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Influence of thermal annealing temperature on electrical properties of Rh and Rh/Au Schottky contacts to n-type GaN

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The effects of thermal annealing temperature on electrical characteristics of rhodium (Rh) and rhodium/gold (Rh/Au) Schottky contacts to n-type GaN (n_d=4.07×10^{17} cm^{-3}) have been investigated by current-voltage (I-V) and capacitance-voltage (C-V) techniques. Measurements showed the barrier height of as-deposited Rh Schottky contact is 0.60 eV (I-V) and 0.98 eV (C-V) respectively. However, the Schottky barrier height is somewhat decreased upon annealing at 500 °C, reaching values of 0.51 eV (I-V) and 0.65 eV (C-V). The Schottky barrier height of as-deposited Rh/Au is found to be 0.57 eV (I-V) and 0.62 eV (C-V). However, the Schottky barrier height increased with annealing temperature up to 500 °C, reaching maximum values of 0.84 eV (I-V) and 1.05 eV (C-V). Significant improvement in the electrical characteristics in the case of Rh/Au Schottky contact is observed upon annealing temperature compared to the Rh Schottky contact. The Rh Schottky contact is relatively stable during annealing temperatures compared with that of Rh/Au Schottky contact.

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Keywords: Schottky barrier height, Schottky diode, Electrical properties, n-type GaN, I-V and C-V techniques

1. Introduction

Chemically and thermally stable Gallium nitride (GaN) semiconductor with a wide direct band gap (3.4 eV) is one of the most promising materials for optoelectronic devices such as blue light emitting diode [1], laser diodes [2] and ultraviolet photovoltaic/ photoconductive detectors [3,4] and for high power/temperature/frequency devices such as high electron mobility transistors (HEMTs) [5] and metal semiconductor field effect transistors (MESFETs) [6]. However, GaN-based Schottky contacts suffer from abnormal leakage currents under reverse bias, which strongly degrade the gate current characteristics and increase power consumption. 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.

Extensive work has been carried out by many researchers on Schottky contacts to n- GaN, e.g., Au [7,8], Ni [9], Re [10], Ni/Au [11], W [12], Ru [13] and Mo [14]. Wang *et al* [8] reported the Schottky barrier height of 0.79 eV (I-V) and 1.05 eV (C-V) for a thickness of 28 nm for Au/n-GaN Schottky contacts. They also investigated the electrical characteristics of Au/n-GaN Schottky contacts with different film thickness. Guo *et al* [9] investigated the electrical properties of Ni/n-GaN Schottky contact and reported a barrier height of 0.56 eV and 0.66 eV by C-V and J-T methods respectively. Venugopalan *et al* [10] showed that the Re Schottky contact was thermally stable on n-GaN and reported a barrier height of 0.82 eV and 1.06 eV after annealing at 500 °C by I-V and C-V measurements. Miura *et al* [11] studied the thermal annealing temperature effects on Ni/Au based Schottky contacts on n-GaN and AlGaN/GaN after inserting high work function metals such Pt, Ir, Pd and Mo. Mehandru *et al* [12] investigated W contacts on n-GaN and reported that the Schottky barrier height reduces to ~0.4 eV after samples were annealed at temperature in the range of 500-600 ºC. Ramesh *et al* [14] studied the electrical properties of Mo/n-GaN Schottky diode, reported that the Schottky barrier height of 0.81 and 1.02 eV for as-deposited, 0.74 and 0.92 for 400 °C and 0.56 and 0.73 eV for 600 °C annealed contacts by I-V and C-V technique. They also have shown that the Mo Schottky contact was fairly stable during annealing at 400 °C. Recently, Khanna *et al* [15] investigated the W_2B-based rectifying contacts to n-GaN and showed that the maximum barrier height of 0.55 eV for as-deposited samples. In this work, rhodium (Rh) was selected because it has a high work-function metal 4.98 eV and is also thermally stable. In the present work, we investigate the thermal annealing temperature effects on the electrical characteristics of Rh and Rh/Au Schottky contacts to n-type GaN (4.07×10^{17} cm^{-3}) using current-voltage (I-V) and capacitance-voltage (C-V) respectively.

2. Experimental details

The n-GaN films used in this work were grown on c-plane sapphire substrates using metal-organic chemical vapor deposition (MOCVD). 2 μm thick undoped GaN layer was first grown on which 2 μm thick layer of n-GaN:Si (n_d = 4.07×$10^{17}$$cm^{-3}$) was grown. The n-GaN layer was initially degreased ultrasonically with warm trichloroethylene and later by acetone and methanol for 5 min. each. This sample was then dipped into boiling aqua regia [HNO_3:HCL=1:3] for 10 minutes to remove the native oxides and rinsed in de-ionized water. The samples were directly loaded into the electron beam evaporation system, and bilayer Ti (15 nm)/Al (30 nm) was deposited to form ohmic contacts on a portion of the n-GaN Fig. 1. Then the samples were annealed in a rapid thermal annealing (RTA) system at 850 °C in nitrogen ambient for 30 s. Rh (50 nm) and Rh/Au (25 nm / 25 nm) Schottky contacts Fig. 1 were fabricated on n-GaN with a circular diameter of 1 mm using electron beam evaporation system with the base pressure of 2×10^{-6} torr. Then the Rh and Rh/Au Schottky contacts were annealed at temperatures ranging from 300 to 500 °C for 1 min in nitrogen ambient in RTA system. The electrical characteristics of Schottky contacts were determined using current-voltage (*I-V*) and capacitance-voltage (*C-V*) techniques at room temperature. I-V and C-V measurements were carried out using Keithly source measure unit (Model No. 230) and Hewlett-Packard LCR meter (Model No. 4274 A).

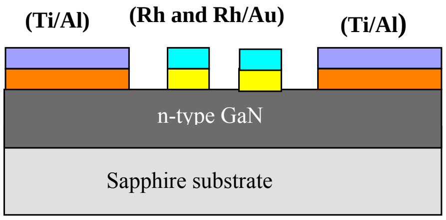


Fig. 1. The schematic diagram of the Rh and Rh/Au Schottky diodes.

3. Results and discussion

The typical forward and reverse *I-V* characteristics of Rh and Rh/Au Schottky contact measured in the range of annealing temperatures 300-500 °C, are shown in Fig. 2(a) and 2(b). It is observed that the characteristics of Rh and Rh/Au Schottky diodes are uniform over different temperatures. For the as-deposited Rh Schottky diode, the leakage current at -1 V 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. In the case of Rh/Au Schottky diode, the leakage current at -1V is 2.3×10^{-4} A. For the samples annealed at temperatures 300 °C, 400 °C and 500 °C the leakage currents are 7.2×10^{-5} A, 2.6×10^{-6} A and 1.4×10^{-8} A at -1V respectively. It is noted that the leakage current decreased for Rh/Au Schottky diode compared to the Rh Schottky diode after annealing at 500 °C. This indicates that the Schottky barrier height is improved for the Rh/Au Schottky diode upon annealing.

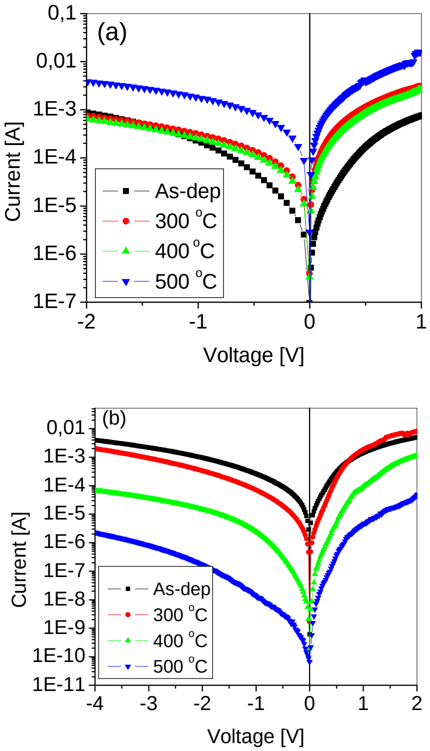


Fig. 2. (a) Current-voltage characteristics of Rh Schottky contacts on n-type GaN as a function of annealing temperatures, and (b) Current-voltage characteristics of Rh/Au Schottky contacts on n-type GaN as a function of annealing temperatures.

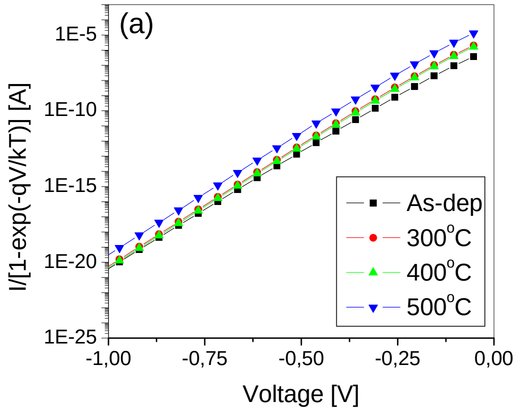
The barrier height and ideality factor of a metal-semiconductor contact were determined using thermionic emission theory is given by [16]

$$I = Is\exp\left[\left(\frac{q(V-IR)}{nkT}\right)-1\right] \qquad (1)$$

with $$Is = AA^{**}T^{2}\exp\left(\frac{-q\phi_b}{kT}\right) \qquad (2)$$

here, I_s is the saturation current, q is the electron charge, V is the applied voltage, R is the series resistance, T is the absolute temperature, n is the ideality factor, k is the Boltzmann's constant, A is the contact area, A^{**} is the effective Richardson constant (26.4 A cm^{-2} K^{-2} for n-GaN) [17], and ϕ_b is the Schottky barrier height (SBH). The value of ϕ_b can be deduced directly from the I-V curves, if the effective Richardson constant A^{**} is known. Equation (1) shows that the logarithmic plot of $I\ /\ [1-\exp(-qV/kT)]$ against V [Fig. 3 (a) and 3 (b)] is linear and I_s is obtained from the y-axis intercept at zero voltage. Using these I_s values in equation (2), the SBH were determined. The series resistance R_s of the diode can be deduced from I-V measurements using the method of Cheung *et al* [18]. The calculated series resistance is in the range R_s=219-633 Ω for the as-deposited and annealed Rh Schottky contacts. 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 estimated series resistance (R_s) of the as-deposited and annealed Rh/Au Schottky contacts is in the range R_s= 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. 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. Table 1 shows the values of Schottky barrier heights and ideality factors of Rh and Rh/Au Schottky diodes as a function of annealing temperature.



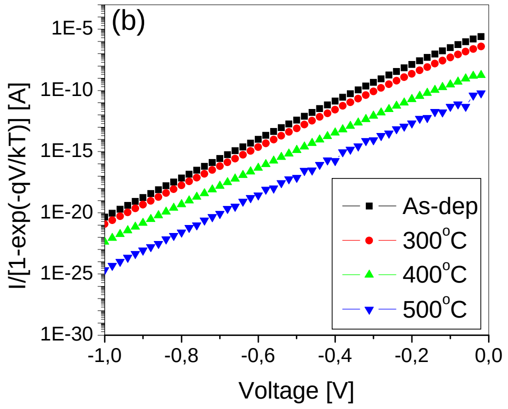


Fig. 3. (a) The plot of I/[1-exp (-qV/kT)] against. V for Rh Schottky contacts annealed at different temperatures, and (b) The plot of I/[1-exp (-qV/kT)] against. V for Rh/Au Schottky contacts annealed at different temperatures.

Table 1. The Schottky barrier heights and ideality factors of Rh and Rh/Au Schottky contacts to n-type GaN as a function of annealing temperature.

	Rh			Rh/Au		
Annealing	SBH ϕ_b(eV)		Ideality	SBH ϕ_b(eV)		Ideality
temperature	I-V	C-V	factor (n)	I-V	C-V	factor (n)
As-dep	0.60	0.98	1.17	0.57	0.62	1.98
300°C	0.56	0.88	1.20	0.62	0.66	1.73
400°C	0.56	0.77	1.21	0.75	0.83	1.12
500°C	0.51	0.65	1.25	0.84	1.05	1.34

Using a plot of natural log of current versus forward bias voltage (plot not shown) for small forward currents where the effect of series resistance is small, the ideality factor (n) was calculated. 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 reasons for larger ideality factor of as-deposited Rh/Au Schottky contact may be explained as follows. The interfacial layer generated by the chemical reaction is small but non-negligible and could affect the I-V characteristics upon room temperature deposition [16]. A part of the voltage is dropped across the interface layers when the bias is applied. Thus the barrier height becomes dependent on the bias voltage, leading to an ideality factor larger than one. Another possibility may be due to presence of excess current and the recombination current through the interfacial layers [19]. Ideality factor values are in good agreement with those reported for Schottky diodes on n-GaN [20-24] that are indicative of nonideal behaviour. This suggests that apart from the thermoionic, there are other transport mechanisms possibly present in these diodes.

The capacitance and voltage characteristics of Rh and Rh/Au Schottky diodes were measured as a function of annealing temperatures. Fig. 4 and 5 shows a plot of $1/C^2$

versus bias voltage for different annealing temperatures. The C-V relationship for Schottky diode is given by [16]

$$\frac{1}{C^2} = \left(\frac{2}{\varepsilon_s q N A^2} \right) \left(V_{bi} - \frac{kT}{q} - V \right) \qquad (3)$$

where ε_s is the permittivity of the semiconductor ($\varepsilon_s = 9.5\ \varepsilon_0$), and V is the applied voltage. The x-intercept of the plot of $1/C^2$ versus V, V_0 is related to the built in potential V_{bi} by the equation $V_{bi} = V_0 + kT/q$. The barrier height is given by the equation $\phi_b = V_0 + V_n + kT/q$. Here $V_n = (kT/q) \ln (N_c/N_d)$. The density of states in the conduction band edge is given by $N_c = 2\,(2\pi m^* kT/h^2)^{3/2}$, where $m^* = 0.22 m_o$ and its value was 2.53×10^{18} cm^{-3} for GaN [7]. The calculated carrier concentration of Rh Schottky contacts is 1.8×10^{16} cm^{-3} for the as-deposited, 1.3×10^{16} cm^{-3} for 300 °C, 1.2×10^{16} cm^{-3} for 400 °C and 1.1×10^{16} cm^{-3} for 500 °C annealed samples. The measured Schottky barrier height of Rh contact is 0.98 eV for as-deposited, 0.88eV for 300 °C annealed, 0.77 eV for 400 °C annealed, and 0.65 eV for 500 °C annealed contacts respectively. The estimated carrier concentration of Rh/Au Schottky contacts is 8.47×10^{16} cm^{-3} for the as-deposited, 5.51×10^{16} cm^{-3} for 300 °C, 4.10×10^{16} cm^{-3} for 400 °C and 3.05×10^{16} cm^{-3} for 500 °C annealed samples. 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.

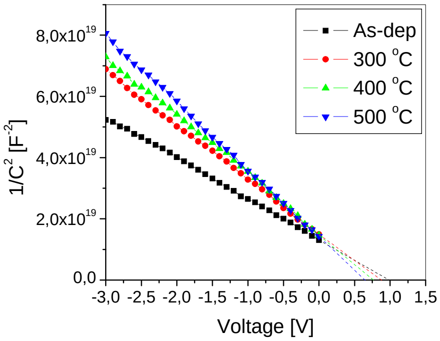


Fig. 4. *A plot of* $1/C^2$ *versus V for Rh Schottky contacts annealed at different temperatures.*

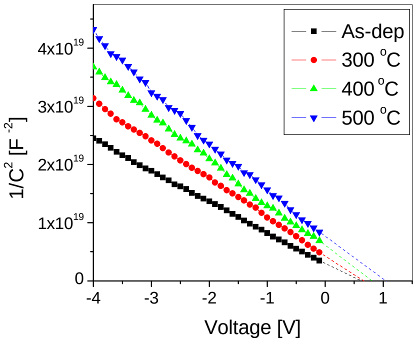


Fig. 5. *A plot of* $1/C^2$ *versus V for Rh/Au Schottky contacts annealed at different temperatures.*

Fig. 6(a) shows a plot of barrier height of Rh/n-GaN as a function of annealing temperature. It is noted that the barrier height of the Rh Schottky diode decreases a bit upon annealing temperature from 0.60 eV for as deposited to 0.51 eV for contacts annealed at 500 °C. The variation in the barrier heights may be attributed to the interface states and chemical reactions between metals and semiconductors at the interface [25]. Fig. 6(a) also shows that except for a slight change (change Δn=0.08), the diode ideality factor stays the same for all annealing temperatures up to 500 °C. The values of ideality factor range through 1.17 to 1.25. These near unity values suggest that the current in forward bias follows thermionic emission model of conduction [26].

The plot of Schottky barrier heights and ideality factors of Rh/Au contacts versus annealing temperature is shown in Fig. 6 (b). The barrier heights due to I-V and C-V characters are almost equal at lower annealing temperatures. The values, however, differ slightly at higher temperatures. Unlike in the case of Rh/n-GaN contacts, the barrier heights increase with increase in temperature and results in decrease in reverse leakage currents. Similar behaviour was observed in Ni/Pt/Au, Ni/Au and Ni/Mo/Au Schottky contacts by Miura *et al* [11]. Upon annealing temperature, the increase in the barrier height may be due to the reduction in the non-stoichiometric defects in the metallurgical interface [27, 28]. Duboz *et al* [29] had reported that the metal/n-GaN interface remains un-effected even after annealing temperature. They also reported that the nature of the metal does not play a major role in the enhancement of barrier height on annealing. Many researchers had observed Fermi level pinning at metal/GaN interface due to the interface related defects. Further, a modification of the defect density on annealing could change the pinning, which leads in the change of barrier height. It is to be noted that the electrical properties of Rh Schottky contacts are relatively thermal stable than that of Rh/Au Schottky contacts. However, the Rh/Au Schottky contact showed better electrical characteristics than the Rh contact after annealing. Also, Fig. 6 (b) shows that the ideality factor is improved in annealing temperature up to 400 °C. However, it is noted that the ideality factor is slightly increased after annealing at 500 °C.

The difference in the values of barrier heights estimated by I-V and C-V (Fig 6 (a) and (b)) measurements, suggests that the presence of native oxides at the metal junction to the semiconductor [30] and is also ascribed to the lowering of barrier height by the image force due to current follow across the barrier [31]. However, the metal perhaps comes into intimate contact with the semiconductor at high temperature annealing. The spatial inhomogeneities of the barrier height also result in a difference between $\phi_{(I\text{-}V)}$ and $\phi_{(C\text{-}V)}$ according to Werner and Guttler [32]. It could also be that the transport mechanism in these diodes is not purely thermionic emission in nature. To these diodes the ϕ_b obtained from I-V method is voltage or electric field sensitive, unlike the ϕ_b obtained from C-V.

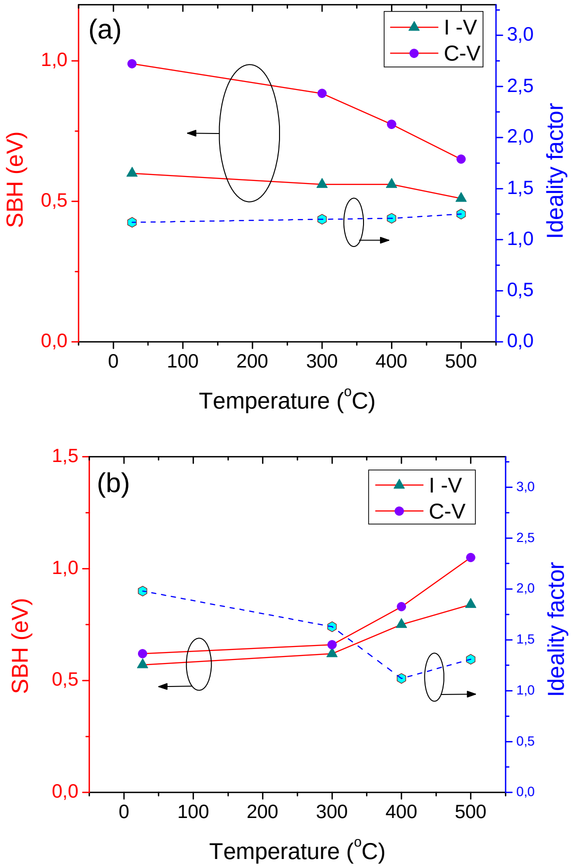


Fig. 6. (a) The barrier heights and diode ideality factors of Rh Schottky contact as a function of annealing temperature, and (b) The barrier heights and diode ideality factors of Rh/Au Schottky contact as a function of annealing temperature.

4. Summary and conclusions

We report on 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}) in the temperature range of 300-500 °C. Calculations showed that the barrier height of as-deposited Rh Schottky contact is 0.60 eV (I-V) and 0.98 eV (C-V) respectively. Upon thermal annealing temperature the barrier height slightly decreased and estimated values are 0.51 eV (I-V) and 0.65 eV (C-V) at 500 °C for 1 min in nitrogen ambient. The barrier heights of as-deposited Rh/Au Schottky diode are 0.57 eV (I-V) and 0.62 eV (C-V) respectively. However, the Schottky barrier height was increased upon thermal annealing temperature and the values are 0.84 eV (I-V) and 1.05 eV (C-V) at 500 °C. Further with increase in annealing temperature the electrical characteristics of Rh/Au contacts are improved compared to the as-deposited one. The Rh Schottky contacts are fairly stable during annealing temperature compared to the Rh/Au contacts. These results indicate that both Rh and Rh/Au can be promising metallization scheme for the device fabrication for high temperature applications.

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