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Effect of thermal annealing of Ni/Au ohmic contact on the leakage current of GaN based light emitting diodes

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The effect of thermal annealing on current–voltage properties of GaN light emitting diodes (LEDs) has been studied. At annealing temperatures above 700 °C, the $p-n$ junction of the diodes became very leaky and Ga-contained metallic bubbles were observed on the surface of Ni/Au $p$-ohmic contact. Transmission electron microscopy and energy dispersive x-ray spectrometer studies revealed that these metallic bubbles resided directly on top of the threading dislocations in GaN and both Ni and Au were indiffused into the LED structure along the cores of the TDs. The conducting paths formed by the metal containing dislocation cores are believed to be the cause for the observed short circuit behavior of $p-n$ junctions at high annealing temperatures. © 2003 American Institute of Physics. [DOI: 10.1063/1.1601306]

GaN-based light emitting diodes (LEDs) operating in the green to violet range of the visible spectrum is commercially available and got a great interest these years. In the device process step, a good ohmic contact is necessary to achieve a high performance device. Also, the thermal stability of these contacts is an important issue for device operation.

In the fabrication of ohmic contact to GaN, different metals were applied in both $n$ and $p$ type. For $n$-type GaN, low resistance ohmic contacts around $10^{-5} - 10^{-8}$ $\Omega$ cm$^2$ range have been obtained using Ti/Al metal series. For $p$-type GaN, the high work function metals such as Ni, Pd, and Pt were applied. The specific contact resistance around $10^{-2} - 10^{-6}$ $\Omega$ cm$^2$ can be achieved in the Ni/Au, Pd/Au, Ni/Pt/Au, Pd/Pt/Au, and Ni/Pd/Au series. The annealing process around 400–750 °C is necessary to achieve good ohmic properties for both $n$- and $p$-type case. However, the heat generated by the ohmic loss in the device operation is an important reason to cause the device degradation. The serious degradation in contact morphology can also be observed at higher temperature process due to the formation of new interfacial phases.

Some literatures reported that the threading dislocation (TD) may degrade the device performance and is a nonradiative recombination center in GaN. The TD provided a diffusion pathway of metals and cause the leakage current in GaN-based devices. It is also an important source of reverse leakage current in diodes and cause the poor electrostatic discharge behavior in the devices.

Thus, we know both contact metals and TDs affect the $I-V$ characteristics of the GaN-based devices. Yet, lack of direct studies about the electric properties of the contact metals and TDs. In this work, we fabricate the GaN-based multiquantum well (MQW) structure LEDs and study the electric properties under different thermal treatment. The surface morphology and microstructure of these LEDs with different thermal treatment have been characterized by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) analysis. Compare with the electrical properties, the existence and influences of dislocations on LEDs can be clearly characterized in this work.

The blue GaN-based MQW LEDs wafers were grown by metalorganic chemical vapor deposition on $c$-plane sapphire substrate. Trimethylgallium, trimethylindium, and ammonia were used as Ga, In, and N precursors, respectively. The layer structure consists of a GaN buffer layer, followed by a 1.5 $\mu$m undoped GaN layer, a 3 $\mu$m Si-$n$ doped GaN layer.

![FIG. 1. $I-V$ characteristics of GaN LEDs at various annealing temperatures.](image-url)
(n\(\sim\)1\(\times\)10¹⁸ cm⁻³), the active layer, a 0.12-μm-thick Mg-(p) doped AlGaN cladding layer (p\(\sim\)5\(\times\)10¹⁷ cm⁻³), and a Mg-(p) doped GaN contact layer (p\(\sim\)7\(\times\)10¹⁷ cm⁻³). The active region, consisting of seven 5 nm/15 nm InGaN/GaN quantum wells is embedded in the region between p-type and n-type layers.

The LEDs are fabricated using standard lithography. In the first process step, a mesa is defined with standard photolithography and etched down into the n-type region by inductively coupled plasma reactive ion etching technology. The thin Ni/Au (5 nm/5 nm) transparent contact layer (TCL) was deposited by electron (e)-beam evaporation and defined on the p-GaN region. A thick Ni/Au (50 nm/150 nm) contact layer was fabricated on the thin Ni/Au TCL with standard lift-off technology by the same e-beam evaporation, followed by a 500 °C annealing process. The Ti/Al/Ti/Au (10 nm/50

FIG. 2. SEM image of Ni/Au on p-GaN contact surface after annealing at 900 °C.

FIG. 3. Cross-section bright-field TEM micrographs of the LEDs structure after annealing at (a) 900 and (b) 600 °C.

FIG. 4. EDS spectra obtained from different regions: (a) EDS-1 at metallic bubble of Fig. 3(a), (b) EDS-2 at threading dislocation of Fig. 3(a), (c) EDS-3 at p-GaN layer of Fig. 3(a), and (d) EDS-4 at threading dislocation of Fig. 3(b).
nm/100 nm/150 nm) metals for the n contact are then deposited on the n-GaN layer, followed by the annealing process at 300 °C.

The wafers were then cut into chips. These chips were then annealed with different temperatures in a furnace with continuous nitrogen flow in ten minutes. The electrical characteristics were measured at room temperature with HP-4155 I–V analyzer. For TEM measurements, the specimens were carried out by JEOL JEM-2100 microscope operated at 200 kV. The SEM surface images were taken with Hitachi S-4000 instrument.

Figure 1 shows the I–V characteristic of GaN based LEDs with different annealing temperatures. In the forward bias region, similar I–V characteristics with the ideal factor around 2.9 can be seen with annealing temperature below 500 °C. Thus, similar electron-hole recombination behavior can be expected in this region. The reverse bias current increase a little as the anneal temperature increase from 700 to 900 °C. The electrical short circuit behavior as shown in Fig. 1 with annealing temperature higher than 600 °C can be realized. Our studies provide the direct evidence that metals indiffusion along the TDs cause the degradation of the LEDs characteristics.

In conclusion, the influences of thermal annealing on electrical properties of GaN LEDs have been investigated. After annealing above 700 °C, the electrical short circuit behavior has been observed. At annealing 900 °C, Ga-containing metallic bubbles have been observed on the p-GaN surface by SEM. Both TEM and EDS analyses reveal that the core of the TD contains Ni and Au after annealing higher temperatures. These results imply direct evidences that the migration and indiffusion of Ni and Au along the TDs cause the short circuit characteristics of the p–n junction at high temperatures.

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