Enhanced vertical and lateral hole transport in high aluminum-containing AlGaN for deep ultraviolet light emitters

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(Received 29 March 2013; accepted 19 May 2013; published online 10 June 2013)

Improved p-type conductivity is demonstrated in AlGaN:Mg superlattice (SL) cladding layers with average Al composition ~60%. The vertical conductivity ranges from $6.6 \times 10^{-5}$ S/cm at a DC current of 1 mA to ~0.1 S/cm at 550 mA and approaches the lateral conductivity that was obtained from Hall-effect measurements. The effective acceptor activation energy ($E_A$) in the SL was determined to be 17 meV, nearly 10× smaller than $E_A$ in homogeneous p-GaN. The devices sustain current densities of 11 kA/cm$^2$ under DC and up to 21 kA/cm$^2$ under pulsed operation. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4809947]

Ultraviolet (UV) light sources are important for a number of applications such as materials processing, dermatology and keratectomy in medicine, and high-density data storage in computing. Such UV sources can be fabricated in the AlGaN alloy system, which provides a direct energy band gap ranging from 3.4 eV (GaN) up to 6.2 eV (AlN). It is feasible to develop AlGaN structures allowing electron-hole band gap ranging from 3.4 eV (GaN) up to 6.2 eV (AlN). It is feasible to develop AlGaN structures allowing electron-hole recombination and emit photons at wavelength from 365 nm down to 210 nm.1 To date, laser diodes emitting at wavelengths down to 336 nm under pulsed operation and 363 nm under continuous-wave (CW) operation have been reported.2,3 A well-known obstacle that inhibits the development of UV laser diode (LD) at even shorter wavelength is the difficulty of achieving both transparency and conductivity in the p-layer. For p-type AlGaN, transparency can be readily achieved by increasing Al composition. However, it is well known that the p-type AlGaN:Mg conductivity decreases with rising aluminum (Al) composition because of the relatively high Mg acceptor activation energy.4,5,7 A superlattice (SL) was demonstrated to facilitate hole activation by utilizing the band offset and strong built-in spontaneous and piezoelectric polarization fields instead of thermal energy.8,9,11

In an effective p-cladding layer, holes are transported in the vertical direction before recombining with electrons within the quantum wells. Employing a short period SL facilitates an increased hole state dispersion that enhances the vertical conductivity. Long period SL can induce higher hole concentration at the interfaces because thicker layers cause a larger change in the potential across the layer. This can lead to p-type dopant ionization and formation of holes, but tunneling across the Al$_x$Ga$_{1-x}$N layer would likely be suppressed. An optimization of the thickness as well as the Al composition discontinuity is required to enhance hole transport, especially in the vertical direction, for deep UV light emitter applications.

Previous studies demonstrated vertical hole-transport in a SL by injecting a current density of 0.2 kA/cm$^2$ through a SL comprising 0.6 nm/1.4 nm AlN/GaN in a p-n diode.12 The corresponding band gap of the SL makes the layer transparent to light of optical energy less than 4.0 eV, which is equivalent to a wavelength of about 310 nm. Short-period SLs with 5.0 eV effective band gap and 1.25 nm period have been previously described.13,14 Although the SLs displayed high vertical conductivity of about 0.02 S/cm, current injected through them was equivalent to current density of less than 1 kA/cm$^2$. In this Letter, a p-type SL is reported which is transparent to 255 nm light and allows a current density up to 21 kA/cm$^2$. The SL reported here was developed on high-quality bulk aluminum nitride (AlN) substrates having a dislocation density less than 10$^6$ cm$^{-2}$.15 The bulk AlN substrate enabled the growth of a higher quality AlGaN/AlGaN SL because of better matching of lattice parameters and thermal expansion coefficients in comparison to sapphire substrate.16–18

The SL was grown by using metal-organic vapor phase epitaxy (MOVPE) on bulk AlN substrates. The growth was initiated with a 50 nm thick slow-growth-rate AlN buffer layer. Then AlN/GaN SPSL transition layers were deposited to reduce defect generation arising from lattice-constant mismatch and layer relaxation. A 200 nm thick Al$_x$Ga$_{1-x}$N/Al$_y$Ga$_{1-y}$N SL, having layer thicknesses $L_1/L_2$ where $(x \times L_1 + y \times L_2)/(L_1 + L_2) = 0.6$, was grown on top of the transition layer. A 16-nm thick Mg-doped GaN contact layer was deposited to ensure formation of an ohmic p-contact to the SL. As seen in Fig. 1(a), cross-sectional transmission electron microscopy (TEM) indicates abrupt interfaces in the p-type SL. X-ray investigations and optical transmission measurements of the p-type SL were performed to confirm the average Al composition. The spectrum, shown in Fig. 1(b), indicates that the sample was transparent to wavelengths above 255 nm at which 50% of normalized transmission was transmitted. This is equivalent to an optical bandgap of about 4.9 eV and corresponds to a band gap of AlGaN with an Al composition of 60%. The Ni/Au metal contacts were then sputtered and processed into Van der Pauw pattern for resistivity measurements. For the electrical
measurement, the p-type GaN layer outside the metal contact region was removed by chemically assisted ion-beam etching (CAIBE) to ensure hole transport only through the SL.

Figure 2 shows the resistivity as a function of temperature for the p-type SL. For comparison the resistivity curves of homogeneous GaN and Al$_0$$_7$Ga$_{0.3}$N (Refs. 19 and 20) are also shown. It is anticipated that the resistivity-temperature curve of a homogeneous p-type Al$_x$Ga$_{1-x}$N (0.0 < x < 0.7) would fall between the solid line and the solid-square line in Fig. 2. The resistivity of homogeneous Al$_x$Ga$_{1-x}$N at room temperature (dashed line) therefore varies from 1 $\Omega$-cm to 1.0 $\times$ 10$^5$ $\Omega$-cm when varying z from zero to 0.7. At room temperature, the resistivity value of the SL with average Al composition of 60% is 9.6 $\Omega$-cm. The result indicates that a substantial number of holes are activated by built-in polarization fields in the SL at room temperature. The weak temperature dependent resistivity curve measured for the SL provides evidence for polarization-field-activated holes that are immune to carrier freeze-out at 100 K. The effective EA can be extracted from temperature-dependent resistivity by employing an Arrhenius equation under the assumption that the mobility is comparatively independent of temperature. The effective EA value of 17 meV obtained for the p-type SL (with an average Al composition of 60%) is much lower than the values of 146 and 323 meV expected for p-type homogeneous GaN and Al$_{0.7}$Ga$_{0.3}$N, respectively.

The highly conductive p-type SL was then incorporated into a p-n diode and compared with another p-n diode having a homogeneous Al$_{0.6}$Ga$_{0.4}$N p-layer. The p-n diodes consisted of a 300 nm thick unintentionally doped AlGaN transition layer on an AlN substrate, a 480 nm thick Si-doped Al$_{0.74}$Ga$_{0.26}$N contact layer (n ~ 8 $\times$ 10$^{18}$ cm$^{-3}$), a 500 nm thick Si-doped SL layer (n ~ 8 $\times$ 10$^{18}$ cm$^{-3}$) having an average Al composition of 74%, a 200 nm thick p-type layer, a 30 nm thick Mg-doped AlGaN grading contact layer, and a 16-nm thick Mg-doped GaN contact layer. The p-layer employed in the diodes was either p-type SL or a homogeneous layer of Al$_{0.6}$Ga$_{0.4}$N. The p-n diodes were then processed into broad-area stripes with two rectangular shaped n-contacts (n$_{pn}$ and n$_p$) adjacent to a mesa, as seen in Fig. 3(a). Fig. 3(b) shows the potential differences $V_{pcontact}$-to-$V_{pn}$ ($V_{pn}$) and $V_{contact}$-to-$n_p$ ($V_{np}$) that arise when incremental current is injected from $p_{contact}$ to $n_{pn}$. We assume that current spreading beyond the bottom edge of the mesa toward $n_p$ is negligible when current flows from $p_{contact}$ to $n_{pn}$. This assumption was verified by the good match between $V_{pn}$ and the summation of $V_p$ plus the potential difference between $n_p$ and $n_{pn}$, at every current level. This shows that $V_p$ can be seen as a measure of the vertical potential drop from $p_{contact}$ across the $p$-layer and the built-in potential.

Table I shows the components of $V_p$ measured for p-n diodes with p-type SL or homogeneous Al$_{0.6}$Ga$_{0.4}$N. To avoid joule heating, a current level of only one mA was employed to estimate the room temperature vertical conductivity. A voltage drop of 0.26 V at the p contact was calculated from the contact area (30 $\mu$m $\times$ 500 $\mu$m) and a contact resistivity of 4 $\times$ 10$^{-2}$ $\Omega$-cm$^2$ obtained from the circular transmission line method (CTLM). We assume that the built-in potential $V_{bi}$ is equivalent to 4.3 V. The voltage drops across the p-type SL and the homogeneous Al$_{0.6}$Ga$_{0.4}$N layer are then calculated to be 2.04 V and 4.04 V, respectively, as seen in Table I. This indicates that the p-type SL is about two times more conductive than the homogeneous layer when current flows in the vertical direction. A vertical conductivity of 6.6 $\times$ 10$^{-3}$ S/cm at room temperature was estimated for the 200 nm p-type SL.

To further characterize the flow of current through the p-type SL, devices were fabricated into broad area geometries with U-shape n-contacts surrounding the mesa stripes. This increased the n-contact area and, therefore, reduced joule heating from the n-contact. A multiple-quantum-well
(MQW) and an electron-blocking-layer (EBL) were also incorporated between the p-layer and n-layer in p-n diodes. The EBL is incorporated in order to suppress the overflow of electrons into the p-layer. Fig. 4 shows the IV curve for the device being operated under DC conditions. A current level of 550 mA could be achieved that is equivalent to a current density of 11 kA/cm². For pulsed operation a current density of 21 kA/cm² before breakdown could be realized.

A lower limit of the vertical conductivity of the p-SL at high current density was estimated under the approximation that the resistivity of the p-SL was the dominant component in the diode heterostructure. With this assumption, the differential resistance of the IV curve above turn-on approximates the resistance from the p-SL. Figure 5 shows the vertical conductivity of the p-SL at various current densities. The vertical conductivity is $6.6 \times 10^{-5}$ S/cm for a current density of 20 A/cm², increases to about 0.01 S/cm at a current density of 1 kA/cm², and reaches 0.1 S/cm for the highest current density of 11 kA/cm². This final value approaches that for the lateral conductivity determined from the Hall-effect measurements described above. Carrier transport in vertical direction relies on tunneling processes via the higher bandgap layers in the SL and might vary with changes in the applied voltage and temperature during operation. Monitoring the QW emission wavelength for different currents indicated a temperature change within the device. Specifically, we observed a blue shift of the QW emission for current densities up to 0.5 kA/cm². For higher drive current densities, the emission shifted to longer wavelengths. The shift to higher energies can be explained by a reduced influence of the quantum confined Stark effect by screening the internal field with injected carriers, whereas the shift to lower energies is related to an increase in temperature within the active zone. This suggests that the strong increase in vertical conductivity at low current levels might result from band bending effects, whereas, for current densities greater than about 0.5 kA/cm², heating might additionally contribute to the increased vertical conductivity at high current levels. The actual vertical conductivity of the p-layer may be even larger than the estimated values because the potential differences across the several contributing resistive components in series were all attributed to only the p-layer for the estimation.

<table>
<thead>
<tr>
<th>Voltage-drop components of p-n diodes with p-type SL and homogeneous p-type Al$<em>{0.5}$Ga$</em>{0.5}$N at 1 mA.</th>
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<tbody>
<tr>
<td>p-n diode</td>
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<td>$V_{pn}$ (measured)</td>
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<td>$V_p$ (measured)</td>
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<tr>
<td>Built-in potential: $V_{bi}$</td>
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<tr>
<td>Voltage drop at p-contact: $V_{pc}$</td>
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<tr>
<td>Voltage drop at p-layer: $V_p = V_{bi} - V_{pc}$</td>
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</table>

FIG. 4. Current-voltage measurement of a multiple quantum well device with p-type SL under DC operation. Inset shows the 2 Ampere pulse shape when injecting into the device.

FIG. 5. A measure of p-SL vertical conductivity (red dots) vs. current density. The dashed line is a guide for the eye.

FIG. 3. (a) Four wire measurement schematics. (b) $V_{pn}$ and $V_p$ versus current of devices with p-type SL and homogeneous Al$_{0.5}$Ga$_{0.5}$N.
In summary, a highly conductive Mg-doped AlGaN SL with an average Al composition of 60% was achieved. Our superlattice is transparent to 255 nm light. For hole transport in the lateral direction, the measurement of finite values of resistivity at temperature down to 100 K provides support for hole activation by the built-in polarization fields in the p-type SL. For hole transport in vertical direction, the measured value of $6.6 \times 10^{-5}$ S/cm for the p-type SL at 1 mA is about two times greater than the conductivity of the homogeneous Al$_{0.6}$Ga$_{0.4}$N. For a drive current density of 11 kA/cm$^2$, the vertical conductivity of the p-SL approached 0.1 S/cm, which was comparable to the value determined in lateral direction from Hall measurements. The demonstration of high current density (e.g., 21 kA/cm$^2$) through a p-type SL structure suggests its applicability toward realizing deep-UV nitride laser diodes.

This work was supported by the Defense Advanced Research Projects Agency CMUVT Program under U.S. Army Cooperative Agreement No. W911NF-10-02-0102.