Vol 18 No 4, April 2009
1674-1056/2009/18(04)/1618-04
Chinese Physics B
© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

Thermal annealing behaviour of Al/Ni/Au multilayer on n-GaN Schottky contacts

Liu Fang(刘 芳)[a], Wang Tao(王 涛)[a], Shen Bo(沈 波)[b],
Huang Sen(黄 森)[b], Lin Fang(林 芳)[b], Ma Nan(马 楠)[b],
Xu Fu-Jun(许福军)[b], Wang Peng(王 鹏)[a], and Yao Jian-Quan(姚建铨)[a]

[a] *College of Precision Instrument and Opto-Electronics Engineering, Institute of Laser and Optoelectronics, Tianjin University; Key Lab of Optoelectric Information Science and Technology of Ministry of Education, Tianjin University, Tianjin* 300072, *China*

[b] *State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing* 100871, *China*

(Received 15 September 2008; revised manuscript received 7 November 2008)

Recently GaN-based high electron mobility transistors (HEMTs) have revealed the superior properties of a high breakdown field and high electron saturation velocity. Reduction of the gate leakage current is one of the key issues to be solved for their further improvement. This paper reports that an Al layer as thin as 3 nm was inserted between the conventional Ni/Au Schottky contact and n-GaN epilayers, and the Schottky behaviour of Al/Ni/Au contact was investigated under various annealing conditions by current–voltage (I–V) measurements. A non-linear fitting method was used to extract the contact parameters from the I–V characteristic curves. Experimental results indicate that reduction of the gate leakage current by as much as four orders of magnitude was successfully recorded by thermal annealing. And high quality Schottky contact with a barrier height of 0.875 eV and the lowest reverse-bias leakage current, respectively, can be obtained under 12 min annealing at 450 °C in N_2 ambience.

Keywords: Schottky contact, barrier height, ideality factor, thermal annealing
PACC: 7340N, 7280E, 7360L

1. Introduction

Due to the attractive features of GaN and related materials, nitride based devices have gained significant interest for high power and high frequency applications, and their superior electrical characteristics over the conventional silicon or GaAs related technologies have been demonstrated.[1]. One of the major factors which limit the performance and reliability of GaN high electron mobility transistor (HEMT) for high-power radio-frequency (RF) applications is their relatively high gate leakage.[2] The gate leakage reduces the breakdown voltage and the power-added efficiency while increasing the noise figure. Therefore, a high quality Schottky contact to GaN must be found.[3]

In 2006, Takuma Nanjo reported a thin Al layer insertion between AlGaN and Schottky gate on the AlGaN/GaN HEMT can reduce the reverse-bias current for four orders of magnitude.[4] But they did not deal with the thermal annealing behaviour. In this paper, we describe how the gate leakage current is reduced by inserting a very thin Al metal layer, which is highly reactive with oxygen, at the boundary of the GaN surface and the gate metal. And we reported the thermal annealing effects on Au/Ni/Al-GaN Schottky contact. Schottky barriers and ideality factors are obtained by using non-linear fitting methods.[5] At last the results are compared with the diodes without inserting Al layer. Results proved that Al_2O_3 layer was formed in the interface between GaN and Ni/Au.

2. Experiments

GaN epilayers were grown by metal-organic chemical vapour deposition (MOCVD) on the (0001) surface of sapphire substrate, nucleation GaN buffer layer was grown at 530 °C, followed by a 1.3 μm thick unintentionally doped GaN(i-GaN) layer deposited at 1070 °C. The van der Pauw geometry was used for Hall measurements. The room temperature mobility and concentration of the electrons in i-GaN are 220 cm^2/Vs and 8.1×10^{16} cm^{-3}, respectively.

Then, for the fabrication of Schottky diodes, ring-shaped Ohmic contacts were formed by standard photolithography on i-GaN surface, using a Ti/Al/Ni/Au

(25/120/45/50 nm) alloy annealed at 850 °C in N_2 for 30 s in a rapid thermal annealing system. Before Schottky metallization, the wafer were cleaned by conventional organic cleaning process. Schottky contacts of Ni/Au, Al/Ni/Au were formed by e-beam evaporation and 3/25/200 nm (Al/Ni/Au) thick, respectively, the diameter of circular Schottky contacts is 800 μm.

To study the thermal annealing effects on Schottky barriers and ideality factors of Al/Ni/Au-n-GaN contact, samples were annealed at 110 °C, 220 °C, 300 °C, 400 °C, 450 °C, 500 °C, 600 °C, 700 °C, respectively for 5min in N_2 atmosphere in a rapid thermal annealing (RTA) equipment. The current-voltage characteristics of the Schottky diodes were performed in air using an Agilent 4155C semiconductor parameter analyser.

3. Results and discussion

Figure 1 shows the I–V curves before annealing Ni/Au Schottky diode and inserting Al diode. The gate leakage current was reduced by inserting a very thin Al metal layer. The gate leakage current is two orders of magnitude in comparison with that in the case without Al metal layer.

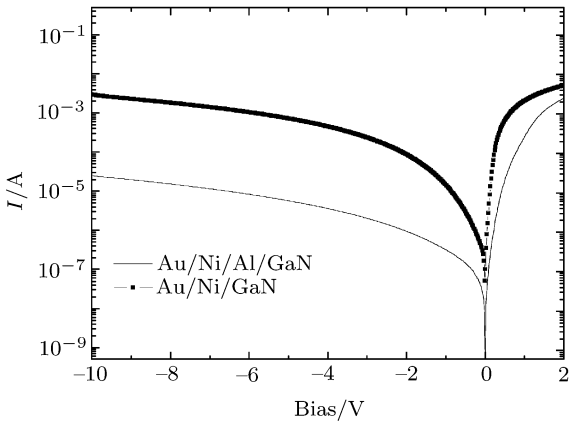


Fig.1. I–V curves before annealing Au/Ni/GaN and Au/Ni/Al/GaN.

The I–V characteristics of Au/Ni/Al/GaN Schottky diodes as a function of annealing temperature (110, 220, 300, 400, 450, 500, 600, 700 °C, for different annealing times) are shown in Fig.2. And I–V characteristics of Au/Ni/GaN Schottky diodes as a function of annealing temperature (110, 220, 300, 400, 450, 500, 600, 700 °C, for different annealing times) are shown in Fig.3. The reverse-biased current reduces with increasing annealing temperature at temperatures lower than 450 °C, but increases with increasing annealing temperature at temperatures higher than 450 °C in the Au/Ni/Al/GaN Schottky diodes. But in the diodes without Al layer, the reverse-biased current increases with increasing annealing temperature at temperature lower than 220 °C, then reduces with increasing annealing temperatures between 220 °C and 400 °C, but increases with increasing annealing temperature at temperatures higher than 400 °C.

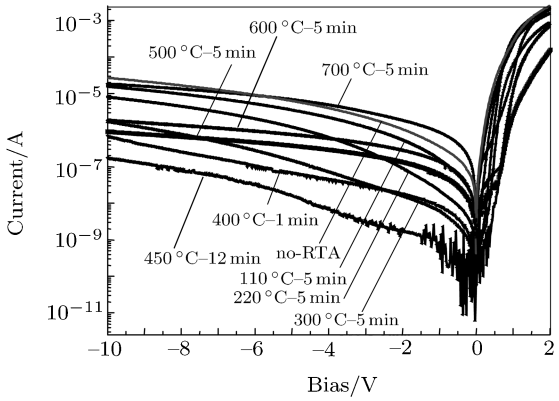


Fig.2. I–V curves of Au/Ni/Al/GaN Schottky diodes measured at various annealing temperatures between 27 °C and 700 °C.

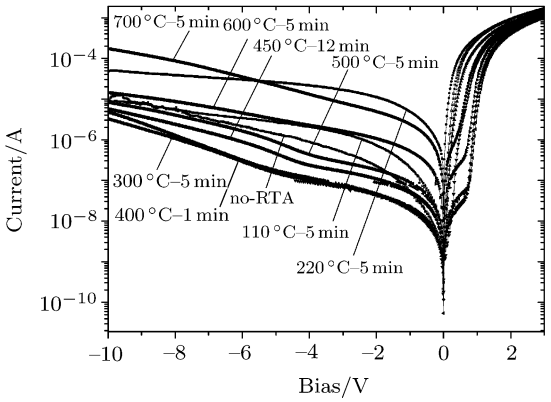


Fig.3. I–V curves of Au/Ni/GaN Schottky diodes measured at various annealing temperatures between 27 °C and 700 °C.

For thermionic emission ($V > 3\,kT/q$), the general diode equations are[6]

$$I = I_{\mathrm{S}}\left[\mathrm{e}^{q(V-IR)/nkT} - 1\right], \tag{1}$$

where $I_{\mathrm{S}} = AA^{**}T^2\mathrm{e}^{-q\Phi_{\mathrm{b}}/kT}$ is the saturation current, R is the series resistance, A and n are the contact area and the ideality factor respectively, Φ_b is the effective barrier height. A^{**} is the effective Richardson constant. In the following analysis, we use 26.4 $A\,\mathrm{cm}^{-2}\,\mathrm{k}^{-2}$ as the A^* calculated from the electron effective mass $m_{\mathrm{e}}^* = 0.22m_{\mathrm{e}}$.

Many methods have been suggested to calculate the barrier heights and ideality factors of a metal-semiconductor Schottky contact from I–V data. Here,

a non-linear fitting method was suggested to fit the obtained data, equation (1)[5] can be expressed as

$$V = \frac{nkT}{q} \ln\left(\frac{I}{I_s} + 1\right) + IR_S. \quad (2)$$

Assume that $P_1 = nkT/q$, $P_2 = 1/I_S$, $P_3 = R_S$. The parameters n, I_S, R_S can be deduced from non-linear fitting method. Curves of barrier heights versus annealing temperatures and ideality factors versus annealing temperatures are shown in Fig.4.

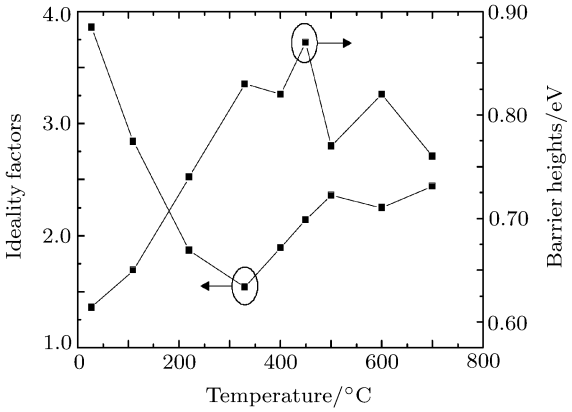


Fig.4. Variation of the resulting barrier heights and ideality factors with annealing temperature with Al layer.

Our sample with a large value of n was attributed to the presence of a thick interfacial insulator layer between the metal and semiconductor.[7−10] As shown in Fig.5, the value of Φ_b for (Al/Ni/Au-GaN) and ideality factor all changed with annealing temperature. At lower temperature, the barrier height increased. But at high temperature (above 450 °C), it decreased apparently with the increase of annealing temperature. Figure 6 shows that the value of Φ_b for (Ni/Au-GaN) and ideality factor changed with annealing temperature. From Fig.6, we can see that the Φ_b for (Ni/Au-GaN) reduces with increasing annealing temperatures but increases with increasing annealing temperature, at last when the annealing temperature is above 450 °C, it reduces with increasing annealing temperature.

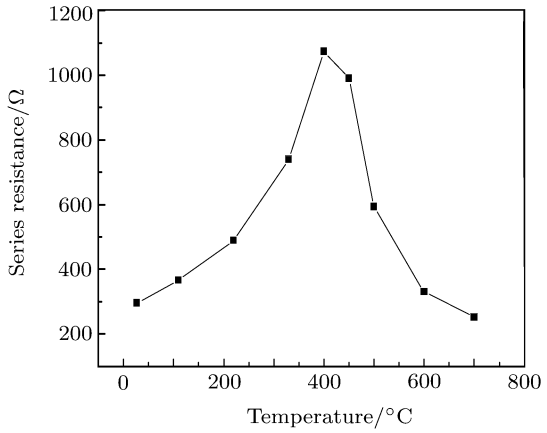


Fig.5. Variation of the contact resistance with annealing temperature with Al layer.

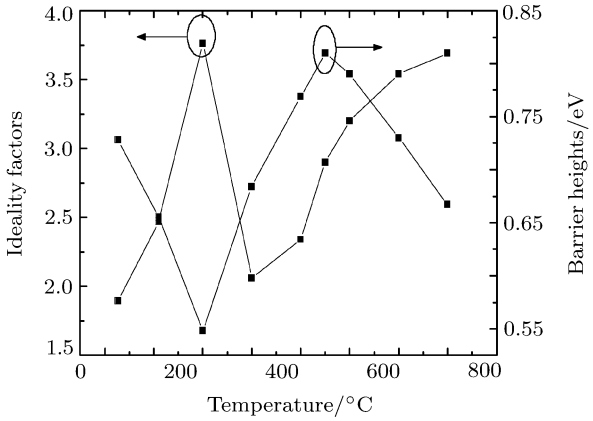


Fig.6. Variation of the resulting barrier heights and ideality factors with annealing temperature without Al layer.

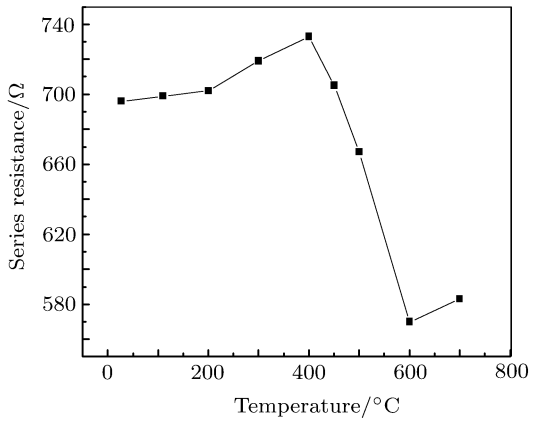


Fig.7. Variation of the contact resistance with annealing temperature without Al layer.

It is well known that the interface states and chemical reactions between metals and semiconductors at interface can play important roles in the electrical properties of devices. In this work, the change in the barrier height of Al/Ni/Au Schottky contact with annealing temperature may be ascribed to the interfacial reaction occurring among the Al and O which exists on the surface of GaN as shown in Fig.8.[11] An increase of the barrier heights may be attributed to the formation of an interfacial layer at the Ni/Au/GaN interface after annealing. When the temperature is not very high, the 3 nm Al oxidizes which results most likely in the formation of Al_2O_3. Consequently, the creation of less conductive Al_2O_3 layer leads to an increase in the contact resistance.

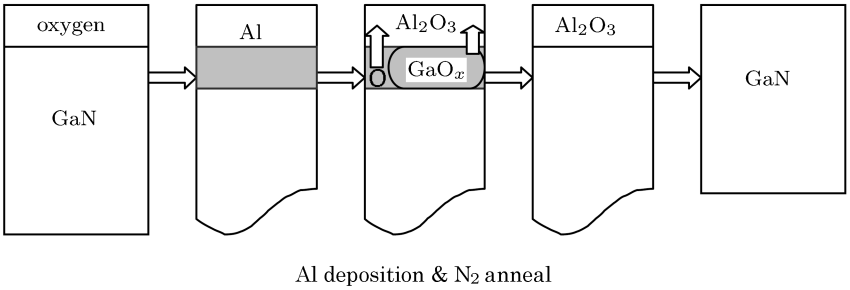


Fig.8. Reaction of Al with GaO_x in company with the increasing annealing temperature.

As shown in Fig.5, the resistance rapidly increases with an increasing annealing temperature below 450 °C. But in the Ni/Au-GaN, the resistance increases slowly with annealing temperature even if it can be ignored from Fig.7. As shown in Figs.5 and 7, when the annealing temperature is above 450 °C, the resistance rapidly reduces with increasing annealing temperature so the thermal annealing behaviour is attributed to the behaviour of Ni/Au. In the following discussion, we treat transport of electrons over the potential barrier using thermionic emission theory. The number of electrons over the potential barrier in constant voltage is decided by the height of potential barrier. The series resistance depends on the number. So in the diode with Al layer, Al_2O_3 barrier becomes thicker with the increasing of annealing temperature and the potential barrier becomes higher. This effect reduces electrons over the potential barrier. As a result the resistance rapidly increases. When the annealing temperature is above 450 °C, the decreasing of barrier height may be attributed to the phase transition of Ni/Au. More and more electrons are able to get across the barrier. So the series resistance reduces.

4. Conclusions

We investigated the effects of the insertion of a thin Al layer into the boundary of the GaN surface and Schottky gate metal on the electrical characteristics of GaN diodes. In the Schottky diodes with a thin Al layer, the gate leakage current is two orders of magnitude in comparison with that in the case without Al insertion layer. This may be attributed to the formation of an interfacial layer at the Al/GaN interface. Then thermal annealing behaviour of Al/Ni/Au on n-GaN Schottky contacts was investigated. It was found that the barrier height and the series resistance increase with the increase of annealing temperature below 450 °C.This may be attributed to the fact that Al_2O_3 is formed and becomes thicker with the increase of the temperature. But the barrier height and the series resistance decrease with the increase of annealing temperature when the annealing temperature is above 450 °C. This is attributed to the annealing behaviour of Ni/Au. And at 450 °C, the reverse-bias current is the lowest in Au/Ni/Al/GaN diode.

References

[1] Miura N, Nanjo T, Suita M, Oishi T, Abe Y, Ozeki T, Ishikawa H, Egawa T and Jimbo T 2004 *Solid-State Electronics* **48** 689

[2] Ye P D, Yang B, Ng K K and Bude J 2005 *Appl. Phys. Lett.* **86** 063501

[3] Wang X J, Zhang J F, Zhang J C and Hao Y 2008 *Acta Phys. Sin.* **57** 3171 (in Chinese)

[4] Nanjo Takuma, Oishi Toshiyuki, Suita Muneyoshi, Abe Yuji and Tokuda Yasunori 2006 *Appl. Phys. Lett.* **88** 043503

[5] Sun Y P, Shen X M, Wang J, Zhao D G, Feng G, Fu Y, Zhang S M, Zhang Z H, Feng Z H, Bai Y X and Yang H 2002 *J. Phys.* D: *Appl. Phys.* **35** 2648

[6] Liu J, Hao Y, Feng Q, Wang C, Zhang J C and Guo L L 2007 *Acta Phys. Sin.* **56** 3483 (in Chinese)

[7] Zeyrek S, Altmdal S, Yuzer H and Bulbul M 2006 *Appl. Surf. Sci.* **252** 2999

[8] Card H C and Rhoderick E H 1971 *J. Phys.* D **4** 1589

[9] Sze S M 1981 *Physics of Semiconductor Devices* (New York: Willey) 2nd ed

[10] Rhoderick E H and Williams R H 1988 *Metal Semiconductor Contacts* (Ocford: Clarendon) 2nd ed

[11] Kaneko Masamitsu and Hashizume Tamotsu 2006 *Phys. Stat. Sol.* (c) **3** 1758