EL spectra under 200 mA pulsed current pumping at different temperatures; (b) The PL spectra of the same LED structure at different temperatures.

mA to reduce the p-n junction contribution to the resistance. In order to avoid the device self-heating by the applied bias, the high current measurements ($I\sim50$ mA) were done under pulse pumping of 500 ns pulses with 0.5% duty cycle. As seen from Fig. 2, the resistance changes from 24 Ω at 300 K up to only 32 Ω at 10 K. This small increase of the differential resistance over large temperature range is primarily associated with small contribution from p layers due to hole accumulation at the AlGaN/Gan interface and small p-GaN layer thickness. The increase of the resistance and the absence of the freeze-out effect are related to the electron hopping transport along the impurity states in highly doped n layers.

The EL spectra at different temperatures under 200 mA pulsed pump current are plotted in Fig. 3(a). As seen, the intensity of QW band-to-band emission peak located at 285 nm increases fast with the reduction of temperature from 300 down to 10 K. The main peak intensity increases at low temperature by more than ten times. Note that increase is a function of the pump current and, at lower bias, this intensity goes up by a factor of 100 from 300 to 10 K. The intensity of the parasitic peak centered at about 330 nm is significantly reduced as the temperature decreases. This parasitic peak is associated with the recombination through the deep levels, which are about 0.5–0.6 eV below the band gap of the p-AlGaN layer.

In addition, in Fig. 3(b), we plotted the photolumines-

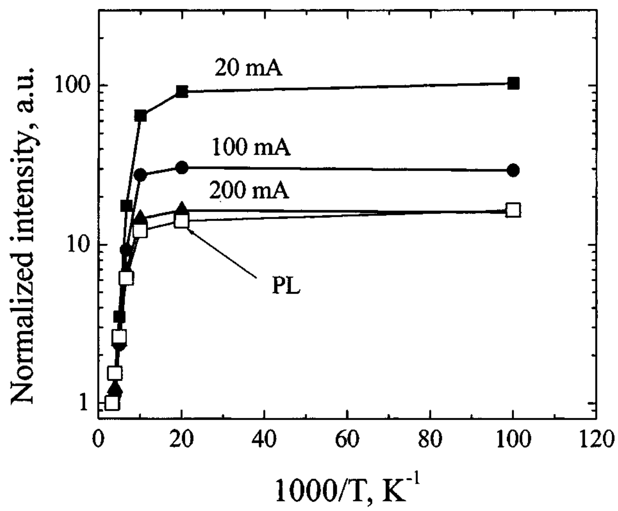

FIG. 4. The normalized integrated intensity of 285 nm peak of EL and PL spectra as a function of temperature.

cence (PL) spectra on the same structure measured in the same temperature range. For PL study, we used the pulsed excimer laser emitting at 193 nm with the pulse duration of 8 ns and the repetition frequency of 100 Hz. As seen from Fig. 3(b), the PL spectra show a similar increase in main QW peak intensity as a function of temperature. The deep level emission peak is not seen in the PL spectrum since the characteristic time of deep levels is much longer than the excitation pulse width of 8 ns. The detailed study of the EL spectra dynamics is now underway and will be published separately.

In Fig. 4, we plotted the integrated 285 nm peak intensity as a function of temperature for different pulsed pump currents. The integrated 285 nm peak intensity of the PL spectrum is also plotted for comparison. All values are normalized with respect to room temperature. As seen from Fig. 4, at high pulsed pumping, the 285 nm peak increases by more than ten times as compared to room-temperature value. A similar increase is seen for the case of PL excitation. This comparison clearly shows that the hole injection into the QW remains the same even at temperatures as low as 10 K. However, at lower electrical pumping, the increase of the 285 nm intensity is much more pronounced. This data show that the ten times increase in the EL spectrum peak can be attributed to the better carrier confinement in the QW and reduced nonradiative recombination at lower temperatures. Since at lower pump currents the intensity increases by more than ten times, the additional effect can be attributed to the better carrier injection into the QW at lower temperatures. This shows the defect-related recombination and carrier confinement in the QW, but not the hole injection, to be the key factors controlling the room-temperature LED performance. Also this implies that the power level of few milliwatts at 285 nm can be obtained at low temperatures.

In summary, we report on low-temperature study of deep UV AlGaN SQW LEDs emitting at 285 nm. The $I-V$ curves show a small increase in differential resistance with a reduction in the temperature showing a small contribution from p layers due to good p doping by polarization-induced hole accumulation at the AlGaN/GaN interface. Temperature independent tunneling carrier transport is seen at low bias levels. The increase of the QW emission peak by more than one order of magnitude is shown at 100 K and below. These experiments show the room-temperature LED performance to be limited mostly by poor electron confinement in the QW region as well as large deep level assisted recombination in p-AlGaN layers. The milliwatt range output power is viable using AlGaN-based LEDs with proper optimization of the structure design and material quality.

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