Determination of the series resistance under the Schottky contacts of AlGaN/AlN/GaN Schottky barrier diodes*

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Rectangular AlGaN/AlN/GaN heterostructure field-effect transistors (HFETs) were fabricated, and the gate and the source of the HFETs consisted of AlGaN/AlN/GaN Schottky barrier diodes (SBDs). Based on the measured forward current–voltage and the capacitance–voltage characteristics of the AlGaN/AlN/GaN SBDs, the series resistance under the Schottky contacts (R_S) was calculated using the method of power consumption, which has been proved to be valid. Finally, the method of power consumption for calculating R_S was successfully used to study the two-dimensional electron gas electron mobility for a series of circular AlGaN/AlN/GaN SBDs. It is shown that the series resistance under the Schottky contacts cannot be neglected and is important for analysing and characterizing the AlGaN/AlN/GaN SBDs and the AlGaN/AlN/GaN HFETs.

Keywords: AlGaN/AlN/GaN heterostructures, Schottky barrier diodes, power consumption, series resistance

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1. Introduction

GaN-based materials have attracted considerable attention for their high power, high frequency, and high temperature applications due to their wide bandgap and high mobility characteristics.[1−5] Among them, AlGaN/AlN/GaN Schottky barrier diodes (SBDs) are promising candidates for high power electronics systems because of their fast speed and high breakdown voltage. Previous work has mainly focused on the improvement of the breakdown voltage and the reduction of reverse leakage current.[6−8] Little attention has been paid to the two-dimensional electron gas (2DEG) electron mobility of AlGaN/AlN/GaN SBDs, which is directly related to the reverse recovery time and the power of the diodes. However, the electron mobility is hard to calculate for planar AlGaN/AlN/GaN SBDs because the series resistance under the Schottky contacts is unkown. To our knowledge, few papers have been published on the investigation of the series resistance under AlGaN/AlN/GaN heterostructure Schottky contacts. Thus, it is of great importance to find a proper method to calculate the series resistance under Schottky contacts in order to conduct further research on AlGaN/AlN/GaN SBDs. If a feasible method to calculate the series resistance under the Schottky contacts is obtained, the series resistance of the ungated gate–drain region and the ungated gate–source region for AlGaN/AlN/GaN heterostructure field-effect transistors (HFETs) can be calculated based on the current–voltage (I–V) curves of the gate–drain and the gate–source, respectively. As a result, the electron mobility in the 2DEG channel can be figured out for different regions, and it is helpful to carry out further research on the carrier scattering in AlGaN/AlN/GaN HFETs.

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In this article, rectangular AlGaN/AlN/GaN HFETs with different gate contact areas have been fabricated. The AlGaN/AlN/GaN SBDs used here were formed by the source and the gate of the HFETs. Based on the forward I–V and capacitance–voltage (C–V) characteristics of the AlGaN/AlN/GaN SBDs and the method of power consumption, the series resistance under the Schottky contacts ($R_{\rm S}$) has been calculated, and with the obtained $R_{\rm S}$, the series resistance between the Schottky contacts and the Ohmic contacts ($R_{\rm C}$) has also been calculated. In addition, $R_{\rm C}$ can also be calculated using the method developed by Lin's group in the corresponding AlGaN/AlN/GaN HFET structures,[9,10] and the two results for the calculated $R_{\rm C}$ have been compared. Finally, the method for calculating $R_{\rm S}$ has been used to calculate the 2DEG electron mobility in a series of circular AlGaN/AlN/GaN SBDs.

2. Experiment

The heterostructure layer employed in this study was grown by molecular beam epitaxy (MBE) on a (0001) sapphire substrate. The structure consisted of a 40 nm AlN nucleation layer, followed by a 3 μm undoped GaN layer, and finally a 22.5 nm undoped $Al_{0.28}Ga_{0.72}N$ layer. There was a 0.5 nm AlN interlayer between the GaN and $Al_{0.28}Ga_{0.72}N$ layers. A sheet carrier density of around 1.1×10^{13} cm^{-2} and an electron mobility of 1800 cm$^2\cdot$V$^{-1}\cdot$s^{-1} at room temperature for the structure were obtained from Hall measurements. The source and drain Ohmic contacts of the rectangular AlGaN/AlN/GaN HFET devices were formed by depositing Ti/Al/Ni/Au using e-beam evaporation and lift-off. The source and drain regions were rectangular and 100 μm in width and 50 μm in length, and the space between the source and drain was 100 μm. These contacts were annealed in a rapid thermal annealing system, and the specific resistivity of the Ohmic contacts was measured to be $5.9\times10^{-5}\Omega\cdot$cm^2. To form the gate, Ni/Au (60 nm/160 nm) rectangular Schottky contacts were symmetrically placed in the between the source and drain, and their sizes were 20 μm/100 μm (length/width), 40 μm/100 μm, 60 μm/100 μm, and 80 μm/100 μm. Taking the gate of these HFETs as the anode, and the source as the cathode, the four AlGaN/AlN/GaN SBDs were formed. Corresponding to the above HFETs, these AlGaN/AlN/GaN SBDs are referred to as 1, 2, 3, and 4 respectively. In addition, the above four AlGaN/AlN/GaN HFETs are also referred to as 5, 6, 7, and 8 respectively. The C–V characteristics of the AlGaN/AlN/GaN HFETs and the AlGaN/AlN/GaN SBDs were measured at room temperature using an Agilent B1520A at 1000 kHz, and the I–V characteristics were also measured at room temperature using an Agilent B1500A for the AlGaN/AlN/GaN HFETs and the AlGaN/AlN/GaN SBDs.

3. Calculation and analysis

Figure 1 shows the measured C–V curves at room temperature for the AlGaN/AlN/GaN SBDs (1, 2, 3, 4) and the AlGaN/AlN/GaN HFETs (5, 6, 7, 8). The C–V measurements of both the SBDs and the HFETs were performed using the source contacts and the gate contacts of the HFETs. The 2DEG electron density can be obtained by integrating the measured C–V curves.[9] The measured I–V curves at room temperature for the AlGaN/AlN/GaN SBDs and the AlGaN/AlN/GaN HFETs with different Schottky contact areas are shown in Figs. 2(a) and 2(b), respectively. In Fig. 2(b), $V_{\rm DS}$ is the applied low voltage between the drain and the source, $I_{\rm DS}$ is the current flowing from the drain to the source. From the forward I–V curves for the AlGaN/AlN/GaN SBDs, the total series resistance of the SBDs ($R_{\rm T}$) can be calculated by using Cheung's method,[11] and the calculated results are shown in Table 1. The specific resistivity of the Ohmic contacts was measured to be $5.9\times10^{-5}\Omega\cdot$cm^2, so the resistance of Ohmic contacts can be neglected in the total series resistance of the SBDs. As a result, the total series resistance of the AlGaN/AlN/GaN SBDs consists of two components, one of which is the series resistance under the Schottky contacts, the other is the resistance between the Ohmic contacts and the Schottky contacts. In order to calculate the series resistance under the Schottky contacts of the AlGaN/AlN/GaN SBDs, a power consumption method is used. When the forward voltage is applied to the Schottky contacts of the AlGaN/AlN/GaN SBDs, the current flows under the Schottky contacts is thought to change linearly with the position. With the forward voltage drop across the Schottky contacts and the Ohmic contacts, it can be seen that there are a series of uniformly distributed diodes between the Schottky metals and the AlGaN barrier layer, and the current flows in these diodes are shown in Fig. 3.

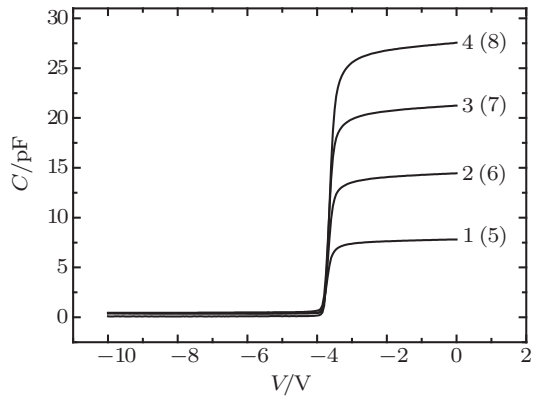


Fig. 1. The measured C–V curves at room temperature for AlGaN/AlN/GaN SBDs and AlGaN/AlN/GaN HFETs .

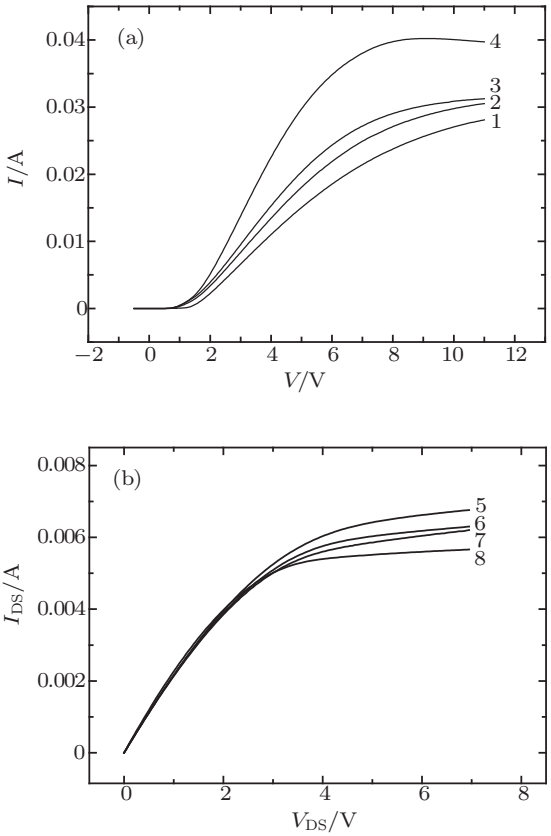


Fig. 2. The measured forward I–V curves at room temperature: (a) for AlGaN/AlN/GaN SBDs, (b) for the AlGaN/AlN/GaN HFETs with zero gate bias.

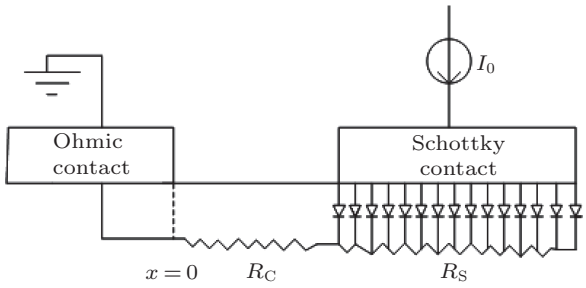


Fig. 3. Schematic diagram of the current and the series resistance distribution in the AlGaN/AlN/GaN SBDs.

The distribution of the current under the Schottky contact is described by

$$I(x) = I_0\left(\frac{L_1+L_2}{L_2} - \frac{x}{L_2}\right). \tag{1}$$

The boundary conditions of the current are

$$I\,|_{x=L_1} = I_0\ , \tag{2}$$

$$I\,|_{x=L_1+L_2} = 0\ , \tag{3}$$

where x is the coordinate along the 2DEG electron channel, L_1 is the space between the Ohmic contact and the Schottky contact, L_2 is the length of the Schottky contact, and I_0 is the total input current of the Schottky contact.

The differential resistance under the Schottky contact is given by

$$\mathrm{d}R_{\mathrm{S}} = \frac{\mathrm{d}x}{qn_{2\mathrm{D}}u_{\mathrm{n}}W}, \tag{4}$$

where q is the electronic charge, $n_{2\mathrm{D}}$ is the density of the 2DEG in the channel , u_{n} is the electron drift mobility of the 2DEG, and W is the width of the Schottky contact.

The whole power consumed by the series resistance under the Schottky contact is given by

$$P = \int_{L_1}^{L_1+L_2} I^2(x)\mathrm{d}R_{\mathrm{S}}. \tag{5}$$

From which we obtain

$$R_{\mathrm{S}} = \frac{P}{I_0^2} = \frac{\dfrac{(L_1+L_2)^3}{3} - \dfrac{L_1^3}{3} + L_1^2(L_1+L_2) - L_1(L_1+L_2)^2}{qn_{2\mathrm{D}}u_{\mathrm{n}}WL_2^2}. \tag{6}$$

The series resistance between the Schottky contact and the Ohmic contact can be described as[10]

$$R_{\mathrm{C}} = \frac{L_1}{qn_{2\mathrm{D}0}u_{\mathrm{n}0}W}. \tag{7}$$

Here, because the thickness of the AlGaN barrier layer is only 22.5 nm, which is negligible compared with the space between the Schottky contact and the Ohmic contact, the influence of the applied bias to the 2DEG

electron density of the region between the two contacts can be neglected. The n_{2D0} and u_{n0} in Eq. (7) are the 2DEG electron density and the electron mobility corresponding to zero bias for the AlGaN/AlN/GaN SBDs, respectively.

Combining Eqs. (6) and (7), we obtain the ratio of the series resistance under the Schottky contacts to the resistance between the Schottky contact and the Ohmic contact (R_S/R_C) as

$$R_S/R_C = \frac{\frac{(L_1+L_2)^3}{3} - \frac{L_1^3}{3} + L_1^2(L_1+L_2) - L_1(L_1+L_2)^2}{L_1 L_2^2}, \tag{8}$$

with the related data substituted into Eq. (8); and combining the known total resistance R_T ($R_T = R_S + R_C$), we obtain the R_C and R_S for the AlGaN/AlN/GaN SBDs (see Table 1).

Table 1. Summary of the calculated values of R_T, R_S/R_C, R_S, R_C from the SBDs, and the values of R_C from the corresponding HFETs (R_C (HFETs)).

	R_T/Ω	R_S/R_C	R_S/Ω	R_C/Ω	R_C (HFETs)/Ω
1	218.99	0.16667	30.59	187.71	174.64
2	191.42	0.44444	58.91	132.51	130.53
3	171.31	1	85.65	85.66	87.89
4	134.07	2.66667	97.50	36.57	40.09

Actually, an approximation is made with the obtained Eq. (8), in which the $n_{2D}u_n$ in Eq. (6) is assumed to be equal to the $n_{2D0}u_{n0}$ in Eq. (7). The 2DEG electron density (n_{2D}) and the electron mobility (u_n) in Eqs. (4) and (6) are the values of those electrons located under the Schottky contacts, and these electrons are biased with forward voltage by which the AlGaN/AlN/GaN SBDs are turned on. As a result, the value of the n_{2D} is larger than that of the n_{2D0} which corresponds to zero bias. While the electron mobility u_n is smaller than the u_{n0} since the 2DEG electrons with forward biases are closer to the AlGaN/AlN/GaN interface where they experience the increased heterointerface roughness scattering compared with those at zero bias. Thus, it may be sensible to make the approximation that the product of the $n_{2D}u_n$ in Eqs. (4) and (6) equals that of the $n_{2D}u_{n0}$ in Eq. (7).

Moreover, R_C corresponds to the series resistance of the ungated gate-source region of the AlGaN/AlN/GaN HFETs, and it can also be calculated as follows:[10]

$$u_{n0} = \frac{L_{DS}I_{DS}}{qn_{2D0}WV_{DS}}, \tag{9}$$

$$R_C = \frac{L_{GS}}{qn_{2D0}u_{n0}W}, \tag{10}$$

where n_{2D0} and u_{n0} are the density of the 2DEG and the electron drift mobility of the 2DEG at zero gate bias, respectively. V_{DS} is the applied low voltage between the drain and the source, I_{DS} is the current flowing from the drain to the source, L_{DS} is the space between the drain and the source, L_{GS} is the space between the gate and the source. The calculated R_C with this HFETs approach is also shown in Table 1.

From Table 1, it can be seen that R_C obtained from the method of power consumption in the AlGaN/AlN/GaN SBDs agrees well with the results calculated from the HFETs approach in the AlGaN/AlN/GaN HFETs. Therefore, a useful method is developed to calculate the series resistance under the Schottky contacts for AlGaN/AlN/GaN Schottky barrier diodes.

In order to evaluate the influence of R_S on the device characteristics, we use the method of calculating R_S to characterize four circular AlGaN/AlN/GaN SBDs with different ring Schottky contact sizes 160 μm/200 μm (inside radius/outside radius), 160 μm/220 μm, 160 μm/240μm, 160 μm/260 μm; their ring Ohmic contact sizes are all 300 μm/350 μm (inside radius/outside radius), and they are referred to as curves *a*, *b*, *c*, *d*, respectively. The material structures and the device processes for the four circular AlGaN/AlN/GaN SBDs are the same as the above rectangular AlGaN/AlN/GaN HFETs. The measured forward *I*–*V* and *C*–*V* curves for these circular AlGaN/AlN/GaN SBDs are shown in Fig. 4. Based on the *I*–*V* curves, R_T of these SBDs is obtained using Cheung's functions, and R_S and R_C are also obtained by making use of the power consumption method. Then the 2DEG electron mobility in the four circular AlGaN/AlN/GaN SBDs are calculated with and without consideration of R_S, and they are referred to as u_{with} and $u_{without}$, respectively. All these results are listed in Table 2.

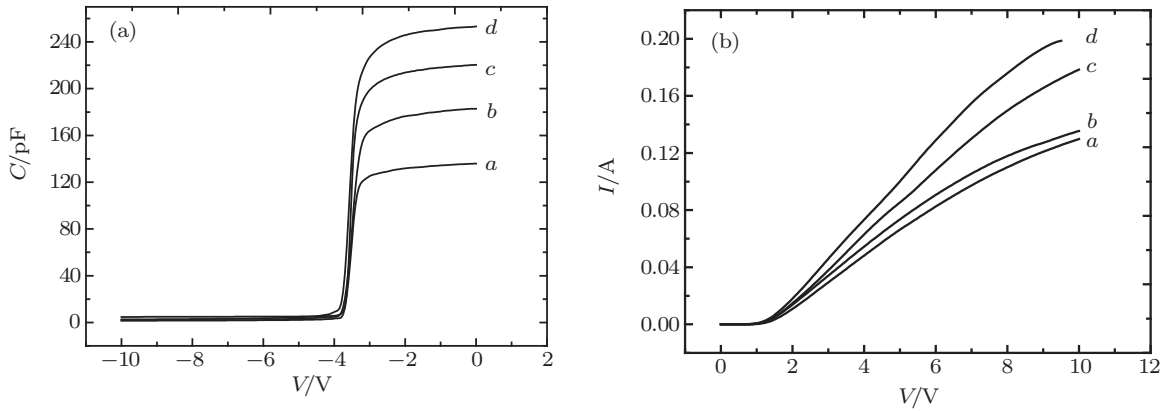


Fig. 4. The measured (a) C–V and (b) I–V curves at room temperature for the circular AlGaN/AlN/GaN SBDs.

Table 2. Summary of $R_{\rm T}$, $R_{\rm S}$, $R_{\rm C}$, the 2DEG electron mobility in consideration of $R_{\rm S}$ ($u_{\rm with}$), and the mobility without consideration of $R_{\rm S}$ ($u_{\rm without}$) for the different circular SBDs.

	$R_{\rm T}/\Omega$	$R_{\rm S}/\Omega$	$R_{\rm C}/\Omega$	$u_{\rm with}/{\rm cm}^2\cdot{\rm V}^{-1}\cdot{\rm s}^{-1}$	$u_{\rm without}/{\rm cm}^2\cdot{\rm V}^{-1}\cdot{\rm s}^{-1}$
a	49.81	7.36	42.44	1505	1282
b	46.70	11.20	35.50	1647	1252
c	40.97	14.47	26.50	1826	1181
d	37.46	18.72	18.74	1877	939

From Table 2, it is found that $R_{\rm S}$ is not negligible compared with the total series resistance ($R_{\rm T}$) and has a significant influence on the 2DEG electron mobility in the four circular AlGaN/AlN/GaN SBDs. Taking $R_{\rm S}$ into consideration, it can be seen that the mobility of the 2DEG electrons increases as the Schottky contact size increases, and this can be attributed to the influence of the polarizating Coulomb field scattering, which was suggested by Lin's group.[9,10] However, if $R_{\rm S}$ is not taken into consideration, the difference between $u_{\rm with}$ and $u_{\rm without}$ is apparent and an opposite variation trend of the 2DEG electron mobility caused by the Schottky contact size occurs. It is shown that the resistance under the Schottky contacts is important for analysing and characterizing AlGaN/AlN/GaN Schottky diodes and AlGaN/AlN/GaN HFETs.

4. Conclusion

In summary, rectangular AlGaN/AlN/GaN HFETs with different gate areas were fabricated. The gate and the source of the HFETs also formed AlGaN/AlN/GaN SBDs. With the measured forward I–V curves for the AlGaN/AlN/GaN SBDs, $R_{\rm S}$ and $R_{\rm C}$ were calculated using the power consumption method. Simultaneously, $R_{\rm C}$ was also figured out in the corresponding HFETs using a widely accepted method (the HFET approach). The calculated values of $R_{\rm C}$ with the two different methods are in good agreement with each other. Therefore, a feasible method for calculating the series resistance under the Schottky contacts has been developed and determined. Then the method has been used to calculate the 2DEG electron mobility in a series of circular AlGaN/AlN/GaN SBDs. It is found that the series resistance under the Schottky contact is not negligible and should be taken into consideration when analysing and characterizing AlGaN/AlN/GaN SBDs and AlGaN/AlN/GaN HFETs.

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