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Milliwatt power deep ultraviolet light-emitting diodes over sapphire with emission at 278 nm

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We report on AlGaN multiple-quantum-well (MQW)-based deep ultraviolet light-emitting diodes over sapphire with peak emission at 278 nm. A new buffer layer growth process was used to reduce the number of defects and hence the nonradiative recombination. The improved material quality and carrier confinement resulted in pulsed powers as high as 3 mW at 278 nm and a significantly reduced deep-level-assisted long-wavelength emission.
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Due to their enormous applications potential, several research groups are actively developing deep ultraviolet light-emitting diodes (LEDs). Nishida *et al.* have reported on milliwatt power UV LEDs with emission at 352 nm over hydride vapor-phase epitaxial GaN substrates.[1] Recently, using sapphire substrates, we have also reported on deep UV LEDs with peak emissions at 325 and 285 nm.[2,3] Our reported devices utilized an innovative AlN/AlGaN superlattice approach for deposition of 2-μm-thick $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ ($x > 0.35$) buffer layers with significantly lower defect levels.[4,5] In addition, we also employed a p-GaN/p-AlGaN hole accumulation layer for improving the p-doping and thereby hole injection into the active region, which, for the 285 nm devices, is comprised of an $\mathrm{Al}_{0.47}\mathrm{Ga}_{0.53}\mathrm{N}/\mathrm{Al}_{0.43}\mathrm{Ga}_{0.57}\mathrm{N}$ single quantum well.[3,6] The emission spectra of these 285 nm LEDs contained a sharp quantum well band-edge peak at 285 nm and a deep-level-assisted emission band at 330 nm.

Our recent studies show that at very low pump currents, the 330 nm emission is stronger than that at 285 nm.[7,8] At higher currents it rapidly saturates with a simultaneous increase in the 285 nm peak, which then dominates the spectra at pump currents in excess of 200 mA. For the 285 nm emission, we previously reported room-temperature power as high as 0.25 mW for a pulsed pump current of 650 mA.[9] These studies[8,9] also concluded that the emission band at 330 nm resulted from a recombination of the electrons via deep neutral acceptor levels in the p-AlGaN layer of our device structure. The data suggested that the weak carrier confinement not only results in a long-wavelength emission (at 330 nm), but it also reduces the 285 nm emitted powers.[9] Additionally, the number of nonradiative defects is a key factor that controls the quantum efficiency of LED devices.[3] The number of nonradiative defects is itself a strong function of the buffer and the active layers material quality. We now report on a 278 nm emission deep UV LED with a design using $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ multiple quantum wells (MQWs) in the active region. This design results in a more efficient carrier confinement, and thereby reduces the long-wavelength emission band at 330 nm. In addition, we further improved the AlN/AlGaN superlattice and the n^+-$\mathrm{Al}_{0.5}\mathrm{Ga}_{0.5}\mathrm{N}$ buffer layer quality by using a unique pulsed atomic-layer epitaxy deposition process.[10] These design and deposition process changes resulted in 278 nm pulse powers as high as 3 mW at a pump current of 1 A.

The epilayer design for the devices of this study is shown in the inset to Fig. 1. Compared to our previously reported 285 nm LEDs, it incorporated several key changes. First, we used a recently developed pulsed atomic-layer epitaxy technique to deposit the ultrahigh-quality strain relief AlN/AlGaN superlattices and the n^+-$\mathrm{Al}_{0.5}\mathrm{Ga}_{0.5}\mathrm{N}$ buffers. We estimate this approach to further reduce the defect density in the active layer by at least a factor of 2.[10] Second, the number of quantum wells in the active region was changed to 2 in order to increase the carrier confinement. Finally, the Al-alloy composition of the well material was also increased to about 44% to push the emission wavelength below 280 nm.

As before, mesa-type LED devices were fabricated using Ti/Al/Ti/Au for the n-side and Ni/Au for the p-side contact. Contact anneal procedures were also identical to those reported earlier.[9] Several 200 μm×200 μm devices were then diced out, flip-chip mounted on AlN carriers, and then wire-bonded onto copper headers.[11] Both single and multiple de-

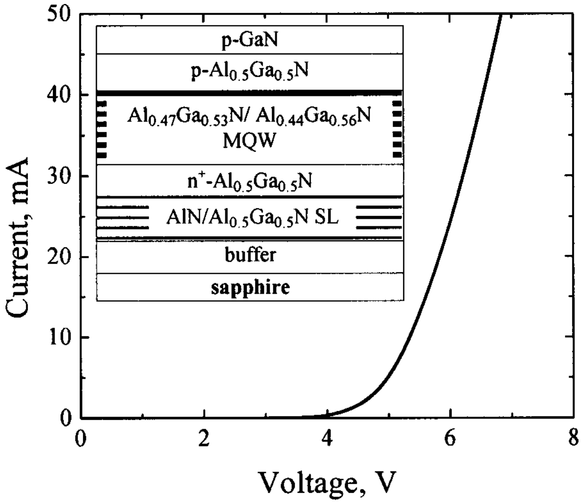

FIG. 1. $I-V$ characteristics of the 200×200 $\mu\mathrm{m}^2$ device. The LED layer structure is shown schematically in the inset.

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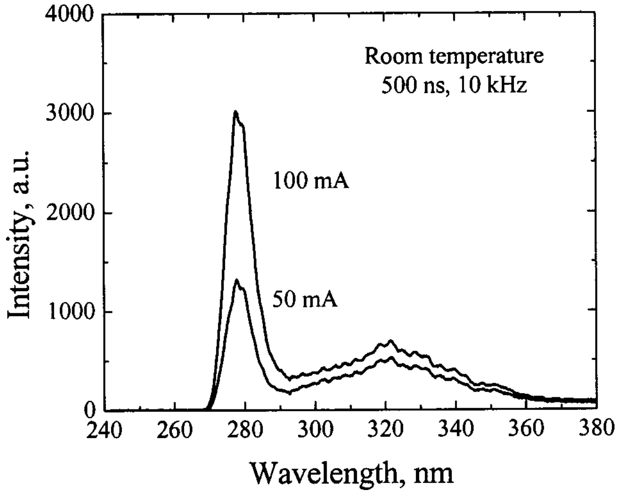

FIG. 2. Electroluminescence spectra of the 200×200 μm^2 under 50 and 100 mA of pulsed pumping.

vice combinations were then tested for their electrical and optical characteristics.

In Fig. 1, we include the current–voltage characteristics for a 200×200 μm^2 device. As seen, a sharp turn-on at 5.2 V and a total series resistance of 28 Ω were measured. For a 1×4 array package with parallel device connections, the total series resistance reduces from 28 to 10 Ω. From transmission line measurement pads, the sheet resistances for the *n*- and the *p*-layers in our device were determined to be 300 $\Omega/\square$ and 140 k$\Omega/\square$, respectively. From these values we estimated a specific resistivity of 6×10^{-2} Ω cm for the 2-μm-thick n^+-Al$_{0.5}$Ga$_{0.5}$N buffer layer. This agrees well with the value derived from Hall measurements, which yielded a doping level of 2×10^{18} cm^{-3} and an electron mobility of about 80 cm^2/V s. Similarly, taking 0.1 μm as the total thickness of the *p*-AlGaN and the *p*-GaN layers, their specific resistivity was estimated to be about 1.5 Ω cm. Note, that with these values of the layer resistivities and thicknesses, we expect a very strong lateral current crowding in our devices. At high pumping levels the characteristic current spreading lengths are expected to be between 10 and 20 μm.[12] Thus, our selected 200×200 μm^2 device geometry is not optimal for a uniform pumping of the LED pixels.

In Fig. 2, we include room-temperature emission spectra at pulsed pump currents of 50 and 100 mA. As seen from Fig. 2, even at such low pump currents, the spectra contain a strong emission peak at 278 nm and a very weak emission band at 330 nm. This is different from our previous reports (using a single-quantum-well design) where, at low pump currents, the 330 nm emission peak was nearly equal to or larger than the band-edge emission at 285 nm.[3] Our data thus demonstrate that the MQW design significantly improves the carrier capture and confinement in the active region. The data of Fig. 2 also agree well with the results of the simulation of our LED performance using the commercial software package APSYS.[13] These simulations show that use of two QWs in the active layer increases the band-edge radiative recombination from the active region by about 30%, while reducing the unconfined carrier density by a factor of 2.

In Fig. 3(a) we plot the room-temperature emitted powers as a function of the dc and the pulsed pump currents for

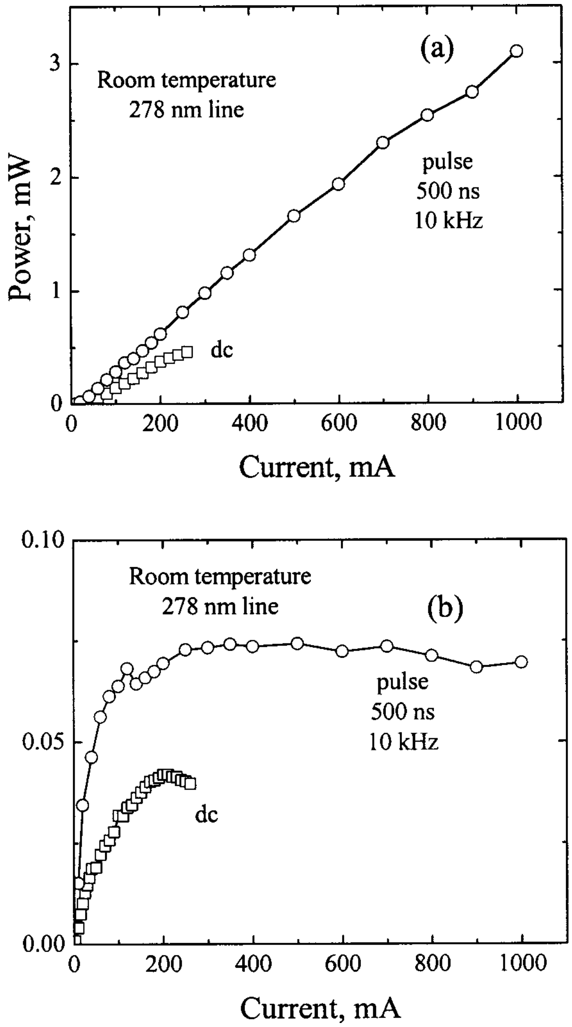

FIG. 3. The optical power (a) and the external quantum efficiency (b) of 278 nm line as a function of dc and pulsed pump current.

the 1×4 array package. A calibrated integrating sphere with a 278 nm bandpass filter was used for these measurements. As seen, the dc power at 278 nm saturates at a record value of 0.47 mW for a pump current of 260 mA. Note that the slope of the dc power versus current characteristics starts to deviate from its value for pulsed pumping at a current as low as 20–30 mA. This shows that improved thermal management can further increase the 278 nm dc power. We also measured a power of 3 mW at a pulsed pump current of 1 A. This, to the best of our knowledge, is also the highest reported power for a 278 nm emission deep UV LED.

Using the data of Fig. 3(a), the LED external quantum efficiency for the 278 nm emission peak was calculated and plotted in Fig. 3(b). As seen, under dc bias the efficiency saturates prematurely at a pump current of 200 mA. This, we believe, is mainly due to the device self-heating. A further increase of the dc pump current results in a reduction of the efficiency. Under pulse pumping, the efficiency reaches its maximum value at a current of 250 mA and then remains nearly constant. This high current value for reaching the peak efficiency is a clear reflection of the reduced injection and band-edge radiative recombination at low pumping. The maximum external efficiency of about 0.075% in the pulse pumping case is still very low and is again an indication of pronounced nonradiative losses. After the saturation, the small reduction of the efficiency with increasing current is possibly due to the nonradiative processes such as Auger recombination, which should be important at high injection levels. It is also interesting to note that the power at 278 nm rises almost linearly, and that the efficiency remains nearly constant up to pulsed pump currents as high as 1 A. Thus, for our devices the carrier injection does not limit the emitted powers and hence the efficiency. We therefore conclude that by reducing the nonradiative recombination channels arising from the structural defects, we can in principle significantly increase the emitted power and the quantum efficiency for the 280 nm deep UV LEDs.

In summary, we report on deep UV LEDs over sapphire with peak emission at 278 nm. Incorporation of a two-quantum-well active-layer design suppressed the long-wavelength emission band at 330 nm. Improved carrier confinement, reduced defects, and efficient hole injection led to devices with dc powers as high as 0.47 mW at 260 mA and pulsed powers of 3 mW at 1 A. These to date are the highest reported powers at the shortest wavelength for III-N UV LEDs.

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[1] T. Nishida, H. Saito, and N. Kobayashi, Appl. Phys. Lett. **79**, 711 (2001).
[2] A. Chitnis, J. P. Zhang, V. Adivarahan, S. Wu, J. Sun, M. Shatalov, J. Yang, G. Simin, and M. Asif Khan, Jpn. J. Appl. Phys. **41**, L450 (2002).
[3] V. Adivarahan, J. P. Zhang, A. Chitnis, S. Wu, J. Sun, R. Pachipulusu, M. Shatalov, and M. Asif Khan, Jpn. J. Appl. Phys. **41**, L435 (2002).
[4] J. P. Zhang, H. M. Wang, M. E. Gaevski, C. Q. Chen, Q. Fareed, J. W. Yang, G. Simin, and M. Asif Khan, Appl. Phys. Lett. **80**, 3542 (2002).
[5] H. M. Wang, J. P. Zhang, C. Q. Chen, Q. Fareed, J. W. Yang, and M. Asif Khan, Appl. Phys. Lett. **81**, 604 (2002).
[6] M. Shatalov, G. Simin, J. P. Zhang, V. Adivarahan, A. Koudymov, R. Pachipulusu, and M. Asif Khan, IEEE Electron Device Lett. **23**, 452 (2002).
[7] A. Chitnis, R. Pachipulusu, V. Mandavilli, M. Shatalov, E. Kuokstis, J. P. Zhang, V. Adivarahan, S. Wu, G. Simin, and M. Asif Khan, Appl. Phys. Lett. **81**, 2938 (2002).
[8] M. Shatalov, A. Chitnis, V. Mandavilli, R. Pachipulusu, J. P. Zhang, V. Adivarahan, S. Wu, G. Simin, M. Asif Khan, G. Tamulaitis, A. Sereika, I. Yilmaz, M. S. Shur, and R. Gaska, Appl. Phys. Lett. (in press).
[9] V. Adivarahan, S. Wu, A. Chitnis, R. Pachipulusu, V. Mandavilli, M. Shatalov, J. P. Zhang, M. Asif Khan, G. Tamulaitis, A. Sereika, I. Yilmaz, M. S. Shur, and R. Gaska, Appl. Phys. Lett. **81**, 3666 (2002).
[10] J. P. Zhang, M. Asif Khan, W. H. Sun, H. M. Wang, C. Q. Chen, Q. Fareed, E. Kuokstis, and J. W. Yang, Appl. Phys. Lett. (in press).
[11] A. Chitnis, V. Adivarahan, J. P. Zhang, S. Wu, J. Sun, R. Pachipulusu, V. Mandavilli, M. Gaevski, M. Shatalov, and M. Asif Khan, Electron. Lett. (in press).
[12] M. Shatalov, G. Simin, V. Adivarahan, A. Chitnis, S. Wu, R. Pachipulusu, V. Mandavilli, K. Simin, J. P. Zhang, J. W. Yang, and M. Asif Khan, Jpn. J. Appl. Phys. **41**, 5083 (2002).
[13] URL [http://www.crosslight.com]