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Thermal annealing dependence of Ni/Ag ohmic contact in oxygen ambience on GaN PN-junction diode

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In this paper, we investigated growth of GaN pn-junction layers on silicon (111) by plasma assisted molecular beam epitaxy (PA-MBE) system and the effect of thermal annealing of Ni/Ag contacts on the sample. The full width at half maximum (FWHM) was measured as 0.34°, indicating a good quality layer of sample. The structural evolution and temperature dependence of the current of Ni/Ag contacts on GaN pn-junction at various annealing were investigated by scanning electron microscopy (SEM) and current-voltage (I-V) measurements. The temperature dependence of the current may be attributed to changes of the surface morphology of Ni/Ag films on the surface. SEM results indicated the degradation of Ni/Ag contacts on GaN pn-junction above 800°C.

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Keywords: GaN/Si, PN-junction, III-nitride

1. Introduction

GaN has a wide direct band gap of 3.4 eV and has attracted considerable interests in high-temperature and high-power applications [1-4]. For these applications, high-quality ohmic and Schottky contacts have been key factors in improving performance and reliability. The operation condition of these applications often involves elevated temperature. Therefore it is vital to understand the behaviour of metal contacts to GaN at high-temperature.

Ni/Ag bi-layer contact has been used for this work. Nickel was selected as the metal at the interface between metal and semiconductor due to its ability to diffuse through the oxide contamination layer between the Ni and GaN and reach directly in contact with GaN itself. The selection of Ag as capping layer over Al was motivated by the thermal stability of the metals. The melting point for Ag is at 962°C while Al is at a very low temperature which is 660.4°C. Therefore, samples with fabricated Ni/Ag on GaN pn-junction were able to be annealed until 800°C to investigate the electrical properties as well as the thermal stability of the samples.

In this work, we report on the structural evolution and temperature dependence of the Ni/Ag ohmic contacts on GaN pn-junction layer at different annealing temperatures.

2. Experimental

All samples were grown in Veeco Gen II MBE system, with radio-frequency plasma source. Silicon and magnesium were used as n-type and p-type sources, respectively. The 3-inch Si (111) substrate was ex-situ cleaned with the standard cleaning procedure by using RCA method before loaded into the MBE system. The substrates were outgassed at 900 °C for 2 hours in ultra-high vacuum. In order to remove SiO_2 on the surface of silicon, a few monolayers of Ga were deposited on the substrate to form Ga_2O_3. A clean Si (111) can be seen from the presence of prominent Kikuchi lines in the typical Si (111) 7 x 7 surface reconstruction pattern. To prevent the SiN formation at the surface, a few monolayers of Al were deposited before the nitrogen source was activated.

The buffer or wetting layer, AlN was first grown on the Si substrate. To grow AlN buffer layer, the substrate temperature was heated up to 870°C, both of the Al and N shutters were opened simultaneously for 15 minutes. Subsequently, n-GaN epilayer was grown on top of the buffer layer followed by p-GaN epilayer. Both pn-junction layers were grown at 45 minutes with substrate temperature set at 870°C, respectively (See Fig. 1). For GaN pn-junction layers, silicon and magnesium were used as n and p dopants, respectively.

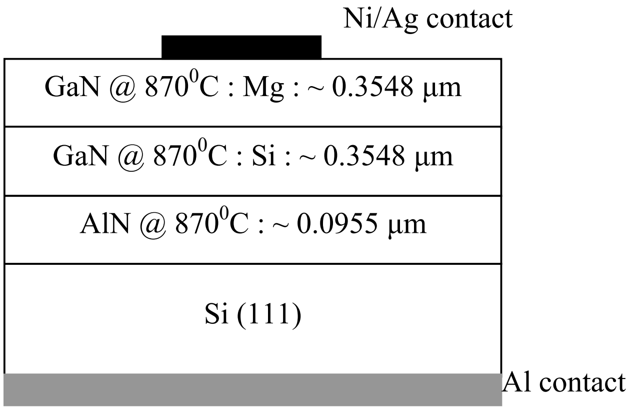


Fig. 1. Sample structure of GaN pn-junction.

The native oxide was removed in the NH_4OH:H_2O = 1:20 solution for 5 min, then rinsed with deionised water. Subsequently, the samples were dipped into HF:H_2O = 1:50 for 20 s then rinsed with deionsed water. The cleaned samples were then chemically etched in boiling aqua regia of HCl: HNO_3 = 3:1 (3 min) to reduce the amount of oxygen (O) and carbon (C) contamination of the GaN surfaces. Wafers were then blown dry with compressed air after cleaning and are ready for the next fabrication step. In order to make GaN p-n junction diode on silicon, ohmic contact has been fabricated. First, nickel (Ni) with 300 nm thick was evaporated onto the p-GaN through a metal mask, followed by the evaporation of 100 nm capping layer of Ag. Ohmic contact on backside substrate was made by thermal evaporation of Al on silicon substrate.

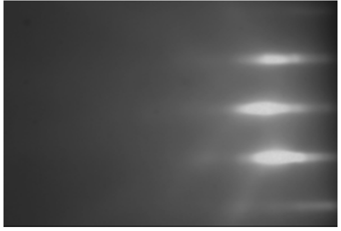
3. Results and discussion

Figs. 2 (a) - (c) show the RHEED images of sample during the growth of GaN pn-junctions on silicon substrate. The Si substrate surface showed a clear 7 x 7 surface reconstructions at high temperature, as shown in Fig. 2 (a). After the growth of AlN, RHEED displayed a streaky pattern indicating good surface morphology as revealed in Fig. 2 (b). During the last step of GaN pn-junctions growth (Fig. 2(c)), the streaky RHEED pattern is sharpened, suggesting the improvement of the crystalline quality of GaN pn-junctions relative to the AlN buffer layer. Fig. 3 indicates the 2Θ XRD spectra of the sample.

The XRD measurement shows that the heterostructure of III-nitrides were epitaxially grown on silicon substrate. It can be seen from the presence of the peak at 34.515^0 which is identified as wurtzite GaN (0002) diffraction, and three peaks at 36.028^0, 72.846^0 and 76.503^0, which correspond to AlN (0002), GaN (0004) and AlN (0004) respectively. The peak at 28.245^0 is from the Si (111). The XRD spectra indicate that no sign of cubic phase of GaN are found within the detection limit of the XRD, so it is confirmed that our samples possessed hexagonal structure.

2(a) Ga cleaning

2(b) AlN



2(c) GaN

Fig. 2. RHEED pattern for the growth process of GaN pn-junction layers on AlN/Si(111).

XRD symmetric RC $\omega/2\theta$ scans of (0002) plane at room temperature was also conducted to verify the crystalline quality of the thin films. The full width at half-maximum (FWHM) is the difference between the energies or frequencies on either side of a spectral line or resonance curve at which the line absorption or emission or the resonant quantity reaches half its maximum intensity. According to Fig. 4, the FWHM of GaN pn-junction sample has been calculated as 0.34^0. This value is comparable to that reported by other researchers [5].

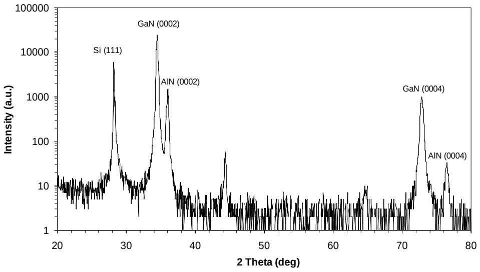


Fig. 3. XRD spectra of GaN pn-junctions on Si (111).

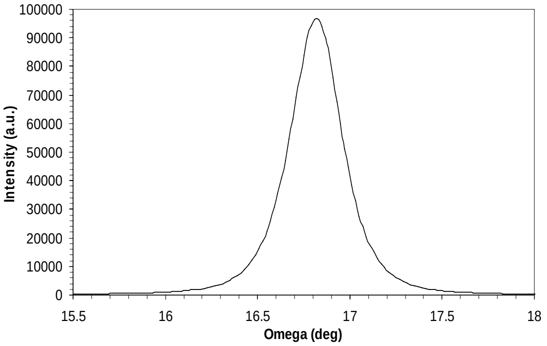


Fig. 4. Rocking curve (RC) ω/2θ scans of (0002) plane for n-type GaN pn-junction sample.

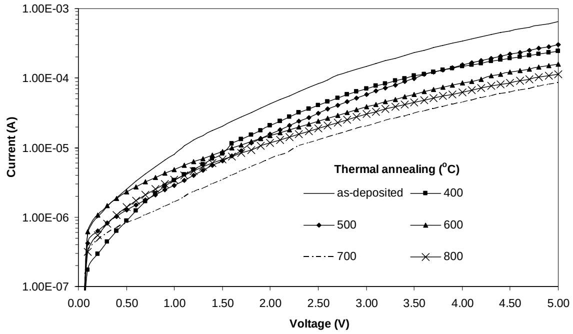
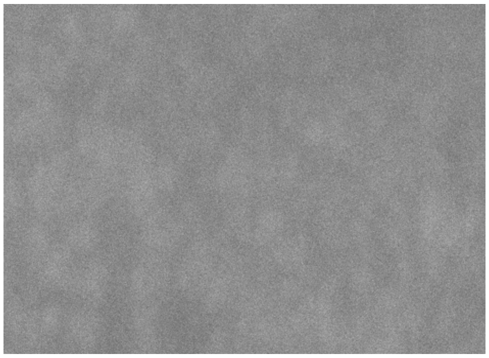
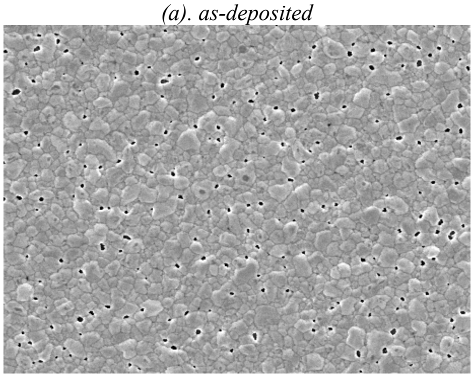


Fig. 5. I-V Characteristics of O_2 annealed Ni/Ag contact on GaN pn-junction under various annealing temperature.

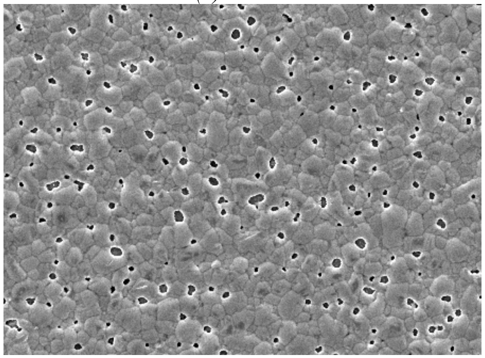
Fig. 5 shows the I-V characteristics of the Ni/Ag contact diode samples under various annealing temperature in oxygen ambient. The GaN pn-junction diode shows the highest current for the as-deposited sample compared than annealed samples. GaN is known to suffer from a high amount of defect densities due to reason like the difference between the thermal expansion coefficient and large lattice mismatch between the substrates and the GaN material, especially of those grown on Si [6-9]. The high amount of current observed can be attributed to the tunneling of carrier across the barrier. This effect can be assisted by the interfacial layer to produce trap-assisted tunnel currents. The existence of a thin interfacial layer cannot be ruled out unless the semiconductor is cleaved in an ultra-high vacuum condition [10-11]. Generally, we found that the thermal annealing on samples in oxygen ambient can reduce the current. The lowest current of diode was for the 700°C annealed sample.



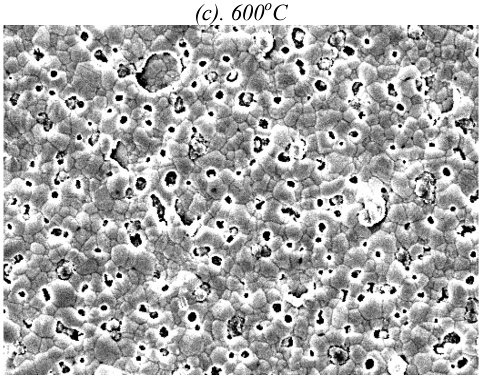
(a). as-deposited



(b). 400°C



(c). 600°C



(d). 800°C

Fig. 6. Ni/Ag contacts on GaN pn-junction annealed for 10 min at (b) 400 °C, (c) 600 °C, (d) 800 °C, in oxygen ambient and (a) as-deposited as a control sample.

The SEM images revealed the surface morphologies of Ni/Ag contacts on GaN pn-junction with different annealing temperature. Fig. 3 shows that the surface morphology of contacts annealed in oxygen ambient for 10 min experience 'balling up' effect at 400^{o}C as compared to a smooth surface of the as-deposited sample. Increasing the annealing temperature to 400^{o}C brings more dramatic changes; the particles of Ag become larger and hollow. After annealing at temperature of 600^{o}C, more dark areas can be seen that have also increased in size. At 800^{o}C, surface became rougher and degraded as compared with as-deposited sample, indicating the non-uniform inter-diffusion and inter-mixing of the metals. We suggest that the reason for the current reduction is due to the metal hollows formation on the samples and the degradation of contact surface.

4. Conclusions

Thermal annealing effects on Ni/Ag/GaN pn-junction were studied by annealing samples in O_2 ambience for 10 min at different temperatures. The structural evolution and temperature dependence of the current of Ni/Ag/GaN pn-junction were investigated. The temperature dependence of the current may be attributed to changes of surface morphology of Ni/Ag films on the surface. When the elevated temperature is above 400^{o}C, the formation of hollow and the low current limit the Ni/Ag/GaN pn-junction contacts make them stable and effective electrical contacts.

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