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Ultraviolet light-emitting diodes at 340 nm using quaternary AlInGaN multiple quantum wells

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An ultraviolet light-emitting diode with peak emission wavelength at 340 nm is reported. The active layers of the device were comprised of quaternary AlInGaN/AlInGaN multiple quantum wells, which were deposited over sapphire substrates using a pulsed atomic-layer epitaxy process that allows precise control of the composition and thickness. A comparative study of devices over sapphire and SiC substrates was done to determine the influence of the epilayer design on the performance parameters and the role of substrate absorption. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1425453]

Recently reported[1–4] approaches using GaN/InGaN multiple quantum well (MQW) light-emitting diodes (LEDs) as pumps for YAG:Ce^{3+} and other inorganic and polymer phosphors for solid state white lighting suffer from severe color rendering and low power conversion efficiency problems.[1] These problems can be greatly minimized by using down-conversion phosphors and ultraviolet (UV) light-emitting diodes with emission wavelengths below 350 nm. Deep UV laser/LED pumps are also required for spectroscopic systems used in chemical identifications where a pulsed light source is preferred for a synchronous detection scheme. UV LEDs with emission wavelengths below 350 nm require the use of ternary AlGaN or quaternary AlInGaN active layers. In the past, several groups have demonstrated UV LEDs with peak emission wavelength around 350 nm using AlGaN/AlGaN MQWs in the active region.[5–7] Nishida *et al.*[5] grew device structures over n^+-SiC substrates, which offer advantages of a vertically conducting geometry and easier thermal management, especially for dc pump currents. However, for wavelengths below 360 nm, n^+-SiC substrates are highly absorbing. Sapphire substrates are a better choice because they allow collection of UV light emitted from both the top and bottom sides. They, however, require better thermal management, especially for high dc pump currents.

The choice of AlGaN/AlGaN MQWs in the active region also puts a limitation on the lowest emission wavelengths that can be used. Deep UV LEDs require use of high Al-content AlGaN/AlGaN MQWs, which has been shown[8] to severely degrade their emission characteristics because of reduced overlap integrals due to physical separation of the electron-hole wave functions. This separation arises from large spontaneous and piezo polarization fields. These fields impact not only the highest Al-mole fraction but also the maximum number of quantum wells that can be used in the active region, thereby limiting the maximum power emitted.

Recently, we have demonstrated a strain energy band engineering (SEBE) approach to tailor built-in strain[9,10] and to significantly improve the quantum well emission properties by using the quaternary AlInGaN material system.[11,12] These improvements result not only from strain management but also from overall material quality improvement as a result of In incorporation into the ternary AlGaN layers.[13] Using quaternary AlInGaN/AlInGaN MQWs in the active region we now present a comparative study of UV LEDs with 340 nm peak emission wavelengths on sapphire and n^+-SiC substrates. The focus of our study was to determine the role of substrate absorption, thermal properties, and the number of quantum wells in the active region in controlling the UV-LED emission characteristics. We also employed a pulsed atomic layer epitaxy (PALE) approach to deposit AlInGaN layers for the quaternary active region. This PALE approach allows accurate control of the active layer's composition and thickness.[14]

The epilayer structure for our UV LED, shown in the inset of Fig. 1, was deposited over basal plane sapphire and n^+-SiC substrates using low-pressure metalorganic chemical

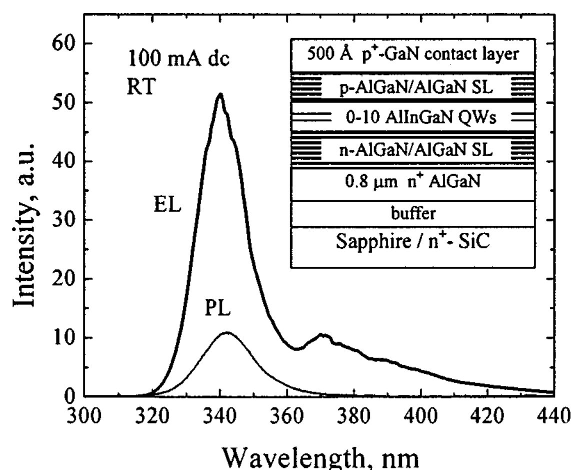

FIG. 1. RT EL spectrum of an UV LED under 100 mA dc drive current. The RT PL spectrum of a corresponding structure is shown for comparison. The inset presents a schematic drawing of the quaternary UV LED structure.

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vapor deposition (LPMOCVD) and growth parameters similar to those in our earlier report.[14] The device structure consists of a 0.8 μm thick n^+-$Al_{0.26}Ga_{0.74}N$ layer followed by a 30 period n^+-$Al_{0.2}Ga_{0.8}N/Al_{0.16}Ga_{0.84}N$ superlattice with periodicity of 30 Å. Both of these layers were n doped to 1×10^{18} cm^{-3} using an In/Si codoping approach.[15] The device active layers consisted of a quaternary $Al_{0.15}In_{0.02}Ga_{0.83}N/Al_{0.1}In_{0.01}Ga_{0.89}N$ MQW, the barrier and well layer thickness of which were each kept at 15 Å and the number of wells was varied from 0 to 10. The MQW was deposited using the PALE approach.[14] Similar to in our previous reports for GaN,[16] AlN,[17] and AlGaN,[18] the PALE approach also allows the deposition of high Al-quaternary AlInGaN layers with superior structural and optical quality even at growth temperatures, 200–300 °C below those of conventional LPMOCVD. Several percent of In can thus be incorporated into the quaternary AlInGaN layers and can significantly improve their structural and optical properties.[13] The composition of the bottom layer n^+-AlGaN contact layer, the n^+-AlGaN/AlGaN superlattice, and the quaternary AlInGaN layers for the MQW active region were selected to give a band-to-band emission at 310 nm, 320 nm, and 340 nm, respectively. This was verified by measuring the room temperature (RT) photoluminescence (PL) of these individual layers using a pulsed excimer laser. The active layers were then capped with a 10 period p-$Al_{0.2}Ga_{0.8}N$ (15 Å)/p-$Al_{0.16}Ga_{0.84}N$ (15 Å) superlattice where bis-Mg was used for the p doping. Finally, a 500 Å Mg-doped p^+-GaN layer was deposited to serve as the p-contact layer.

LED structures with 300×300 μm^2 geometry were then fabricated. For the sapphire substrates, access to the bottom n-contact $Al_{0.26}Ga_{0.74}N$ layer was made by use of a reactive ion etching process. The n contact consisted of Ti (100 Å)/Al (600 Å)/Ti (200 Å)/Au (2000 Å) and was annealed at 800 °C for 1 min in forming gas. For the n^+-SiC substrates, the n contact was formed on the entire backside using Ni/Al/Au and a 800 °C 1 min anneal in forming gas, thereby resulting in LED structures with vertical conduction geometry. For either substrate type, a top transparent p contact was formed using Pd (50 Å)/Au (50 Å) e-beam metallization. The contact was annealed at 450 °C for 1 min in oxygen ambient. A Ti (200 Å)/Au (2000 Å) p-probe contact was also deposited on part of the transparent p contact.

In Fig. 1, we show RT elctroluminescence (EL) emission spectra for the sapphire based UV LED at forward bias of 100 mA measured from the substrate side. Also included is the RT PL signal for the quaternary MQW of the active region obtained using a pulsed excimer laser pump (193 nm). As can be seen, the peak emission wavelengths for the EL and for the PL signals at 340 nm are in good agreement. These data clearly establish the feasibility of using quaternary AlInGaN active layers for deep UV LEDs and lasers. The peak emission wavelength and the spectral features of SiC substrate based LEDs were also very similar to those on sapphire (Fig. 1).

In the inset of Fig. 2, we show the current–voltage characteristics of an UV LED device structure on sapphire with 10 quantum wells. As can be seen, the device turns on at forward bias of 5 V and its series resistance is around 60 Ω. This latter value is about a factor of 2 higher than that for

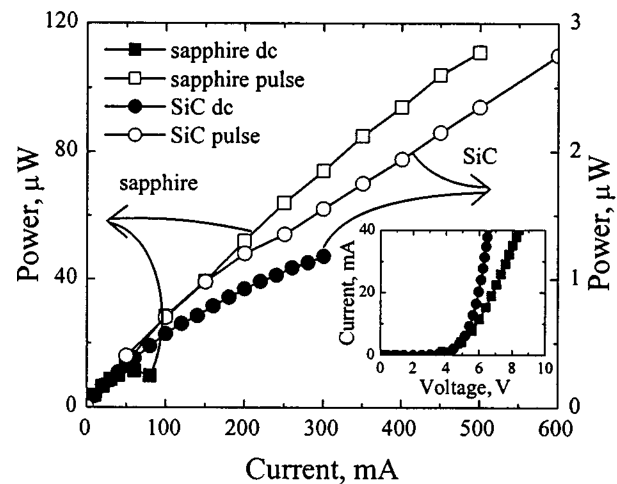

FIG. 2. Output power vs bias current for an AlInGaN MQW UV LED on sapphire (squares) and on SiC (circles) under dc (closed symbols) and pulsed (open symbols) pumping. The dc current–voltage characteristics of sapphire (squares) and SiC (circles) based devices are shown in the inset.

identical geometry high quality GaN/InGaN MQW LEDs on sapphire with emission wavelengths in the blue–green region.[12] In Fig. 2, we also have included the power emitted as a function of the forward bias current, both under dc and pulsed pumping using 500 ns pulses with a 0.1% duty cycle. As can be seen, the dc power emitted (at 340 nm) saturates rapidly at about 11 μW for pump current of 50 mA. This we believe is due to the poor thermal conductivity of the sapphire substrate and can be avoided by proper heat sinking. In pulsed mode, the LEDs demonstrated stable operation with output power of 0.11 mW at bias current of 500 mA. These power levels are a factor of 1.6 higher than those reported by Nishida *et al.* for their 350 nm LEDs on a SiC substrate.[5] We believe that our power levels should increase further by using better thermal management and employing packaged devices that would allow the collection of light emitted from the edges and from the top p-contact side.

Finally we also studied the absorption of p-GaN and the AlInGaN/AlInGaN superlattices by measuring the output power from the transparent p-contact side. This value was measured to be only 1.1 μW at a pump current of 50 mA. This factor of 10 reduction in the measured power suggests strong absorption by the 500 Å thick p-GaN layer which has a band gap that corresponds to 365 nm. From these data, we estimated the absorption coefficient of the p-GaN layer to be 5×10^5 cm^{-1} at 340 nm. Decreasing the p-GaN layer thickness to 150 Å should result in an increase in the top power by a factor of 4. Therefore, the use of thick GaN epilayers or substrates is detrimental to deep UV emission devices.

The data in Fig. 2 indicate two key problems that need to be overcome to improve the emission characteristics of UV LEDs on sapphire substrates. First, the forward differential resistance, R_s, is quite high. The spreading resistance from the bottom n contact and the active region quantum well heterojunction barriers are the key contributors to R_s. Second, the low thermal conductivity of sapphire results in early saturation of the dc-emitted powers. To further study the role of the substrate, we deposited several MQW LED structures over n^+-SiC substrates that had conducting n^+-$Al_{0.26}Ga_{0.74}N$ as a buffer layer, with the rest of the device

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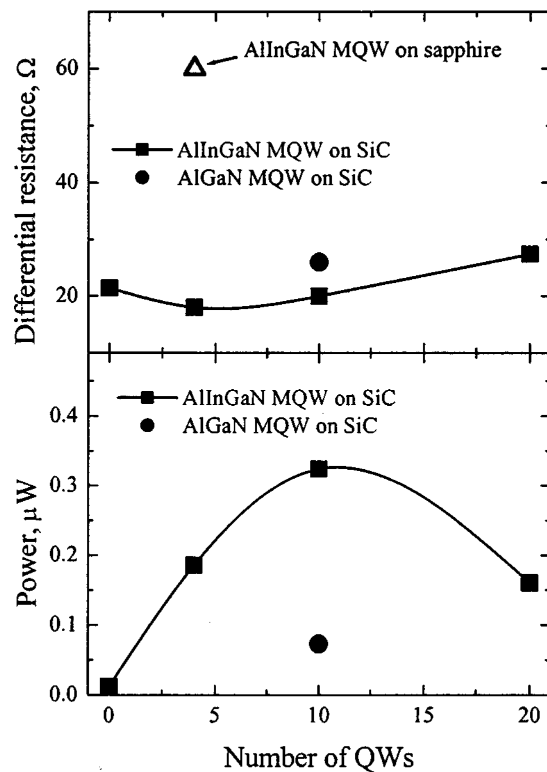

FIG. 3. Differential resistance (top) and output power (bottom) vs the number of QWs in active region for SiC based LEDs. The differential resistance of a LED on sapphire is shown for comparison.

structure identical to that of the LEDs over sapphire. The number of quantum wells in the active region varied from 0 to 10. Vertically conducting LED structures identical in size to our sapphire based devices were then fabricated.

In the inset of Fig. 2, we also include the $I-V$ characteristics for a SiC based UV LED with 10 quantum wells in the active region. As can be seen, it had a turn-on voltage of 5 V and a differential resistance of only 18 Ω. We thus conclude that lateral conduction geometry and the resistivity of the bottom n-contact layer add nearly 42 Ω to the total resistance of a $300\times300\ \mu m^2$ UV LED over a sapphire substrate. Also included in Fig. 2 is the dc power for the SiC based LED measured from the top p-contact side as a function of the bias current. As can be seen, no power saturation is observed even for dc pump current as high as 200 mA, thereby establishing the thermal management superiority of SiC. These data support our contention that by proper heat sinking and improved conductivity of the bottom n-contact n^+-$Al_{0.26}Ga_{0.74}N$ layer we should achieve stable high-power operation for sapphire based UV-LEDs under dc-current pumping.

In Fig. 3 we include the differential resistance and total power emitted from identical MQW UV LEDs on a SiC substrate as a function of the number of quantum wells in the active region. It is interesting to observe that total power emitted first increases as the number of quantum wells increases to 10 and then decreases with a further increase in the number of the wells. Also for a fixed number of wells (10), the power emitted decreases by a factor of 5 when the quaternary AlInGaN wells and barriers are replaced by ternary AlGaN well/barriers of appropriate composition. These data clearly establish the superiority of our approach of using quaternary AlInGaN layers for UV LED devices. Although the power goes up nearly linearly with the number of quantum wells, the differential resistance increases as well (see Fig. 3). From these data it is easy to see that an optimal device design should contain 4–10 quantum wells in the active region.

In summary, using quaternary AlInGaN/AlInGaN multiple quantum wells in the active region, we have reported on a deep UV LED on sapphire and SiC substrates with a peak emission wavelength of 340 nm. A pulsed atomic layer epitaxy procedure was used for the deposition of quaternary AlInGaN layers in the active region. The LEDs reported are well suited for spectroscopic systems for chemical identification. They can also serve as phosphor pumps for solid-state white lighting. Our study clearly points out that careful selection of the top p-contact (GaN) layer thickness, the number of quantum wells in the active region, and the substrate type are key factors that strongly influence the device's differential resistance and the total emitted power.

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[1] T. Tamura, T. Setomoto, and T. Taguchi, J. Lumin. **87–89**, 1180 (2000).
[2] I. Akasaki and H. Amano, Jpn. J. Appl. Phys., Part 1 **36**, 5393 (1997).
[3] Y. Sato, N. Takahashi, and S. Sato, Jpn. J. Appl. Phys., Part 2 **35**, L838 (1996).
[4] F. Hide, P. Kozodoy, S. P. Denbaars, and A. J. Heeger, Appl. Phys. Lett. **70**, 2664 (1997).
[5] T. Nishida, H. Saito, and N. Kobayashi, Appl. Phys. Lett. **78**, 399 (2001).
[6] A. Kinoshita, H. Hirayama, M. Ainoya, Y. Aoyagi, and A. Hirata, Appl. Phys. Lett. **77**, 175 (2000).
[7] N. Otsuka, A. Tsujimura, Y. Hasegawa, G. Sugahara, M. Kume, and Y. Ban, Jpn. J. Appl. Phys., Part 2 **39**, L445 (2000).
[8] T. Deguchi, K. Sekiguchi, A. Nakamura, T. Sota, R. Matsuo, S. Chichibu, and S. Nakamura, Jpn. J. Appl. Phys., Part 2 **38**, L914 (1999).
[9] M. Asif Khan, J. W. Yang, G. Simin, R. Gaska, M. S. Shur, and A. Bykhovsky, Appl. Phys. Lett. **75**, 2806 (1999).
[10] M. Asif Khan, J. W. Yang, G. Simin, R. Gaska, M. S. Shur, H.-C. zur Loye, G. Tamulaitis, A. Zukauskas, D. J. Smith, D. Chandrasekhar, and R. Bicknell-Tassius, Appl. Phys. Lett. **76**, 1161 (2000).
[11] J. P. Zhang, J. W. Yang, G. Simin, M. Shatalov, M. Asif Khan, M. S. Shur, and R. Gaska, Appl. Phys. Lett. **77**, 2668 (2000).
[12] M. Shatalov, A. Chitnis, V. Adivarahan, A. Lunev, J. Zhang, J. W. Yang, Q. Fareed, G. Simin, A. Zakheim, M. Asif Khan, R. Gaska, and M. S. Shur, Appl. Phys. Lett. **78**, 817 (2001).
[13] G. Tamulaitis, K. Kazlauskas, S. Jursenas, A. Zukauskas, M. A. Khan, J. W. Yang, J. Zhang, G. Simin, M. S. Shur, and R. Gaska, Appl. Phys. Lett. **77**, 2136 (2000).
[14] J. P. Zhang, E. Kuokstis, Q. Fareed, H. Wang, J. W. Yang, G. Simin, M. Asif Khan, R. Gaska, and M. S. Shur, Appl. Phys. Lett. **79**, 925 (2001).
[15] V. Adivarahan, G. Simin, G. Tamulaitis, R. Srinivasan, J. W. Yang, M. Asif Khan, M. S. Shur, and R. Gaska, Appl. Phys. Lett. **79**, 1903 (2001).
[16] M. Asif Khan, R. A. Skogman, J. M. Van Hove, D. T. Olson, and J. N. Kuznia, Appl. Phys. Lett. **60**, 1366 (1992).
[17] M. Asif Khan, J. N. Kuznia, R. A. Skogman, D. T. Olson, M. MacMillan, and W. J. Choyke, Appl. Phys. Lett. **61**, 2539 (1992).
[18] M. Asif Khan, J. N. Kuzina, D. T. Olson, T. George, and W. T. Pike, Appl. Phys. Lett. **63**, 3470 (1993).

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