Electrical properties and thermal stability of Ti/Al ohmic contact on n-GaN Schottky diode

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(Received 6 December 2006)

In this paper, we investigated the electrical properties and thermal stability of Ti/Al bilayer metal as an ohmic contact on n-GaN Schottky diode. The Ti/Al was first deposited on n-GaN substrate, annealed at range of 400°C to 900°C in N_2 ambient for 20 s, and then Ti/Pt bilayer metal was deposited as a Schottky contact annealed at 400°C in N_2 ambient for 10 s. The electrical, structural and surface morphology of n-GaN Schottky diode were observed at annealing 400°C~900°C. It was found that at annealing 900°C, Ti/Al ohmic metal produced the best (I-V) characteristics barrier height (ϕ_B) 1.75 eV and ideality factor (η) 0.85 compared to other annealing temperature. The (C-V) characteristics of n-GaN Schottky diode were also observed at annealing 400°C~900°C at 100 kHz. It was found that at annealing 900°C the depletion region is maximum with capacitance value varied from 150 pF~240 pF as the applied voltage varied from –Ve to +Ve voltage. At low frequency 100 kHz the capacitance increase with increasing forward voltage which is frequency independent. The surface morphology, structural characteristics of Ti/Al was observed by SEM and XRD. It was found that Ti/Al shows surface morphological stability appeared even at higher temperature 900°C, the TiN compound is formed which is responsible for low electrical resistivity, chemical inertness, metallurgical stability and reliability at high temperature.

I. INTRODUCTION

Current progress in the fabrication of nitride-based electronic and optical devices, such as visible light-emitting diodes and metal–semiconductor field-effect transistors, makes the formation of reliable metal contacts to GaN essential. [1-3]

The development of thermally stable ohmic contacts to GaN is one of the main challenges for GaN-based device technology because of the large barrier height which develops when a metal is deposited on the semiconductor material. At elevated temperatures the onset of metal– GaN reactions can change the interface morphology substantially, a general concern in the fabrication of Ga–N based devices. However, the nature of these metal/GaN interactions is not well understood [4]. It also remains unclear just how the changes in interface morphology affect the electrical properties of the contact.

Many efforts to reduce the ohmic contact resistance of metal contacts on n-GaN epilayers have been reported recently. The metallization schemes generally include Al-only contact, Ti –only contact, Ti/Al bilayer contact and modification of the Ti/Al bilayer contact [5]. Ti as the first metal layer reported that interfacial reactions between the Ti-based contacts and the n-GaN can beneficially affect the electrical properties of the contacts. In particular, studies have indicated that formation of a TiN layer may be important for ohmic contact development because of its low work function and the creation of nitrogen vacancies in the GaN below the contact layer when the Ti and GaN react [6].

The present investigation focuses on the temperature induced electrical and morphological changes of Ti/Al on n-GaN Schottky diode. Current-voltage (I-V) and capacitance-voltage (C-V), Scanning electron microscopy ~SEM, X-ray diffraction ~XRD techniques are used to obtain electrical, morphological and structural information of interface areas.

II. EXPERIMENT

The n-GaN diode thickness 0.002mm (n~8e16 cm^{-3}) was grown on c-plane Al_2O_3 substrate (Fig. 1). Prior to the metallization, the native oxide was removed with NH_4OH:H_2O= (1:20) solution, followed by dipping in a HF: H_2O= (1:50) solution. The boiling aqua regia HCl: HNO_3= (3:1) was used to chemically etch and clean the samples. The fabrication process of n-GaN Schottky diode start with Ti/Al metal deposited using dc sputtering/thermal evaporator by mechanical mask (1mm) as an ohmic contacts. The samples were annealed in a temperature range from 400°C to 900°C for 20 s in N_2 ambient accordingly and then Ti/Pt metal was deposited using dc sputtering as a Schottky contact on n-GaN annealed at 400°C for 10 s in N_2 ambient. Finally, the current-voltage (I-V) and capacitance- voltage (C-V), Scanning electron microscopy (SEM) and X-ray diffraction (XRD) techniques was used to observe the electrical characteristics, surface morphology and chemical compounds formed between metal and semiconductor contact before and after annealing.

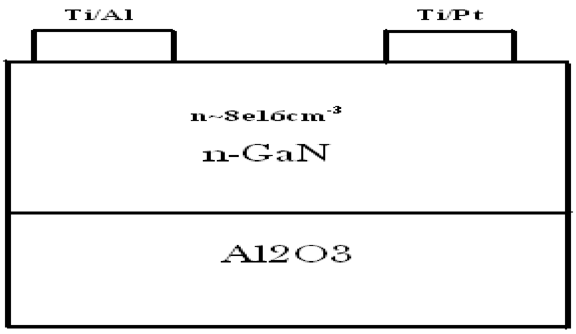


FIG. 1. Structure of n-GaN Schottky diode.

III. RESULTS AND DISCUSSION

The (I-V) characteristics of the Schottky diode, Φ_B and η, were determined assuming thermionic emission,

$$I = I_S\left[\exp\left(\frac{qv}{\eta kT}\right) - 1\right] \quad (1)$$

$$I_S = AA^{**}T^2\exp\left(\frac{-q\phi_B}{kT}\right) \quad (2)$$

Here I_S is the saturation current, A is the contact area, and A* is the effective Richardson constant (24 A/cm^2 k^2 for n-GaN and 72 A/cm^2 k^2 for p-GaN based on $A^* = 4\pi m^* qk^2/h^3$ with $m^* = 0.20m_0$ for n-GaN and $m^* = 0.60m_0$ for p-GaN), T is temperature, q is the electron charge, k is the Boltzman constant, and V is the applied voltage [7]. Fig. 2 shows the (I–V) characteristics of n-GaN Schottky diodes after annealing at different temperatures from 400°C ~900°C. The temperature dependence Schottky barrier height, Ideality factor is shown in the Table I. Annealing at temperature 700°C and 900°C the n-GaN Schottky diodes shows optimum barrier height (ϕ_B) 1.53 eV and 1.75 eV respectively, while ideality factor approaches to unity 0.75, 0.85 respectively. As the annealing temperature increases above 500°C the barrier height increases while ideality factor approaches to unity. At higher annealing temperature the leakage current is an approach to minimum as a result breakdown voltage increases. At higher annealing temperature there is preferential loss of nitrogen from the GaN surface. The nitrogen vacancies are thought to increase the carrier concentration at the metal/n-GaN interface [7].

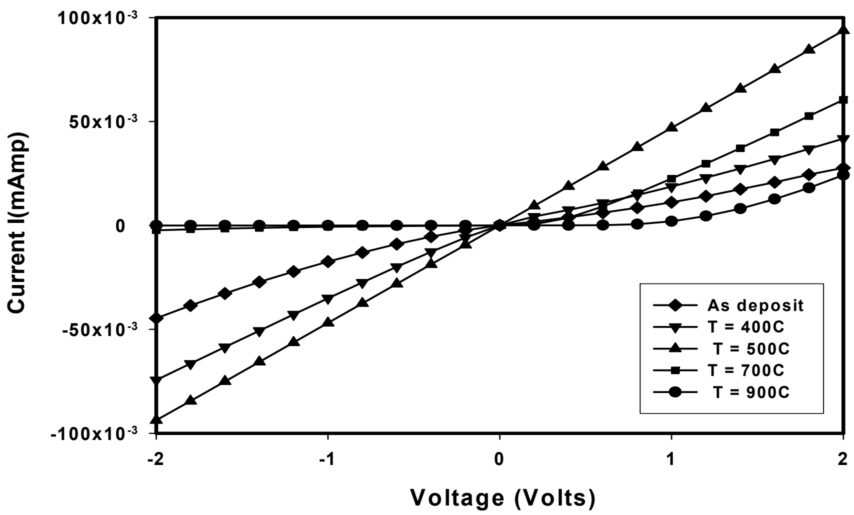


FIG. 2. (I-V) characteristics of n-GaN Schottky diode.

TABLE I. Summary of (I-V) characteristics of n-GaN Schottky diode.

Annealing Temperature	Barrier height (eV)	Ideality factor (η)
As deposited	0.70	0.53
400°C	0.79	0.34
500°C	1.26	0.30
700°C	1.53	0.75
900C	1.75	0.85

The variation of the external voltage applied through the metal contact will produce variation in the charged carrier at the surface of the semiconductor. Therefore the variation of the applied voltage will cause a variation of the capacitance. The capacitance of n-GaN Schottky diode can be determined as follows [8],

$$C = \frac{\varepsilon_0 \varepsilon_r A}{\sqrt{(2\varepsilon_0 \varepsilon_r / qND) \bullet (V_{bi} - Vapp)}} \, . \quad (3)$$

The (C-V) characteristics of n-GaN Schottky diode were measured at 100 kHz frequency at different annealing temperature is shown in Fig. 3. At 100 kHz frequency annealing at 400°C, 900°C and as deposited the diode sweep from accumulation to inversion mode through the depletion mode.

The variation of the depletion layer can be observed as a variation of capacitance. At annealing temperature 900°C, the depletion region is maximum with capacitance value increase rapidly from minimum value 150 pF to maximum value 240 pF as the applied voltage varied from –Ve to +Ve voltage. The capacitance increases with increasing forward voltage at low frequency 100 kHz which is frequency independent behavior [9].

The surface morphology of Ti/Al annealed at 500°C, 700°C and 900°C are observed by SEM images are shown in Fig. 4. The island form of surface morphology occurred at annealing 500°C, produced extremely poor results from electrical and structural point of view. While annealing at higher temperature 700°C and 900°C the Ti/Al did not show any loss of dimensional stability or surface morphology degradation respectively. Annealing at 400°C Schottky contact Ti/Pt did not shows any surface morphology degradation as shown in Fig. 4. At higher annealing temperature the interfacial reaction due to dissociation of GaN rapidly increasing, there is significant indiffusion of Ti, Al and Ti, Pt, outdiffusion of Ga and nitrogen at the interface vicinity**.**

To investigate interfacial reaction, 2θ XRD measurement performed on the as deposited, 700°C and 900°C annealed sample shown in Fig. 5. The main spectra peaks of Ti/Al and Ti/Pt are shown at 30º < 2θ < 90º. For the case of as deposited Ti/Al, XRD peaks corresponding to GaN (111) at 2θ = 34.6º, Ti (200) at 2θ = 44.3 º, Ti (220) at 2θ = 64.73º and Ti (222) at 2θ = 82.15º. Annealed at 700°C the XRD peaks corresponding to GaN (111) at 2θ = 34.61, TiN (200) at 2θ = 41.74º, $AlTi_2$ (102) at 2θ = 44.34º and for Schottky contact Ti/Pt compound are also observed, Pt_8Ti (301) at 2θ = 39.74º and Ga_3Ti_5 (223) at 2θ = 72.95º. At 900°C annealed the peaks observed GaN (111) at 2θ = 34.61º, Pt_5Ti_3 (004) at 2θ = 44.41º, Pt_5Ti_3 (514) at 2θ = 64.69º and Pt_5Ti_3 (802) at 2θ = 72.93º.

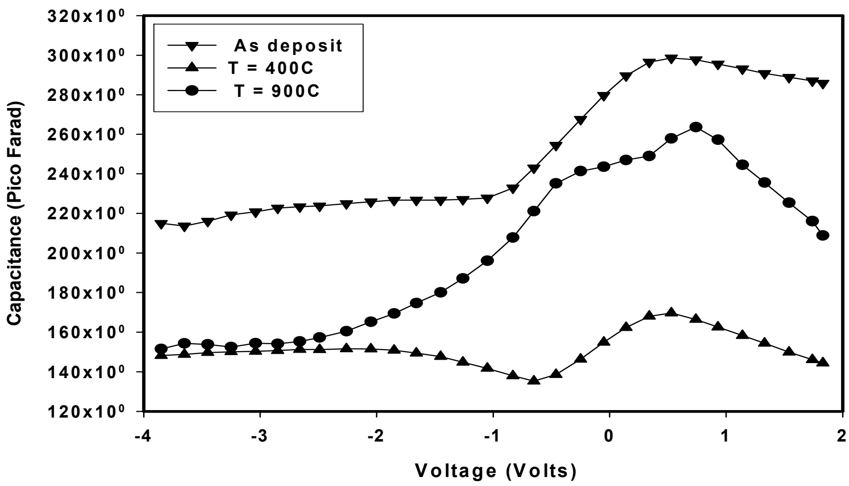


FIG. 3. (C-V) characteristics of n-GaN Schottky diode.

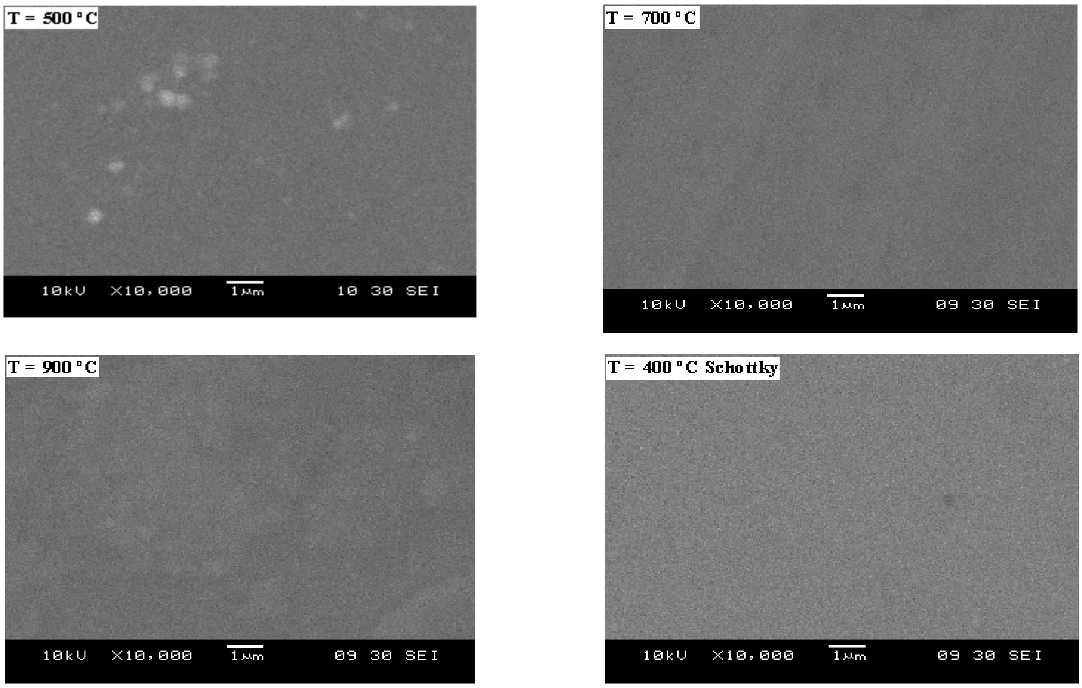
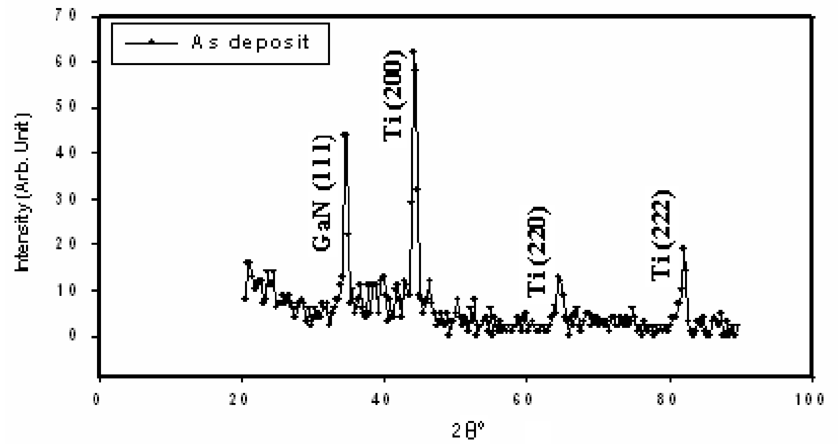
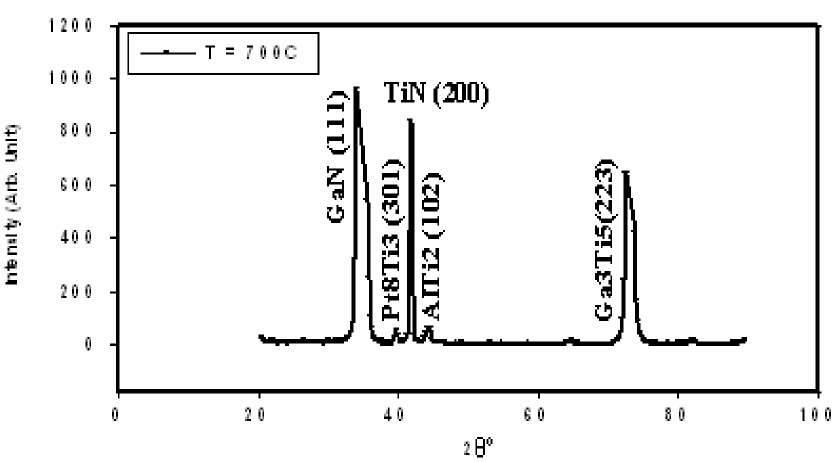


FIG. 4. SEM images of Ti/Al ohmic contact at 500ºC, 700ºC, 900ºC and Ti/Pt Schottky contact at 400ºC.





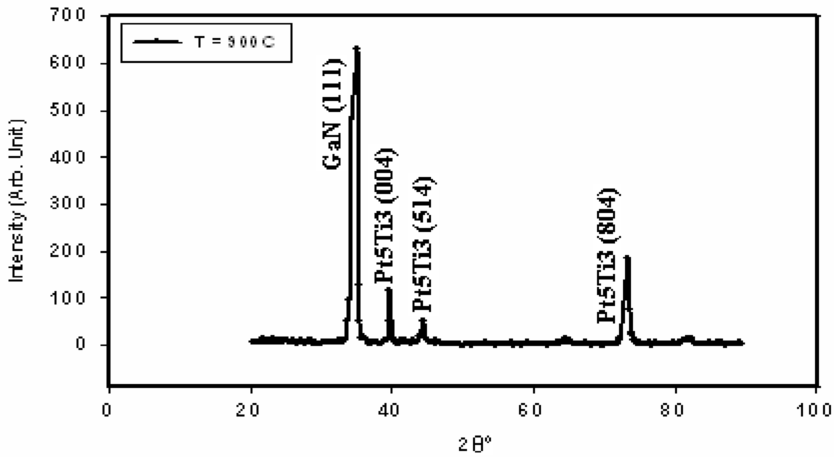


FIG. 5. XRD spectra of samples as deposited, 700°C and 900°C.

It was found in XRD study that the interface geometry changed substantially when it was annealed at 700ºC, TiN (200) at 2θ = 41.74º peaks is very prominent. There is no evidence of a TiN compound was formed on as-deposited Ti/Al contacts on n-GaN. TiN peak is observed on sample annealed at T = 700ºC is formed via the reaction of Ti with GaN and the TiN compound is thermodynamically stable in contact with GaN and most likely governs the electrical properties of the alloyed contact. It shows low electrical resistivity, low work function, chemical inertness, metallurgical stability and reliability at high temperature beneficially affect the electrical properties of the n-GaN Schottky diode [10]. The reaction of Ti with GaN results in the formation of N vacancies in the GaN layer, which function as shallow donors and promote higher conductivity of the Ti/Al contacts to n-GaN Schottky diode [6].

IV. CONCLUSION

The electrical properties and thermal stability of Ti/Al bilayer metal as an ohmic contact on n-GaN Schottky diode were observed by annealed at range of 400°C to 900°C in N_2 ambient for 20 s. It was found that at annealing 900°C, Ti/Al ohmic metal produced the best (I-V) characteristics barrier height (ϕ_B) 1.75 eV and ideality factor (η) 0.85 compared to other annealing temperature. At low frequency 100 kHz, it was found that at annealing 900°C the depletion region is maximum with capacitance value varied from 150 pF~240 pF as the applied voltage varied from –Ve to +Ve voltage. At higher temperature annealing the Ti/Al show improved surface morphology, less severe degradation. TiN has been identified at high annealing temperature, TiN show low electrical resistivity, low work function, chemical inertness, metallurgical stability and reliability at high temperature beneficially affect the electrical properties of the n-GaN Schottky diode.

ACKNOWLEDGEMENT

This work was conducted under IRPA RMK-8 Strategic Research grant. The support from Universiti Sains Malaysia is gratefully acknowledged. The financial support from MTCP (Malaysian Technical co-operation Program) is gratefully acknowledged.

REFERENCES

[1] G. Popovici, H. Morkoc and S. N. Mohammad, *Group III Nitride Semiconductor Compounds*, Clarendon, Oxford (1998), 19-69.
[2] A. Barinov, L. Casalis, L. Gregoratti and M. Kiskinova, Phys. Rev., **63** (2001).
[3] M. A. Khan, J. N. Kuznia, A. R. Bhattarai and D. T. Oslon, Appl. Phys. Lett., **62**, 1786 (1993).
[4] A. N. Bright and C. J. Humphreys, Philos. Mag. B, **81**, 1725 (2001).
[5] Q. Z. Liu and S. S. Lau, Solid-State Electronics, **42**, 677-691 (1998).
[6] C. J. Lu, A. V. Davydov, D. Josell and L. A. Bendersky, J. Appl. Phys., **94**, 245-253 (2003).
[7] K. N. Lee, X. A. Cao, C. R. Abernathy, S. J. Pearton and A. P. Zhang, Solid-State Electronics, **44**, 1203-1208 (2000).
[8] A. Shabbir, *Study of Indium Tin Oxide for Novel Optoelectronics Devices*, Ph.D. Thesis, University of London, (1998).
[9] A. Turut, M. Saglam, H. Efeoglu and N. Yalcin, Physica B., **205**, 41-50 (1995).
[10] C. A. Dimitriadis, Th. Karakostas, S. Logothetidis, G. Kamarinos, J. Brini and G. Noutet, Solid-State Electronics, **43**, 1969-1972 (1999).