Thermal stability of tungsten and tungsten nitride Schottky contacts to AlGaN/GaN

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Thin tungsten nitride (WN_x) films were produced by reactive DC magnetron sputtering of tungsten in an Ar–N_2 gas mixture. The films were used as Schottky contacts on AlGaN/GaN heterostructures. The Schottky behaviours of WN_x contact was investigated under various annealing conditions by current–voltage (I–V) measurements. The results show that the gate leakage current was reduced to 10^{-6} A/cm^2 when the N_2 flow is 400 mL/min. The results also show that the WN_x contact improved the thermal stability of Schottky contacts. Finally, the current transport mechanism in WN_x/AlGaN/GaN Schottky diodes has been investigated by means of I–V characterisation technique at various temperatures between 300 K and 523 K. A TE model with a Gaussian distribution of Schottky barrier heights (SBHs) is thought to be responsible for the electrical behaviour at temperatures lower than 523 K.

Keywords: AlGaN/GaN heterostructures, tungsten nitride, Schottky contacts

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1. Introduction

Due to the attractive features of GaN and related materials, nitride-based devices have attracted 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] The Schottky contact is an essential part of these devices, acting as a metal gate to control the current.[2] In order to realize the materials for high-temperature applications, high-quality Schottky contacts operating at high temperature without deteriorating the performance of the device are required.[3] The thermally stable contact materials such as Ni,[4] Pt,[5] PtSi,[6] Pd,[7], and other metals have also been reported. Refractory metals and their nitrides have wide applications in various fields including microelectronics due to their excellent hardness, high melting point, good chemical stability and high electrical conductivity.[8–12] However, the Schottky contact characteristics of the refractory metal and their nitrides, such as tungsten and tungsten nitride with AlGaN/GaN heterostucture, have few reported.

In this work, WN_x is formed by reactive sputtering from pure W target in an Ar–N_2 gas mixture. These films deposited with different flow ratio of Ar to N_2 are used as Schottky contact for AlGaN/GaN heterostructure. The thermal stability and electrical stability are investigated after prolonged (1 min) annealing at 400 °C–700 °C in N_2 ambient. Schottky barrier heights and ideality factors are obtained by using the difference method.

2. Experiments

The AlGaN/GaN was grown on (0001)-oriented sapphire using metal–organic chemical vapour deposition (MOCVD). The device structure consists of a 30-nm undoped AlGaN barrier layer and 1.3-μm insulating GaN(i-GaN) layer on a buffer layer [GaN (20 nm)]. In the AlGaN layer Al content was maintained to be 0.25. The carrier concentration of 1.2×10^{13} cm^{-2} and carrier mobility of 1200 cm^2/(V·s) were obtained by Hall measurement at room temperature.

Then, Ohmic contacts were formed by standard photolithography on AlGaN/GaN surface, using a Ti/Al/Ni/Au(25 nm/120 nm/45 nm/50 nm) metal layer annealed at 850 °C in N_2 for 30 s in a rapid thermal annealing system. Wafers were first cleaned by conventional organic cleaning process; and the Schottky contact materials of tungsten and tungsten nitride were deposited by dc-magnetron reactive sputtering with a pure tungsten target and the sputtering atmo-

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sphere was composed of Ar and N_2. Prior to sputtering, the deposition chamber was pumped down to 5×10^{-4} Pa and then pre-sputtered for 15 min in a mixture of Ar and N_2 gases. The flow rate of the Ar gas was 100 mL/min and that of the N_2 was 0, 50 and 400 mL. The sputtering was performed at 120-W dc power with a total pressure of 0.5 Pa. The time of sputtering was 5 min. Film deposition condition is given in Table 1, and the sample top view is shown in Fig. 1.

Table 1. Film deposition parameters for samples A, B and C.

Sample	Deposition pressure/Pa	N_2 flow /(mL/min)	Ar flow /(mL/min)	Substrate temperature/°C	DC power/W	Base pressure/Pa
A	0.5	0	100	150	120	5×10^{-4}
B	0.5	50	100	150	120	5×10^{-4}
C	0.5	400	100	150	120	5×10^{-4}

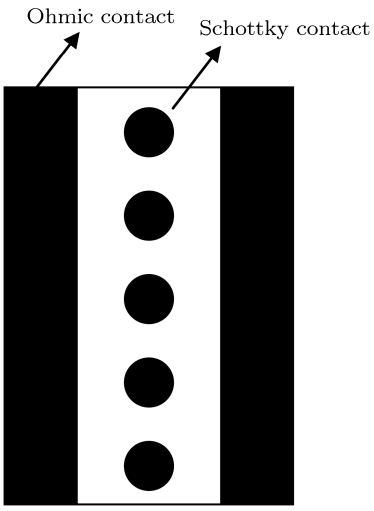


Fig. 1. Schematics of the top view of the sample.

To study the thermal annealing effects on Schottky barriers of WN_x–AlGaN/GaN contact, samples A, B and C were annealed at 400, 500, 600, and 700 °C for 1 min in N_2 atmosphere in a rapid thermal annealing (RTA) equipment. The current–voltage characteristics of the Schottky diodes were performed using an Agilent 4155C semiconductor parameter analyser.

3. Results and discussion

3.1. Electrical examinations

The I–V characteristics of WN_x/AlGaN/GaN Schottky contacts obtained in different N_2/Ar gas ratios as a function of annealing temperature (as deposited, 400, 500, and 600 °C, for a few minutes of annealing time) are shown in Fig. 2. The reverse-biased current increases with increasing annealing temperature in sample A. From the current–voltage characteristics in Fig. 2(b), the increase in the reverse leakage current is apparent only after annealed at 600 °C, implying a stable contact below this temperature.

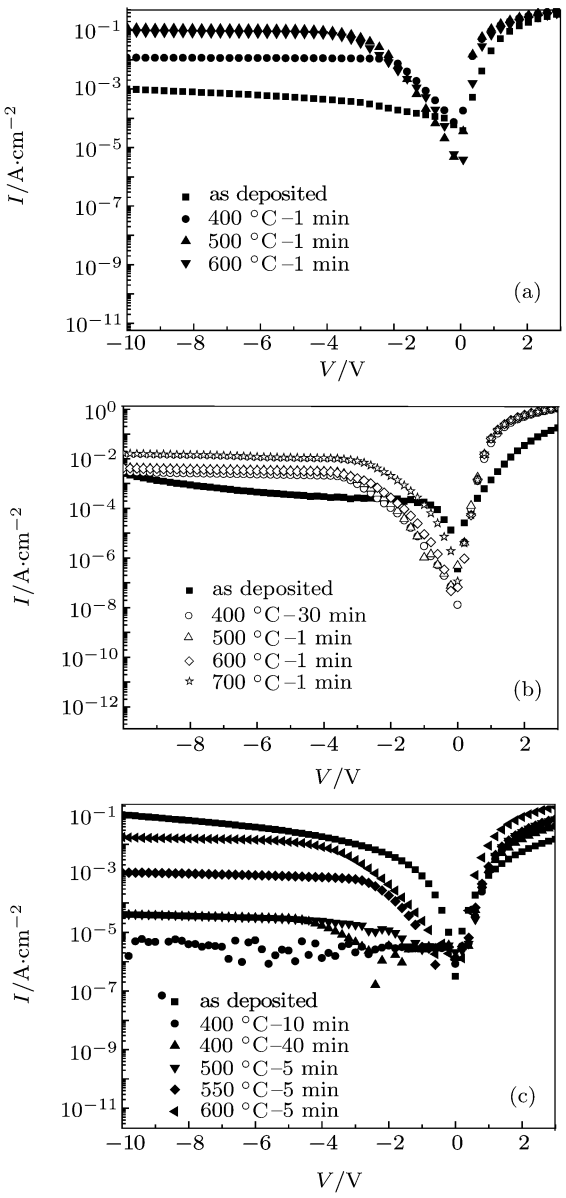


Fig. 2. The I–V characteristics of the WN_x/AlGaN/GaN Schottky contacts for different annealing temperatures with deposition condition for (a) sample A: N_2 = 0 mL/min, (b) sample B: N_2 = 50 mL/min, and (c) sample B: N_2 = 400 mL/min.

In the Ni/Au/AlGaN/GaN contact, the stable temperature is about 400 °C. The I–V characteristic deteriorates at above 400 °C. So the WN_x gate (N_2 = 50 mL) improves the reliability of the contacts at high temperatures. When the N_2 gas flow rate is 400 mL/min, as shown in Fig. 2(c), the increase in the reverse leakage current is apparent only after annealing at 500 °C. And the reverse leakage current is about 10^{-6} A/cm^2 at −10 V when the annealing temperature is 400 °C. The gate leakage current is two orders of magnitude higher than that of the Ni/Au gate, which has the reverse leakage current usually of 10^{-4} A/cm^2.

3.2. TE model with a Gaussian distribution of Schottky barrier heights

In general, thermionic-emission (TE) mechanism dominates the current transport mechanism of Schottky diodes at high temperatures for the contact of Ni/Au/AlGaN/GaN. In this study, the I–V measurements were performed on WN_x/AlGaN/GaN Schottky diodes between 27 °C and 350 °C. The results show that TE mechanism also dominates the current transport mechanism of Schottky diodes at high temperatures in WN_x/AlGaN/GaN for sample B.

The forward-biased current of a Schottky diode whose current is dominated by TE can be described as follows:[12]

$$I = I_{\rm TE}(\mathrm{e}^{e(V-IR_S)/nKT} - 1), \tag{1}$$

$$I_{\rm TE} = A \cdot A^* T^2 \mathrm{e}^{-e\phi_{b0}/KT}, \tag{2}$$

where $R_{\rm s}$ is the series resistance, n the ideality factor, $I_{\rm TE}$ the saturation current, A the junction area of the diode, A^* the effective Richardson constant and ϕ_{b0} the apparent Schottky barrier height of the junction. In the following analysis, we use A^* = 34.04A cm^{-2}·K^{-2}.

Figure 3 shows the temperature dependence of ϕ_{b0} derived from Eqs. (1) and (2). The ϕ_{b0} increases dramatically with increasing temperature when the temperature is lower than 523 K. TE mechanism with a Gaussian distribution of Schottky barrier height was suggested and has been recently confirmed by local current–voltage measurements using atomic force microscopy. Therefore, a mean SBH $\bar{\phi}_{b0}$ with a standard deviation ρ_0 is tried in our study to simulate the temperature-dependent behaviour of WN_x/AlGaN/GaN Schottky diodes at temperatures below 523 K. The ϕ_{b0} is given by[13]

$$\phi_{\rm B} = \bar{\phi}_{b0} - \frac{q\rho_0^2}{2kT}. \tag{3}$$

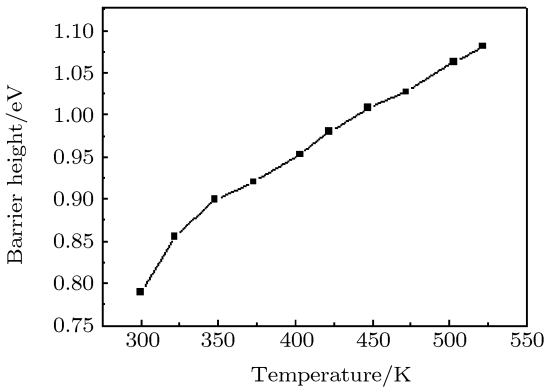


Fig. 3. The apparent Schottky barrier height ϕ_{b0} as a function of temperature with the effective Richardson constant $A^* = 34.04A$ cm^{-2}·K^{-2}. The voltage range for fitting is between 0.3 V and 0.9 V.

Figure 4 shows linear fitting results of ϕ_{b0} at temperatures lower than 523 K. We obtain $\bar{\phi}_{b0}$ = 1.4409 eV from the intercept of the slope of $\phi_{b0}(I-V)$. A combination of Eqs. (2) and (3) gives the following expression[14]

$$\ln\left(\frac{I_0}{T^2}\right) - \left(\frac{q^2\rho_0^2}{2k^2T^2}\right) = \ln(AA^*) - \frac{q\bar{\phi}_{b0}}{kT}. \tag{4}$$

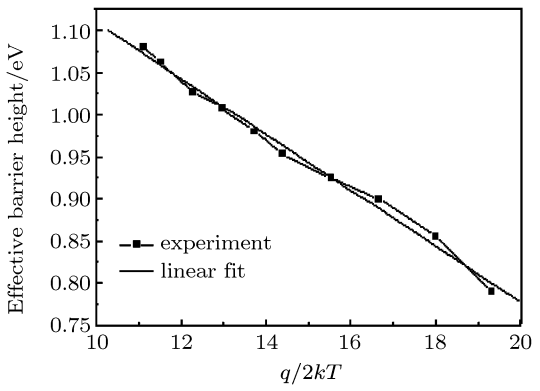


Fig. 4. Linear fits of $\phi_{b0}(I-V)$ versus $(2kT)^{-1}$ plots at temperatures between 300 K and 523 K.

In Fig. 5, we show the modified $\ln(I_0/T^2)$–$(q^2\rho_0^2/2k^2T^2)$ versus q/kT plot. Linear fitting of the curve gives the mean SBH $\bar{\phi}_{b0}$ and the effective Richardson constant A^*. Their values are $\bar{\phi}_{b0}$ =

1.4416 eV and $A^* = 34.78A$ cm^{-2}·K^{-2}. Excellent agreement is obtained between the theoretical effective Richardson constant $A^* = 34.04A$ cm^{-2}·K^{-2} and the one by fitting the experimental data. This is an important proof of the model of Gaussian distribution for SBHs in WN_x/AlGaN/GaN.

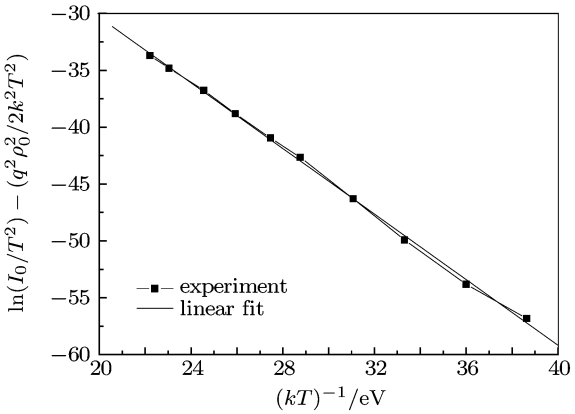


Fig. 5. Linear fit of $\ln(I_0/T^2) - (q^2\rho_0^2/2k^2T^2)$ versus $(kT)^{-1}$ plots for the modified Richardson at temperatures between 300 K and 525 K.

4. Conclusions

In summary, we have obtained WN_x films by reactive DC sputtering, which were used as Schottky contacts on AlGaN/GaN heterostructures. The nitrogen content in the film was controlled by varying the nitrogen-to-argon gas flow ratio during the reactive sputtering deposition. When the N_2 flow increased to 400 mL/min and Ar was kept unchanged, minimum leakage current could be achieved as 10^{-6} A/cm^2 at −10 V. This value is lower than that of the current Ni/Au diode. Tungsten nitride can not only improve the leakage current, but also improve the thermal stability of Schottky contacts on AlGaN/GaN. A TE model with a Gaussian distribution of SBHs is thought to be responsible for the electrical behaviour at temperatures lower than 523 K in sample B. The effective Richardson constant is determined to be $34.78A$ cm^{-2}·K^{-2}, in excellent agreement with the theoretical value.

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