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Time-resolved electroluminescence of AlGaN-based light-emitting diodes with emission at 285 nm

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We present a study on the time evolution of the electroluminescence (EL) spectra of AlGaN-based deep ultraviolet light-emitting diodes (LEDs) under pulsed current pumping. The EL spectra peaks at 285 nm and 330 nm are found to result from recombination involving band-to-band and free carriers to deep acceptor level transitions. The 330 nm long-wavelength transitions to deep acceptor levels in the p-AlGaN layer as well as the nonradiative processes significantly influence the LED internal quantum efficiency. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1536729]

We have recently reported on nitride-based deep ultraviolet (UV) light-emitting diodes (LEDs) with peak emission at 285 nm.[1,2] Our results showed the internal quantum efficiency of these devices to be mostly limited by the defects originating from the high Al-mole fraction AlGaN buffer layers, which control the nonradiative recombination, and by the deep level assisted radiative recombination, which significantly reduces the carrier injection into the quantum well (QW).[3] For our reported device design, the introduction of AlN/AlGaN superlattice strain relief buffer layers and p-AlGaN/p-GaN hole accumulation layers resulted in a significant reduction of the nonradiative recombination and in a more efficient hole injection.[1–5] The LED spectra comprised of a band-to-band emission peak at 285 nm and a long wavelength emission band at 330 nm. This deep level assisted radiative recombination at 330 nm was found to be especially significant at low pump currents. For the 285 nm LEDs, we now report on a detailed study of the steady-state and the time-resolved electroluminescence (EL) spectra to determine the origin and the transient behavior of the spectral emission at 330 nm. Suppression of this deep level related recombination is expected to improve the quantum efficiency of the desired 285 nm emission.

A schematic of the epilayer structure for the 285 nm LED is shown in Fig. 1. The structure 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.[1] This was followed by a ten period Aln (20 Å)/$Al_{0.4}Ga_{0.6}N$ (300 Å) superlattice 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 superlattice insertion approach reduces the threading dislocation density by a factor of 5 and thus enables the deposition of the 1.8 μm thick n^+-$A_{0.4}Ga_{0.6}N$ buffer layers without cracking.[1,4] The device active region consisted of an $Al_{0.36}Ga_{0.64}N$ (100 Å)/$Al_{0.32}Ga_{0.68}N$ (30 Å)/$Al_{0.36}Ga_{0.64}N$ (100 Å) single quantum well, 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.

Square-geometry $p-n$ junction devices were then 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 and the contact annealing procedures were identical to our earlier reports.[1] A single-pass spectrometer TRIAX-550 with an UV-enhanced cooled charge coupled device (CCD) detector was used for the measurements of the quasisteady-state EL spectra. An intensified CCD with a digitally controlled variable-delay electro-optical (EO) shuttering was utilized to perform measure-

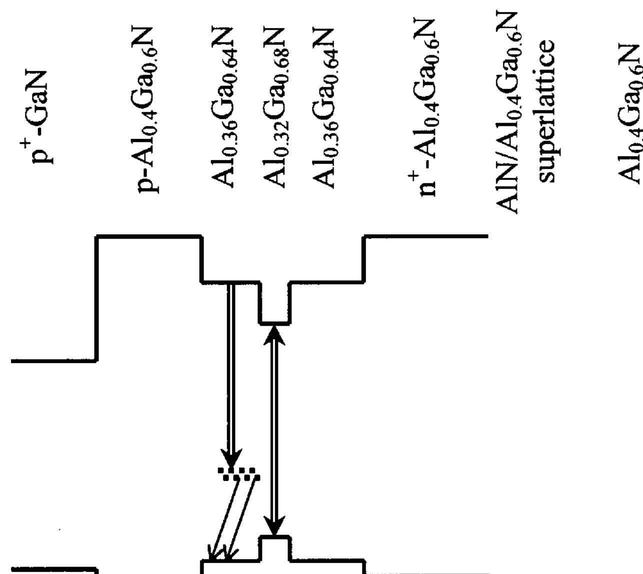

FIG. 1. The schematic LED band diagram and recombination paths corresponding to 285 nm and 330 nm EL peaks.

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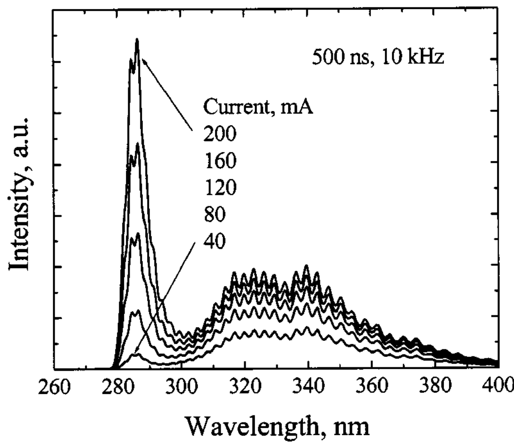


FIG. 2. 285 nm LED EL spectra as a function of pulsed current.

ments of the time-resolved EL spectra with a 5 ns time resolution.

The EL spectra of the 285 nm LED as a function of the pulsed pump currents are presented in Fig. 2. For these measurements, 500 ns long electrical pulses at 10 kHz repetition rate were used to provide quasisteady-state pumping conditions and avoid heating. As seen, the main peak at 285 nm corresponding to the band-to-band emission in the QW gradually increases with current. However, the long wavelength peak centered at 330 nm dominates at low currents and then it saturates at high bias currents. Similar long-wavelength peaks in EL spectra were also observed in previous reports of AlGaN-based deep UV LEDs emitting at 325 nm and 340 nm.[6–8] These long-wavelength peaks arise from the radiative recombination involving deep levels. To determine their origin, we studied the transient behavior of both the 285 nm and the 330 nm EL peaks.

The time-resolved EL spectra were measured using a 1 μs long 70 mA pump current pulse with a rise and decay time of less than 10 ns. Using the intensified CCD and the EO shutter, the spectra were measured every 10 ns after the start of the pump current pulse. For clarity, in Fig. 3, we only plot the spectra corresponding to times of 0 ns, 10 ns, 100 ns, 300 ns, and 600 ns after the application of the pump current pulse. Note that time duration for the capture of each spectrum was 10 ns. As seen, the luminescence peak at 285 nm builds up rapidly with a time scale shorter than the minimum delay step of our study (10 ns). Meanwhile, the build up of the long-wavelength band proceeds considerably slower, and the steady state of this peak is reached within approximately 300 ns after the start of the current pulse. Thus, for the first several tens of nanoseconds after the start of the current injection the spectrum is dominated by emission at 285 nm, while the broad 300 nm long-wavelength band prevails at delays longer then 200 ns.

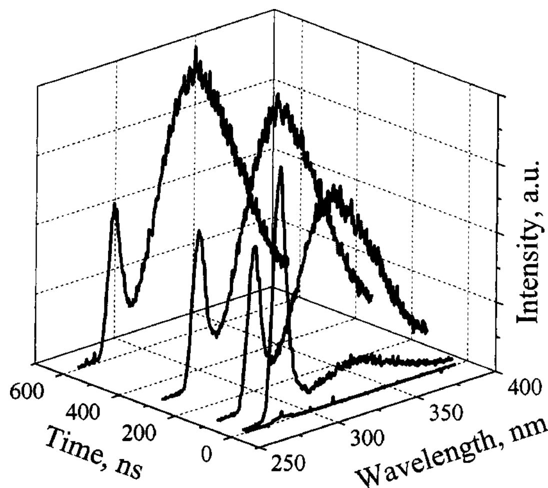
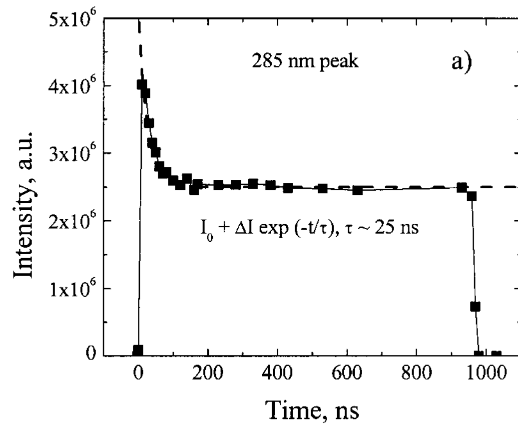


FIG. 3. Time resolved LED EL spectra under 1 μs long current pulse of 70 mA.



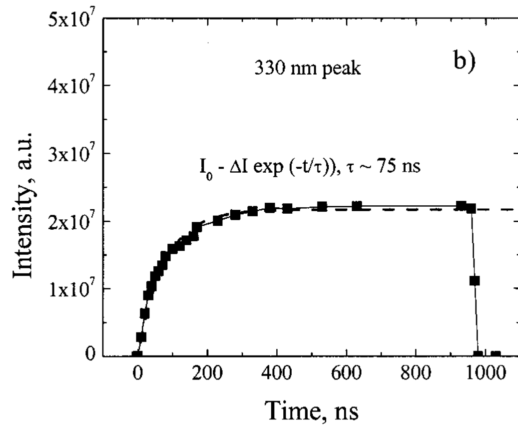


FIG. 4. Spectrally integrated intensity of the main 285 nm band (a) and the long-wavelength band (b) as a function of time when 1 μs long current pulse of 70 mA is applied.

The time evolution of the EL is revealed in more detail in Fig. 4, where the spectrally integrated intensity of both bands is depicted as a function of time. Note that after reaching its peak value, the intensity of the 285 nm band decays within the first 100 ns after the current pulse is applied [see Fig. 4(a)]. This intensity reduction can be fitted by an exponential function:

$$I(t) = I_0 + \Delta I \exp(-t/\tau) \quad (1)$$

with a characteristic time constant of about 25 ns. The rise of the 330 nm long-wavelength peak also proceeds exponentially as

$$I'(t) = I'_0 - \Delta I' \exp(-t/\tau'), \quad (2)$$

however, with a different characteristic time of 75 ns [see Fig. 4(b)]. This difference in the time constants of the two processes indicates that different injection or/and recombination mechanisms are responsible for the 285 nm and 330 nm bands. Note that when the pump current is switched off, the

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fall time for both 285 nm and long-wavelength peaks is fast and within the time resolution limit of our experiment (10 ns).

All the features in the EL time evolution are consistent with a simple model involving two radiative recombination channels. These channels are schematically shown in Fig. 1. The first channel, a band-to-band recombination results in the narrow band at 285 nm. The peak position of the long-wavelength band (at 330 nm) indicates transitions involving deep levels. The emission wavelengths for localized excitons or carriers typically observed in blue LEDs with an InGaN active region and in GaN homojunction LEDs are closer to the band gap and they usually have decay times in excess of 100 ns.[9–11] Also, the donor–acceptor emission is usually redshifted during the decay due to a higher probability of recombination of the closest pairs. The short decay time of our 330 nm long-wavelength emission peak (about 10 ns) and an absence of the redshift during the decay exclude the donor–acceptor recombination as a possible mechanism responsible for the 330 nm band. Our data, therefore, suggest that the 330 nm long-wavelength band to be caused by the recombination of the free carriers through deep levels. This conclusion is also supported by our results of the low-temperature EL of these LEDs, where the intensity of the 330 nm peak reduced without spectral shift when the temperature was lowered.[3]

The energy position of the deep level responsible for the 330 nm EL peak should be 0.6 eV to 0.85 eV from the band edge. For *p* GaN, the Mg-related deep acceptor states are about 0.55 eV above the valence band.[11] Recently, the photoluminescence study of Mg-doped AlGaN layer showed similar peaks due to the recombination of free electrons with neutral Mg acceptors.[12] For these *p*-AlGaN layers, the energy position of the neutral Mg-acceptor levels scales with the band gap and, hence, with the Al-mole fraction. We, therefore, conclude that the 330 nm long-wavelength peak in our EL spectra arises from the recombination of the conduction band electrons and the holes populating the Mg-related deep acceptor levels. These are neutral acceptors located on the *p* side of the QW in the *p*-AlGaN barrier and blocking layers of our device design (see Fig. 1).

The slow rise time of the long-wavelength emission peak can also be easily understood in terms of this recombination model. At zero bias, the built-in field can ionize the deep acceptor levels in the *p* AlGaN, and thus no radiative transitions can occur. Under the forward bias, some of these levels become neutral, thereby allowing for the 330 nm radiative transitions. Thus, the 75 ns rise time of the 330 nm long-wavelength peak is primarily limited by the deep acceptor deionization time. As most of these levels become neutral, the intensity of the long-wavelength band reaches its saturated steady state. This process also results in the partial intensity reduction of the main band-to-band recombination, since the carrier injection in the QW should decrease. Note that at low current pumping in steady state, the spectrally integrated intensity of the long-wavelength band is about ten times higher than that of the main 285 nm emission. This is an indication of a pronounced recombination through the deep acceptor states induced by Mg doping. Therefore, in principle, it should be possible to increase the carrier injection into the QW by a factor of 10 by reducing the 330 nm deep level recombination. Thus, the 285 nm emission powers (0.25 mW at 650 mA) can also be increased significantly due to enhanced carrier injection.[2]

In summary, we report on the study of the time-resolved EL spectra of deep UV LEDs emitting at 285 nm. The emission peak located at 285 nm arises due to the band edge emission from the QW. The long-wavelength emission band centered at 330 nm is caused by the carrier recombination from the conduction band to the deep acceptor levels in the *p*-AlGaN layer at room temperature. Time-resolved EL measurements yield the rise time of the 330 nm EL peak to be 75 ns. This time is attributed to the hole capture by the deep acceptor levels in the *p*-AlGaN layers. Our data also show that the quantum efficiency of the 285 nm LED emission can be increased at least by a factor of 10 by reducing the density of the defects, which act as radiative and nonradiative recombination centers. Hence, our results indicate that using the III–N material system milliwatt power LEDs at 280 nm wavelength are viable.

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