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Summary, Conclusions & Future Work
Gallium nitride (GaN) is a thermally stable, wide direct band gap $(E_g = 3.4 \text{ eV})$ semiconductor material. They are highly attractive materials for optoelectronic devices such as photo-detectors, light emitting diodes and laser diodes operating in short wavelength region. In addition, these materials also have been recognized as prospective candidates for high-temperature and/or high power devices such as metal-semiconductor field effect transistors (MESFETs), metal-insulator field effect transistors (MISFETs) and high electron mobility transistors (HEMTs). To achieve high functional performance of such devices, the fabrication of high quality ohmic and Schottky contacts are required.

Ohmic contacts are integral components of devices and integrated circuits. Without low resistance and reliable ohmic contacts, the intrinsic properties of semiconductor devices can be impeded. The development of low-resistance ohmic contacts to GaN is particularly challenging, as compared to the other well-studied III-V compounds (GaAs and InP) because of its large band-gap (3.4 eV). Though many attempts have been made to find ways of lowering contact resistivity mostly using variation of metal schemes and surface treatments, there is still much work to be done to understand the means to improve the performance and efficiency of devices.

The concept of Schottky barrier height is used to describe the properties of a rectifying contact. The electronic properties of the Schottky contact, namely the Schottky barrier height, the reverse bias leakage current, and the thermal stability critically influence the performance of the electronic and optoelectronic devices. In GaN-based Schottky contacts, the excess reverse bias leakage current is still a major impediment even though continuous improvement in the synthesis of III–nitride materials
by different growth techniques leads to increased device quality. Therefore, the development of more reliable and thermally stable Schottky contacts is essential for the application of power amplifiers and optoelectronic devices operating at high temperatures.

To develop high quality GaN-based semiconductors, it is essential to carry out some important research into the properties of metal-GaN interfaces. The present research work involves mainly the development of high quality ohmic and Schottky contacts to p- and n-type GaN. The electrical and structural properties of both ohmic and Schottky contacts were investigated by current-voltage (I-V), capacitance-voltage (C-V), Auger electron microscopy (AES) x-ray diffraction (GXRD) measurements before and after annealing temperature. High resolution electron microscopy (HREM) and scanning electron microscopy (STEM) combined with energy dispersive spectroscopy (EDS) was performed to carry out microstructure of the Ti/W/Au ohmic contact. Atomic force microscopy (AFM) was also employed to characterize the surface morphology of the samples before and after annealing.

A Pt (20 nm)/Ag (50 nm)/Au (30 nm) metallization scheme has been developed for the formation of ohmic contacts on moderately doped p-GaN (1.3×10^{17}cm^{-3}). It was shown that the electrical properties of the Pt/Ag/Au contacts improved with an increase in annealing temperature. Calculations showed that the specific contact resistivity is 4.43×10^{-3} \Omega\text{cm}^2 for the as-deposited samples and 1.02×10^{-3} \Omega\text{cm}^2 and 6.61×10^{-4} \Omega\text{cm}^2 for the samples annealed at 550 °C and 650 °C respectively. The specific contact resistance as low as 1.70×10^{-4} \Omega\text{cm}^2 was obtained after annealing at 800 °C for 1 min in N_2 ambient. The AES and XRD results showed the formation of particular types of interfacial phases at the metal/GaN
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interface such as Ga-Pt, Ga-Ag and GaAu. The occurrence of these gallide phases causes deep accepter-like Ga vacancies to be generated near the GaN surface. Thus, the increase in the carrier concentration near the surface of the GaN layer is likely to be responsible for the improved electrical characteristics of the Pt/Ag/Au contacts after annealing. The AFM results showed that the surface morphology of the contact annealed at 800 °C (RMS roughness of 19.9 nm) became somewhat degraded compared to the as-deposited sample (RMS roughness of 3.3 nm).

Low-resistance thermally stable Ti/W/Au ohmic contacts to n-type GaN (4.07x10^{18} cm^{-3}) were investigated as a function of the annealing temperature. It was shown that the I-V characteristics of the contacts became degraded upon annealing at temperatures below 750 °C for 1 min in N$_2$ ambient compared with that of the as-deposited sample. However, it was improved drastically when annealed at temperatures above 850 °C. Measurements showed that the contact annealed at 900 °C produces a low specific contact resistance of 8.4x10^{-6} Ωcm$^2$. The effective SBHs determined by the Norde and I-V methods were in the range of 0.43 – 0.27 eV and 0.48–0.32 eV, for the as-deposited and annealed at 900 °C, respectively. The AES, XRD, HREM and STEM results shows the formation of TiN interfacial layer at the metal composite-GaN interface. The formation of this TiN interfacial layer and, associated with it, an excess of N vacancies near the GaN surface region could be the reason for the low resistance of the Ti/W/Au contacts. However, a thin Au-Ga layer was also detected at the interface. An EDX analysis of the GaN interface indicates the presence of 46.8 at % Ti, 53.1 at % N, 3.0 at % W, 33.3 at % Au and 66.6 at % Ga. It is shown that the interfacial layer is rich in Ti and N (TiN) compared to that of Au-Ga layer according to STEM and EDX.
line profile. The AFM results showed that there was no significant degradation in the surface morphology (RMS roughness of 3.8 nm) of the contact during annealing at 900 °C, compared to the as-deposited one (RMS roughness of 3.0 nm).

The effect of thermal annealing temperature on the electrical properties of Rh and Rh/Au Schottky contacts to n-type GaN (4.07×10^{17} cm⁻³) has been investigated in the temperature range of 300-500 °C. For the as-deposited Rh Schottky diode, the leakage current at -1V is 2.3×10⁻⁴ A whereas the leakage current remains almost same for the samples annealed at temperatures 300 °C and 400 °C. However, the leakage current is increased to 1.8×10⁻³ A at -1 V when the sample is annealed at 500 °C. The calculated series resistance is in the range Rs = 219 – 633 Ω for the as-deposited and annealed Rh Schottky contacts. The estimated series resistance (Rs) of the as-deposited and annealed Rh/Au Schottky contacts is in the range Rs = 279 – 490 Ω. In the case of Rh/Au contacts, it was found that the series resistance of the diode increased with an increase in the annealing temperature. Measurements showed that the SBH values of Rh/n-GaN Schottky diode is 0.60 eV for as-deposited, 0.56 eV for 300 °C, 0.56 eV for 400 °C and 0.51 eV for 500 °C annealed contacts. The measured Schottky barrier heights of Rh/Au contact is 0.57 eV for as-deposited, 0.62 eV for 300 °C, 0.75 eV for 400 °C and 0.84 eV for 500 °C annealed contacts by I-V method. Norde method was also used to extract the Schottky barrier height of Rh and Rh/Au contacts. Calculations showed that the Schottky barrier heights of Rh contacts are 0.61 eV for as-deposited, 0.57 eV at 300 °C, 0.57 eV at 400 °C and 0.52 eV at 500 °C. The measurements showed that the SBH of Rh/Au contacts are 0.59 eV for as-deposited, 0.65 eV at 300 °C, 0.76 eV at 400 °C and 0.88 eV at 500 °C.
which are in good agreement with those obtained by current-voltage (I-V) method. The typical values of ideality factor, in case of Rh and Rh/Au Schottky diodes are found to be 1.17 and 1.98 (as-deposited) respectively. However, the ideality factor due to Rh/Au Schottky contact is improved to 1.12 after annealing at 400 °C.

The calculated carrier concentration of Rh Schottky contacts is $1.8 \times 10^{16}$ cm$^{-3}$ for the as-deposited, $1.3 \times 10^{16}$ cm$^{-3}$ for 300 °C, $1.2 \times 10^{16}$ cm$^{-3}$ for 400 °C and $1.1 \times 10^{16}$ cm$^{-3}$ for 500 °C annealed samples. The estimated carrier concentration of Rh/Au Schottky contacts is $8.47 \times 10^{16}$ cm$^{-3}$ for the as-deposited, $5.51 \times 10^{16}$ cm$^{-3}$ for 300 °C, $4.10 \times 10^{16}$ cm$^{-3}$ for 400 °C and $3.05 \times 10^{16}$ cm$^{-3}$ for 500 °C annealed samples using capacitance-voltage (C-V) technique. The measured Schottky barrier height of Rh contact is 0.98 eV for as-deposited, 0.88 eV for 300 °C annealed, 0.77 eV for 400 °C annealed, and 0.65 eV for 500 °C annealed contacts respectively. For Rh/Au Schottky contact, the Schottky barrier height is found to be 0.62 eV for as-deposited, 0.66 eV for 300 °C annealed, 0.83 eV for 400 °C annealed and 1.05 eV for 500 °C annealed contacts by C-V method.

Based on the I-V, Norde and C-V results, the Rh Schottky contact is relatively stable during annealing temperatures compared with that of Rh/Au Schottky contact. However, with an increase in the annealing temperature the Schottky barrier heights are enhanced for Rh/Au Schottky contact compared to the Rh Schottky contacts. This may be due to Rh/Au metal layers that react with the GaN, as will be confirmed by AES and XRD examinations. The interfacial reactions between Rh/Au metals and n-GaN layer were carried out by Auger electron microscopy and x-ray diffraction as a function of annealing temperature. The AES and XRD results showed that there are no interfacial phases in the
as-deposited sample. However, for the sample annealed at 400 °C and 500 °C, gallide phases are formed at the Rh/Au/n-GaN interface. The formation of GaAu$_2$, GaRh$_2$ and AuGa interfacial phases, results in the accumulation of gallium vacancies at the GaN surface. These compound phases may have different work functions than the Rh/Au contact layer, which is responsible for the increase of barrier heights.

**Future Work**

The electrical parameters of all the devices fabricated and characterized have been determined at room temperature. It will be interesting to study temperature dependent I-V and C-V characteristics of Schottky contacts.

DLTS measurements will be carried out to obtain trap parameters such as activation energy, trap density, and capture cross section of the defects before and after annealing at different temperatures. This can be the subject of our future work.