Ultraviolet Light-Emitting Diodes at 340 nm using Quaternary AlInGaN Multiple Quantum Wells

V. Adivarahan
A. Chitnis
J. P. Zhang
M. Shatalov
J. W. Yang

See next page for additional authors

Follow this and additional works at: https://scholarcommons.sc.edu/elct_facpub

Part of the Electromagnetics and Photonics Commons, and the Other Electrical and Computer Engineering Commons

Publication Info

This Article is brought to you by the Electrical Engineering, Department of at Scholar Commons. It has been accepted for inclusion in Faculty Publications by an authorized administrator of Scholar Commons. For more information, please contact digres@mailbox.sc.edu.
Ultraviolet light-emitting diodes at 340 nm using quaternary AlInGaN multiple quantum wells

V. Adivarahan, A. Chitnis, J. P. Zhang, M. Shatalov, J. W. Yang, G. Simin, M. Asif Khan, R. Gaska, and M. S. Shur

Citation: Applied Physics Letters 79, 4240 (2001); doi: 10.1063/1.1425453
View online: http://dx.doi.org/10.1063/1.1425453
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/79/25?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Quantum-well and localized state emissions in AlInGaN deep ultraviolet light-emitting diodes

Influence of residual oxygen impurity in quaternary InAlGaN multiple-quantum-well active layers on emission efficiency of ultraviolet light-emitting diodes on GaN substrates

Effects of In composition on ultraviolet emission efficiency in quaternary InAlGaN light-emitting diodes on freestanding GaN substrates and sapphire substrates
J. Appl. Phys. 98, 113514 (2005); 10.1063/1.2134885

Improved performance of 325-nm emission AlGaN ultraviolet light-emitting diodes
Appl. Phys. Lett. 82, 2565 (2003); 10.1063/1.1569040

Localization of carriers and polarization effects in quaternary AlInGaN multiple quantum wells
Recently reported\textsuperscript{1–4} approaches using GaN/InGaN multiple quantum well (MQW) light-emitting diodes (LEDs) as pumps for YAG:Ce\textsuperscript{3+} and other inorganic and polymer phosphors for solid state white lighting suffer from severe color rendering and low power conversion efficiency problems.\textsuperscript{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. 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.\textsuperscript{5–7} Nishida et al.\textsuperscript{5} grew device structures over n\textsuperscript{+}-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\textsuperscript{+}-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\textsuperscript{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\textsuperscript{9,10} and to significantly improve the quantum well emission properties by using the quaternary AlInGaN material system.\textsuperscript{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.\textsuperscript{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\textsuperscript{+}-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.\textsuperscript{14}

The epilayer structure for our UV LED, shown in the inset of Fig. 1, was deposited over basal plane sapphire and n\textsuperscript{+}-SiC substrates using low-pressure metalorganic chemical
vapor deposition (LPMOCVD) and growth parameters similar to those in our earlier report.\textsuperscript{14} The device structure consists of a 0.8 $\mu$m 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 $1 \times 10^{18}$ cm$^{-3}$ using an In/Si co-doping approach.\textsuperscript{15} The device active layers consisted of a quaternary $Al_{0.15}In_{0.05}Ga_{0.85}$N/$Al_{0.1}In_{0.05}Ga_{0.85}$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.\textsuperscript{14} Similar to in our previous reports for GaN,\textsuperscript{16} AlN,\textsuperscript{17} and AlGaN,\textsuperscript{18} the PALE approach also allows the deposition of high Al-quantum 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.\textsuperscript{13} The composition of the bottom layer $n^+$-$AlGa$N contact layer, the $n^+$-$AlGa$N/AlGa$N$ superlattice, and the quaternary AlInGa$N$ 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 $p$-$Al_{0.26}Ga_{0.74}$N (15 Å)/$p$-$Al_{0.10}Ga_{0.84}$N (15 Å) superlattice where bis-Mg was used for the $p$ doping. Finally, a 500 Å Mg-doped $p^+$-Ga$N$ layer was deposited to serve as the $p$-contact layer.

LED structures with 300×300 $\mu$m$^2$ 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 using 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 electroluminescence (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 AlInGa$N$ 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 $\Omega$. This latter value is about a factor of 2 higher than that for identical geometry high quality GaN/InGaN MQW LEDs on sapphire with emission wavelengths in the blue–green region.\textsuperscript{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. The dc current–voltage characteristics of the $p$-contact side. This value was measured to be only 1.1 $\mu$W at a pump current of 50 mA. This factor of 10 reduction in the measured power suggests strong absorption by the 500 Å thick $p$-Ga$N$ layer which has a band gap that corresponds to 365 nm. From these data, we estimated the absorption coefficient of the $p$-Ga$N$ layer to be $5 \times 10^5$ cm$^{-1}$ at 340 nm. Decreasing the $p$-Ga$N$ 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, $R_+\prime$, is quite high. The spreading resistance from the bottom $n$ contact and the active region quantum well heterojunction barriers are the key contributors to $R_+\prime$. 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
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 and output power 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 decreases by a factor of 5 when 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.

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.

This work was supported by the Ballistic Missile Defense Organization (BMDO) under U.S. Army SMDC Contract No. DASG60-98-1-0004, monitored by Terry Bauer, Dr. Brian Strickland, and Dr. Kepi Wu.