Directly extracting both threshold voltage and series resistance from the conductance–voltage curve of an AlGaN/GaN Schottky diode*

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An Ni/Au Schottky contact on an AlGaN/GaN heterostructure has been prepared. By using the peak-conductance model, the threshold voltage and the series resistance of the AlGaN/GaN diode are simultaneously extracted from the conductance–voltage (G–V) curve and found to be in good agreement with the ones obtained by using the capacitance–voltage (C–V) curve integration and the plot of $\mathrm{d}V/\mathrm{d}(\ln I)$ versus current I. Thus, a method of directly and simultaneously extracting both the threshold voltage and the series resistance from the conductance–voltage curve for the AlGaN/GaN Schottky diode is developed.

Keywords: AlGaN/GaN heterostructure, Schottky diode, threshold voltage, series resistance

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1. Introduction

AlGaN/GaN heterostructure field-effect transistors (HFETs) have been the subject of intense investigation for many years due to their importance for microwave and high temperature/high power applications.[1–3] The threshold voltage V_{T} and series resistance R_{s} of the Schottky diode are of great importance for device performance and reliability. The series resistance is an important parameter for judging the noise level and power dissipation of the Schottky diode.[4] A small series resistance can improve the current density and reduce the noise level and power dissipation. The threshold voltage of the Schottky diode is normally determined by capacitance–voltage (C–V) curve integration.[5] The series resistance can be calculated by many methods, such as using the plot of $\mathrm{d}V/\mathrm{d}(\ln I)$ versus current I.[6–8] However, in the above methods, the range of the selected voltages affects the value of the series resistance, making the above methods relatively ambiguous and complex. Here we present a much simpler way for directly extracting both the threshold voltage and the series resistance from the conductance–voltage (G–V) curve for the AlGaN/GaN Schottky diode.

In this paper, an Ni/Au Schottky contact on an AlGaN/GaN heterostructure is prepared. The G–V curve is obtained from the differential of the current–voltage (I–V) curve of the AlGaN/GaN Schottky diode. Two peaks appear in the G–V curve in the reverse and forward directions, respectively. It is found that the voltage corresponding to the reverse conductance peak is constant to the threshold voltage obtained by the C–V curve integration. And the inverse of the forward peak conductance agrees well with the series resistance calculated with the plot of $\mathrm{d}V/\mathrm{d}(\ln I)$ versus I. Thus, we obtain a simple way for directly extracting both the threshold voltage and the series resistance from the G–V curve for the AlGaN/GaN Schottky diode. And a physical explanation is given for this simple method.

2. Experiment

The AlGaN/GaN heterostucture employed in this work was epitaxially grown by metal–organic chemical vapor deposition (MOCVD) on a (0001) sapphire substrate. The AlGaN/GaN heterostructure consisted of a low-temperature nucleation layer, followed by a 2 μm S. I. GaN, a 1 nm AlN interlayer, and finally a 22.5 nm thick undoped $Al_{0.3}Ga_{0.7}N$ barrier layer. Hall measurements indicated a sheet carrier density around 1.1×10^{13} cm^{-2} and an electron mobility of 1800 cm^2/(V·s) at room temperature. For device processing, an Ohmic contact of Ti/Al/Ni/Au was fabricated by e-beam evaporation and lift-off. The Ohmic contact was a ring with an inside diameter of 600 μm and an outside diameter of 650 μm. A rapid thermal annealing was taken to form a good Ohmic contact. With transmission line method patterns, the specific resistivity of the Ohmic contact in the sample was measured to be 5.9×10^{-5} Ω·cm^2. An Ni/Au (50 nm/200 nm) circular Schottky contact with a diameter of 300 μm was then de-

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posited by e-beam evaporation. The C–V measurement was performed at room temperature using an Agilent B1520A at 1 MHz. The current–voltage (I–V) measurement was performed at room temperature using a Keithley 4200 semiconductor parameter analyzer, and the G–V curve was obtained by differentiating the I–V curve.

3. Calculation and analyses

Figure 1(a) shows the measured C–V curve at room temperature for the Ni Schottky contact on the AlGaN/GaN heterostructure. By integrating the C–V curve (inset in Fig. 1(a)), the threshold voltage V_T is determined to be -3.25 V for the AlGaN/GaN Schottky diode.[5]

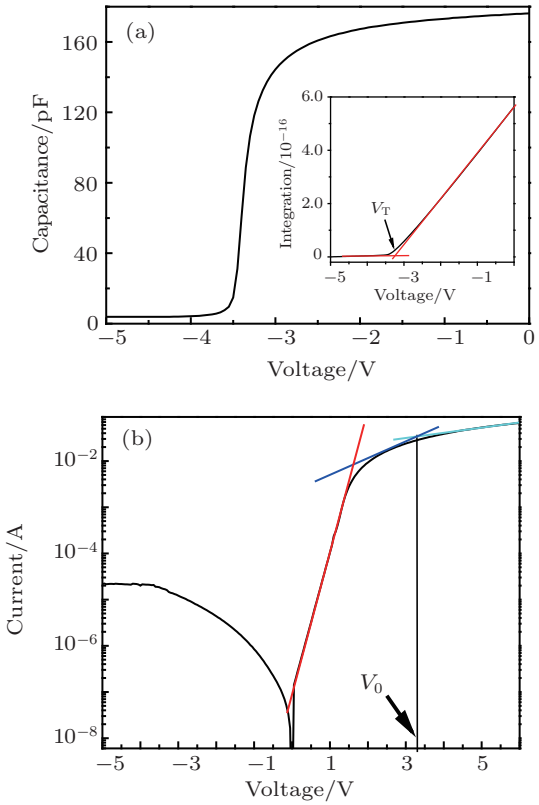


Fig. 1. (color online) Measured (a) C–V and (b) I–V curves of the prepared AlGaN/GaN Schottky diode. Inset shows the integration of C–V curve.

Figure 1(b) shows the measured I–V curve of the prepared AlGaN/GaN Schottky diode. The forward I–V characteristics of a Schottky diode obey the thermionic emission model given by[6]

$$I = I_S \exp[q(V_D - IR_S)/nkT], \tag{1}$$

where I_S is the reverse saturation current, V_D is the voltage applied on the diode, q is the electronic charge, k is the Boltzmann constant, n is the ideal factor, and T is the absolute temperature. Differetiating Eq. (1) with respect to I and rearranging terms, we obtain[6]

$$\frac{dV}{d(\ln I)} = R_S I + \frac{nkT}{q}. \tag{2}$$

Thus, the value of R_S can be obtained with the plot of $dV/d(\ln I)$ versus I, as shown in Fig. 2(a).[6] The results for the AlGaN/GaN Schottky diode are shown in Table 1. As one can see from Table 1, the range of the chosen voltage affects the value of R_S obviously.

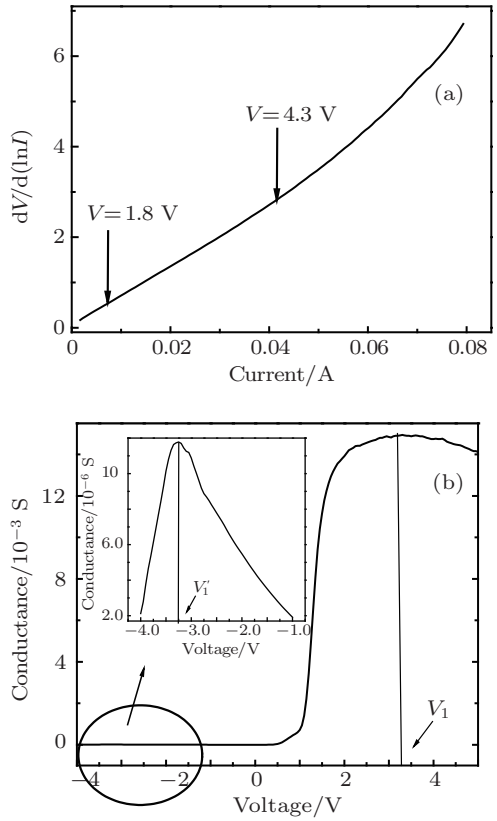


Fig. 2. (a) The $dV/d(\ln I)$ versus I and (b) obtained G–V curve by differentiating the I–V curve for the AlGaN/GaN Schottky diode. Inset shows the conductance at low voltages.

Figure 2(b) shows the obtained G–V by differentiating the I–V curve of the prepared AlGaN/GaN Schottky diode. For the AlGaN/GaN Schottky diode, two conductance peaks appear in the reverse and forward directions, respectively. The voltage corresponding to the conductance peak in the reverse direction is masked as V_1' and is -3.25 V. From Table 1,

Table 1. Calculated V_T and R_S for AlGaN/GaN Schottky diode.

	V_T/V	V_T/V	R_S/Ω ($dV/d(\ln I)$ vs. I)			R_S/Ω
	(C–V integration)	(peak-conductance)	1.8–2.8 V	1.8–3.8 V	1.8–4.3 V	(peak-conductance)
AlGaN/GaN	–3.25	–3.25	64.8	65.6	67.5	66.9

we find that V_1' equals to the threshold voltage V_T for the AlGaN/GaN Schottky diode. Besides, the inverse of the forward peak conductance is 66.9 Ω, which is constant to the value of R_S obtained with the plot of $dV/d(\ln I)$ versus I for the AlGaN/GaN Schottky diode. Thus, the threshold voltage and the series resistance can be simultaneously extracted from the G–V curve for the AlGaN/GaN Schottky diode. And it can be explained as follows.

As shown in Fig. 3, the total resistance of the AlGaN/GaN Schottky diode consists of the resistance of the Ohmic contact (R_O), the channel resistance (R_C) between the Ohmic and the Schottky contacts, the channel resistance (R_G) under the Schottky contact, the resistance of the AlGaN barrier layer (R_B), and the resistance of the Schottky metal contact (R_S). When the Schottky diode is reverse biased ($|V_S| < |V_T|$), the voltage mainly drops on the AlGaN barrier layer due to the large resistance R_B. The two-dimensional electron gas (2DEG) is fully depleted before the threshold voltage is reached, then the channel resistance under the Schottky contact is very large due to the channel depletion. Once the absolute value of the reverse bias is larger than the threshold voltage, the voltage dropped on the AlGaN barrier layer will be invariant, and any additional voltage will drop primarily on R_G.

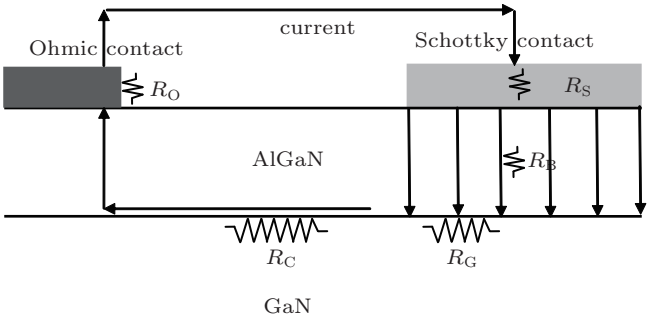


Fig. 3. Equivalent resistance model for the AlGaN/GaN Schottky diode.

The reverse Schottky leakage current is usually given by[9,10]

$$I_S = I_{sur} + I_{TT} + I_{DT}, \tag{3}$$

where I_{sur} is caused by the shunt conduction due to the surface electronic states,[10] I_{TT} is due to the trap-assisted tunneling, and I_{DT} is due to the direct tunneling.[11] They are given by

$$I_{sur} = \rho V, \tag{4}$$

$$I_{TT} = \frac{qS}{E}\int_{\phi_2}^{\phi_B+\varphi_F} R\,d\phi, \tag{5}$$

$$I_{DT} = \frac{q^2SE^2}{8\pi h\phi_B}\exp\left(-\frac{\alpha}{E}\phi_B^{3/2}\right), \quad \alpha = \frac{8\pi\sqrt{2mq}}{3h}, \tag{6}$$

where ρ is the conductance of the shunt path, S is the Schottky contact area, ϕ_B is the Schottky barrier height, R is the tunneling rate, h is the Planck' constant, ϕ_F is the difference between the conduction band edge and the Fermi level in the substrate, ϕ_2 is the effective trap band edges into the band, and E is the electric field in the barrier layer.[11]

As one can see from Eqs. (4)–(6), the reverse leakage current and the conductance both increase with increasing reverse bias. However, the vertical electric field beneath the Schottky contact, which controls I_S, does not change for $|V_S| > |V_T|$, as the extra voltage $|V_S|$–$|V_T|$ drops laterally on the depletion region from the Schottky contact to the Ohmic contact.[9] Then the tunneling current (I_{TT} and I_{DT}) saturates for $|V_S| > |V_T|$. Thus, there appears a peak under the threshold voltage in the inverse of the G–V curve.

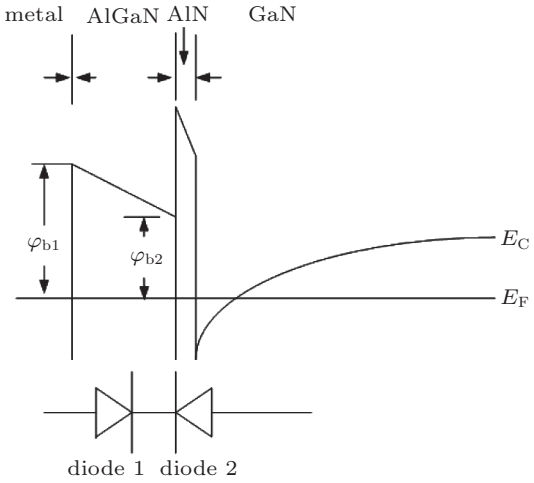


Fig. 4. Band diagram and the two-diode equivalent circuit of the AlGaN/GaN heterostructure under zero gate bias.

According to Chen's two-diode model,[12] an AlGaN/GaN structure consisting of a metal gate can be considered as two diodes connected in series back to back, as shown in Fig. 4. The left diode (diode 1) represents the Schottky contact between the Schottky metals and the AlGaN barrier layer, the right diode (diode 2) represents the effective Schottky contact between the AlGaN barrier layer and the two-dimensional electron gas. According to the two-diode model, three straight lines are fitted to the forward I–V curves (Fig. 1(b)), and they stand for the currents of diode 1, diode 2, and the Schottky diode resistance, respectively. The voltage at the intersection of the second and the third fitted lines is marked as V_0. With increasing forward bias, the current and the conductance increase rapidly due to the reduction of the effective Schottky heights of diodes 1 and 2. Once the forward bias reaches V_0 (as shown in Fig. 1(b)), the effective Schottky heights of diodes 1 and 2 drop to the minimum, and the conductance rises to the maximum. By further increasing the forward bias, the current will increase slowly and the conductance will decrease. This may be due to the invariance of the electron velocity and the

hot effect. Thus, the resistance under voltage V_0 should be the series resistance of the Schottky diode. The same values of V_0 and V_1 for the AlGaN/GaN Schottky diode indicate that the series resistance can be calculated by the inverse of the forward peak conductance. Although there are many other methods to calculate the series resistance, they are all faced with the problem that the range of the chosen voltage seriously affects the value of R_S. However, the peak in the G–V curve is clear, making extracting the series resistance from the G–V curve much more simple and accurate.

4. Conclusion

In summary, a Ni/Au Schottky contact on an AlGaN/GaN heterostructure has been prepared. The threshold voltage and the series resistance are calculated with the C–V curve integration and the plot of $\mathrm{d}V/\mathrm{d}(\ln I)$ versus I, respectively. Based on the calculated G–V curve, it is found that the voltage corresponding to the reverse peak conductance equals to the obtained threshold voltage and the inverse of the forward peak conductance agrees well with the calculated series resistance. Thus, a method for directly extracting both the threshold voltage and the series resistance from the G–V curve for and AlGaN/GaN Schottky diode is developed. Based on the mechanism of reverse current and the two-diode model, a simple physical explanation is given for the new method.

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