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High-quality p–n junctions with quaternary AlInGaN/InGaN quantum wells

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We report on quaternary AlInGaN/InGaN multiple quantum well (MQW) light emitting diode structures grown on sapphire substrates. The structures demonstrate high quality of the p–n junctions with quaternary MQW. At low forward bias (below 2 V), the temperature dependent of current–voltage characteristics are exponential with the ideality factor of 2.28, which is in a good agreement with the model of the injected carrier recombination in the space charge region. This ideality factor value is approximately three times lower than for conventional GaN/InGaN light emitting diodes (LEDs). The obtained data indicate the recombination in p–n junction space charge region to be responsible for a current transport in LED structures with quaternary quantum wells. This is in contrast to InGaN based LEDs, where carrier tunneling dominates either because of high doping of the active layer or due to the high density of localized states. © *2000 American Institute of Physics.* [S0003-6951(00)01550-3]

High-brightness blue and green light emitting diodes (LEDs) with the operation lifetime exceeding 10^4 h and external quantum efficiencies more than 10% on sapphire and SiC substrates have been successfully demonstrated and commercialized using ternary InGaN material system. The expansion of GaN-based light emitter performance into ultraviolet (UV) spectral range requires the introduction of AlGaN barrier layers with wider energy gap. So far, however, little success has been demonstrated in developing AlGaN/GaN LEDs. A poor performance of UV AlGaN/GaN LEDs can be attributed to (i) a large built-in strain and associated strong electric fields, which reduce the rate of optical band-to-band transitions; and (ii) lower quality of AlGaN/GaN heterointerfaces compared to those in GaN/InGaN quantum well structures.

Recently, we demonstrated the lattice and energy band engineering approach using AlInGaN materials.[1,2] This technique allowed us to eliminate the lattice mismatch in AlInGaN/GaN structures and, at the same time, to retain large energy band offsets. In addition, the incorporation of even small amounts of In significantly improved the quality of AlGaN layers grown at reduced temperatures.[3,4] This points to a high potential of quaternary AlInGaN material system for the development of efficient UV light emitters.

In this letter, we report on GaN-based p–n junctions with quaternary AlInGaN barriers and InGaN quantum wells in the space charge region. We measured the electrical properties of these structures and compared these devices to commercial InGaN-based blue LEDs. Our data on the superior electroluminescence of AlInGaN/InGaN multiple quantum well (MQW) LEDs will be published elsewhere.

GaN p–n junctions with AlInGaN/InGaN MQWs were grown over sapphire substrates using low pressure metalorganic chemical vapor deposition. A deposition of 200-Å-thick AlN nucleation layer was followed by the growth of 3-μm-thick n^+-GaN layer doped with Si up to $5\times10^{18}\,\mathrm{cm}^{-3}$. The growth was performed at 76 Torr and 1000 °C. The nominally undoped $\mathrm{Al_{0.15}In_{0.04}Ga_{0.81}N/In_{0.14}Ga_{0.86}N}$ MQWs were grown on n^+-GaN and were capped with a 200-Å-thick p-$\mathrm{Al_{0.15}Ga_{0.85}N}$ electron blocking layer followed by the growth of 0.25-μm-thick p-GaN layer doped with Mg up to about $5\times10^{17}\,\mathrm{cm}^{-3}$. The quantum well and barrier thickness in MQWs structures were 25 and 50 Å, respectively.

After growth, a 300×300 μm square geometry 0.8 μm deep mesa was etched to make the bottom n contact. Then n-type ohmic contact consisting of Ti/Al/Ti/Au was deposited and annealed. An approximately 100-Å-thick transparent Pd/Au p-ohmic contact was deposited on top of the mesa, followed by the formation of a thick Ti/Au contact pads.

The current–voltage (I–V) characteristics of the devices exhibited sharp turn-on close to 3.5 V with the differential resistance of 36 Ω (see Fig. 1). A typical turn-on voltage and differential resistance of commercial Nichia blue InGaN LEDs are 3 V and 25 Ω, respectively. We attribute a higher turn-on voltage and differential resistance for the AlInGaN barrier devices to the differences in the current injection for the two structures. The Al and In composition of the quaternary material was chosen to match the lattice constant, a, of the AlInGaN layer to that of the surrounding GaN layers, while the band gap of the quaternary layer was larger than that of GaN by approximately 300 meV. This could impede the current injection into the MQW region under moderate forward bias.

The electroluminescence (EL) spectrum of the AlInGaN device under 50 mA dc forward current is plotted in the inset to Fig. 1. As can be seen from the figure, the spectrum of the AlInGaN/InGaN LEDs exhibits a peak at around 430 nm. The spectrum full width at half maximum is below 20 nm, which indicates a reasonable MQW layer quality.

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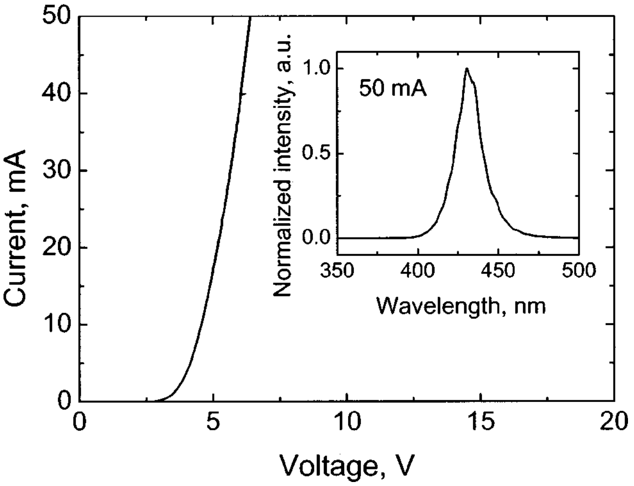


FIG. 1. dc $I-V$ characteristics of AlInGaN/InGaN MQW LED at room temperature. The EL spectrum at 50 mA is shown in the inset.

In order to determine the recombination mechanism in AlInGaN LEDs, we measured the current of AlInGaN devices in the voltage range from 0.5 to 5 V using an HP 4156B parameter analyzer. We were not able to measure accurately the currents smaller than 10^{-12} A because of the system limitations. The $I-V$ curves of the AlInGaN LEDs are plotted on semilogarithmic scale in Fig. 2. The $I-V$ characteristic of AlInGaN LED has two distinct slopes, at low and moderate voltages, respectively, as seen from Fig. 2. In the low voltage range (0.5–2 V), the slope of semilogarithmic plot is close to that described by Sah–Noyce–Shockley model of a $p-n$ diode with the carrier recombination in the space charge region.[5] From these curves, we have found the ideality factor η of 2.28 for the AlInGaN device. For comparison, the dashed line shows the slope with ideality factor $\eta=2$ for room temperature. Much higher values of ideality factors $\eta\approx 6-7$ have been reported for GaN based $p-n$ diodes and AlGaN/InGaN LEDs.[6–8] Such values are commonly attributed to the carrier tunneling rather than to the thermal diffusion and recombination.[6,7] In commercially available blue LEDs at low bias, the carrier tunneling in space charge region occurs either because of high doping of the active layer or due to the high density of localized states. Such a process is shown schematically in Fig. 3(a).

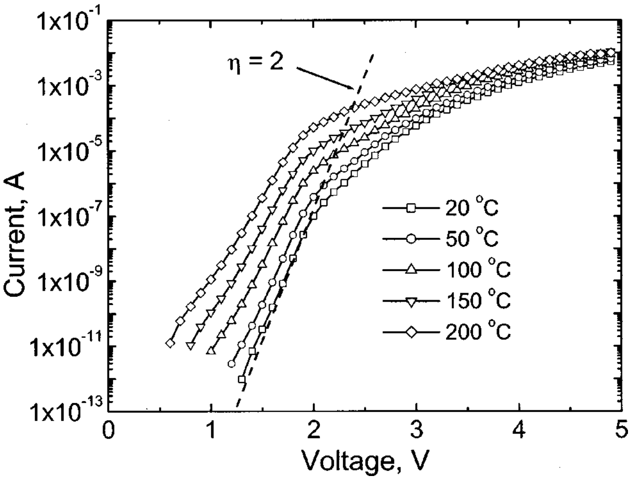
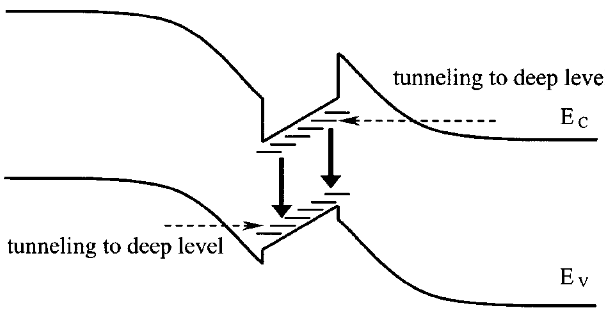


FIG. 2. Low current $I-V$ curves of AlInGaN device at different temperatures. The slope with ideality factor $\eta=2$ is shown by dashed line.

(a) InGaN-based DH structure



(b) AlInGaN/InGaN MQW structure

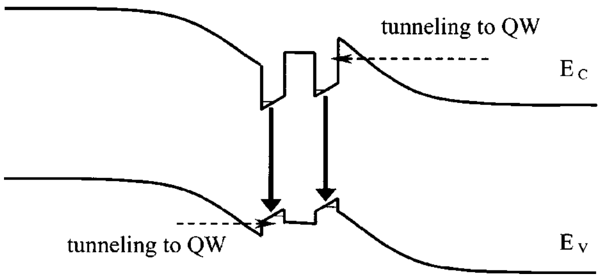


FIG. 3. Schematic of the carrier tunneling in (a) blue InGaN based LEDs with high doping or high density of localized states and in (b) MQW AlInGaN/InGaN LEDs at moderate bias.

When the tunneling current plays the major role, the slope of the $I-V$ characteristic should be temperature independent because the tunneling transparency of the barrier practically does not depend on temperature.[6–8] For our structure, the temperature dependence of the $I-V$ slopes is proportional to 1/kT with practically no temperature dependence of the ideality factor, η. The fact that in our samples η is close to 2 indicates that the recombination current is a major mechanism of the current transport, in contrast to commonly observed tunneling mechanism for standard blue AlGaN/InGaN LEDs and GaN $p-n$ diodes.[6–8] The dependence of the saturation current on temperature for the AlInGaN LED was exponential with the activation energy of 1.22 eV. This value is about 200 meV smaller than that expected from the InGaN energy gap.

In order to estimate the possible contribution of tunneling in the carrier transport we measured capacitance–voltage ($C-V$) characteristics for both device types. The slope of $1/C^2$ vs V was linear showing the ionized impurity concentration of $1.4\times 10^{18}\,\mathrm{cm}^{-3}$ for AlInGaN/InGaN structure. The space charge thickness at zero bias found from $C-V$ measurements is about 0.1 μm. With that thick space charge region direct tunneling from conduction to valence band is not possible.

As can be seen from Fig. 2, at the medium voltage range (2–3 V) the slope of the $I-V$ curves changes. We believe that at higher bias the barriers in the active layer produced by piezoelectric field and by spontaneous polarization limit the current transport and the tunneling through these barriers oc-

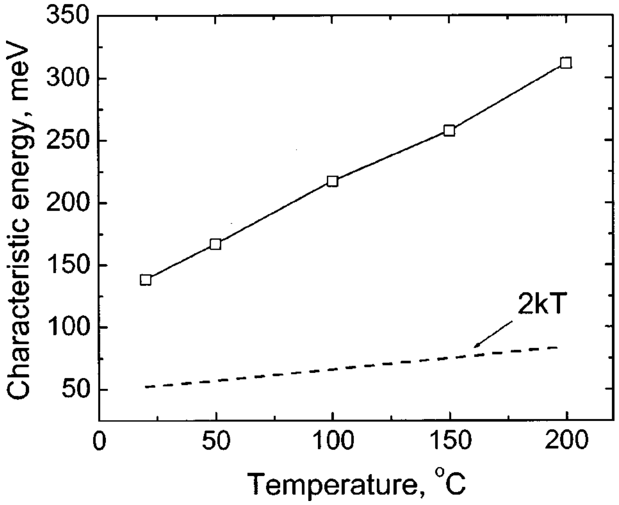


FIG. 4. The dependence of the characteristic energy parameter E for AlInGaN LEDs on temperature. The slope of 2 kT is shown for comparison.

curs. The schematic diagram of this process is shown in Fig. 3(b). This process results in a different slope of $I-V$ curve at higher biases. In this range, the $I-V$ curve can be approximated by an exponential function

$$I = I_1 \exp\left(\frac{qV}{E}\right), \qquad (1)$$

where V is applied voltage and E is the characteristic energy.[7] Note that the device series resistance is small enough and is not important in this voltage range. In Fig. 4, we plotted the temperature dependence of the characteristic energy E for AlInGaN LEDs. The slope of 2 kT, which is characteristic for the carrier recombination in space charge region, is shown for comparison. In contrast to the commonly observed lack of the temperature dependence of the parameter E in InGaN based LED (typical for the tunneling mechanism) we observe a strong temperature dependence of the parameter E. At room temperature, the value of the parameter E of about 140 meV is close to the values reported for InGaN LEDs (148–182 meV),[7] which shows that the barrier transparency for the tunneling is about the same for both types of devices. However, at higher temperatures, the characteristic energy E for the quaternary structure increases showing the reduction of the barrier transparency. This increase in the effective barrier width can be attributed to the temperature dependence of strain and polarization in the quaternary MQW region.

In conclusion, the high quality of $p-n$ junction with quaternary MQW was demonstrated. The measured $I-V$ curves of AlInGaN/InGaN MQW LEDs show the value of ideality factor of 2.28 at room temperature. This value is close to theoretical prediction for the carrier recombination in the space charge region. Thus, the results obtained indicate a good quality of the quarternary AlInGaN layers and AlInGaN/InGaN heterointerfaces. This opens up the way to develop the efficient UV and visible light sources using the quarternary AlInGaN/InGaN quantum well devices.

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