Influence of Schottky drain contacts on the strained AlGaN barrier layer of AlGaN/AlN/GaN heterostructure field-effect transistors*

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(Received 26 June 2012; revised manuscript received 1 August 2012)

Rectangular Schottky drain AlGaN/AlN/GaN heterostructure field-effect transistors (HFETs) with different gate contact areas and conventional AlGaN/AlN/GaN HFETs as control were both fabricated with same size. It was found there is a significant difference between Schottky drain AlGaN/AlN/GaN HFETs and the control group both in drain series resistance and in two-dimensional electron gas (2DEG) electron mobility in the gate–drain channel. We attribute this to the different influence of Ohmic drain contacts and Schottky drain contacts on the strained AlGaN barrier layer. For conventional AlGaN/AlN/GaN HFETs, annealing drain Ohmic contacts gives rise to a strain variation in the AlGaN barrier layer between the gate contacts and the drain contacts, and results in strong polarization Coulomb field scattering in this region. In Schottky drain AlGaN/AlN/GaN HFETs, the strain in the AlGaN barrier layer is distributed more regularly.

Keywords: AlGaN/AlN/GaN HFET, Schottky drain contact, AlGaN barrier layer strain, polarization Coulomb field scattering

PACS: 71.55.Eq, 72.10.–d, 73.61.Ey **DOI:** 10.1088/1674-1056/22/4/047102

1. Introduction

AlGaN/GaN heterostructure field-effect transistors (HFETs) are one of the most promising candidates for high power and microwave applications due to their wide bandgap and excellent transport properties.[1,2] Recently a new technology based on the use of Schottky metallization in the drain contact of AlGaN/GaN HFETs has been used to improve device performance. Compared with conventional AlGaN/GaN HFETs, current gain cut-off frequency (f_T), maximum oscillation frequency (f_{max}), and three-terminal breakdown voltage are all better in Schottky drain AlGaN/GaN HFETs.[3,4] It has been demonstrated that there is strain variation in AlGaN barrier layer that leads to polarization Coulomb field scattering in conventional AlGaN/GaN HFETs,[5–7] and it is meaningful to research the strain distribution in the AlGaN barrier layer of Schottky drain AlGaN/AlN/GaN HFETs.

In this letter, capacitance–voltage (C–V) curves and current–voltage (I–V) curves of Schottky drain AlGaN/AlN/GaN HFETs were measured, along with conventional AlGaN/AlN/GaN HFETs as a control group. We calculated the drain series resistance and the two-dimensional electron gas (2DEG) electron mobility in the gate–drain channel for these two kinds of AlGaN/AlN/GaN HFETs. For Schottky drain AlGaN/AlN/GaN HFETs, it was found that the drain series resistance is much lower and the 2DEG electron mobility in the gate–drain channel is much higher than those of the control group. The lower drain series resistance is of great importance in improving the high-frequency performance of AlGaN/GaN HFETs.[8] Results of energy dispersive spectroscopy (EDS) analysis show that for the control group an apparent transverse diffusion of metal atoms happens and lots of oxygen atoms near the drain are brought in during rapid thermal annealing in the gate–drain regions. We conclude that the annealing of Ohmic contacts has an important effect on the strained AlGaN barrier layer, and Ohmic contacts are an important source of polarization Coulomb field scattering in AlGaN/AlN/GaN HFET devices. In contrast, the influence of Schottky contacts on the strained AlGaN barrier layer is smaller, and the strain in AlGaN barrier layer is distributed more regularly.

2. Experiments

The layers used in this study were grown by molecular beam epitaxy (MBE) on a (0001) sapphire substrate. The structure consists of a 40-nm AlN nucleation layer, followed by a 3-μm undoped GaN layer, a 0.5-nm AlN interlayer and a 22.5-nm thick undoped $Al_{0.28}Ga_{0.72}N$ layer. Hall measurements indicate a sheet carrier density of around 1.1×10^{13} cm^{-2} and an electron mobility of 1800 cm^2/V·s at room temperature. For device processing, mesa isolation was performed using Cl_2/BCl_3 reactive ion etching. The source Ohmic contacts of the rectangular Schottky drain Al-

*Project supported by the National Natural Science Foundation of China (Grant No. 11174182) and the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20110131110005).

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GaN/AlN/GaN HFETs, and the source and drain Ohmic contacts of the conventional AlGaN/AlN/GaN HFETs were formed by depositing Ti/Al/Ni/Au using e-beam evaporation and lift-off. All these rectangular contacts were annealed in a rapid thermal annealing system, and the specific resistivity of the Ohmic contacts was 1.8×10^{-4} Ω·cm^2. Ni/Au (60 nm/160 nm) Schottky contacts were deposited by e-beam evaporation to form the gate and drain of the Schottky drain AlGaN/AlN/GaN HFETs, and the gate of the conventional AlGaN/AlN/GaN HFETs. Source contacts and drain contacts of both kinds of AlGaN/AlN/GaN HFETs were 100-μm wide and 50-μm long with a 60-μm distance between them. For Schottky drain AlGaN/AlN/GaN HFETs, rectangular gate contacts were symmetrically placed in the middle between the source and the drain with their sizes 12 μm/100 μm (length/wide), 24 μm/100 μm, 36 μm/100 μm, and 48 μm/100 μm and are referred to as 1, 2, 3, and 4, respectively. For the control group, the gate contacts had the same sizes and geometric position as those in the Schottky drain AlGaN/AlN/GaN HFETs, and they are referred to as 5, 6, 7, and 8, respectively. *C*–*V* measurements were performed using an Agilent B1520A with 1 MHz at room temperature, and *I*–*V* measurements were also performed using an Agilent B1500A semiconductor parameter analyzer. EDS analysis was carried out using INCAx-sight 7421 EDS analysis system.

3. Results and discussion

The series resistance and 2DEG electron mobility of samples 5, 6, 7, and 8 can be obtained with a method that has been accepted.[5] However, this method is not applicable for samples 1, 2, 3, and 4. The series resistance under Schottky drain contacts and the asymmetry of source contacts and drain contacts for Schottky drain AlGaN/AlN/GaN HFETs should be taken into consideration. Figure 1 shows the resistance distribution in the Schottky drain AlGaN/AlN/GaN HFET when the gate bias (V_G) > the threshold voltage (V_T) and the drain bias (V_{DS}) > turn-on voltage of the Schottky drain contact (V_{on}). $R_{Schottky}$ is the series resistance under the Schottky drain contacts, R_S is the source series resistance, R_D is the drain series resistance, and R_G is the channel resistance under the gate. The drain is represented as a series of uniformly distributed identical diodes. Since the source Ohmic contact has low specific resistivity, the source contact resistance can be ignored. The whole resistance between the drain and source of the Schottky drain HFET (R_T) can be expressed as $R_T = R_{Schottky} + R_S + R_G + R_D$. With the device under zero gate bias, R_T can be obtained using Chueng's functions [9] with the *I*–*V* curve between the drain and the source, and $R_{Schottky}$ can be calculated using the power consumption method.[10] R_S can be obtained with the *I*–*V* curve between the gate and source. The influence of annealing the source Ohmic contact on the gate–drain region can be ignored because of the long distance from the source contact. So R_G and R_D will be determined considering the length ratio of their corresponding 2DEG channel. Because the thickness of the AlGaN barrier layer is only 22.5 nm, and is negligible compared with the gate–source and gate–drain spaces, the influence of the gate bias to the 2DEG electron density of the ungated regions can be neglected. $R_{Schottky}$, R_S, and R_D will not be affected by the gate bias.

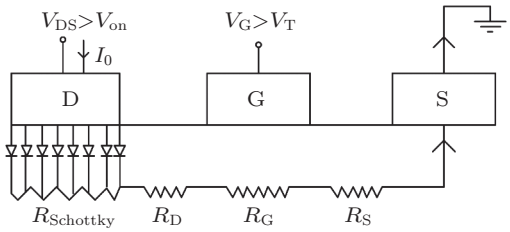


Fig. 1. Diagram of resistance distribution in the Schottky drain AlGaN/AlN/GaN HFET under working conditions.

Figures 2(a) and 2(b) show the *C*–*V* curves of the Schottky drain AlGaN/AlN/GaN HFETs and the corresponding conventional AlGaN/AlN/GaN HFETs, respectively. These *C*–*V* measurements were performed using gate contacts and source contacts. Figure 3 shows the calculated 2DEG electron density under different gate biases for the two kinds of AlGaN/AlN/GaN HFETs by integrating the measured *C*–*V* curves.[6] The *I*–*V* characteristics for both Schottky drain AlGaN/AlN/GaN HFETs and conventional AlGaN/AlN/GaN HFETs at zero gate bias are shown in Fig. 4. Figure 5 shows the measured *I*–*V* curves between gate contacts and source contacts for Schottky drain AlGaN/AlN/GaN HFETs; n_{2DEG} is defined as the 2DEG density in the channel between gate contacts and drain contacts for samples 1, 2, 3, 4. R'_S, R'_D, and u'_{2DEG} are defined as the source series resistance, the drain series resistance, and the 2DEG density in the channel between gate contacts and drain contacts for samples 5, 6, 7, 8, respectively. R'_S and R'_D are equal because of the structural symmetry in the conventional AlGaN/AlN/GaN HFETs. Based on the measured *C*–*V* curves and *I*–*V* curves for Schottky drain AlGaN/AlN/GaN HFETs and conventional AlGaN/AlN/GaN HFETs, $R_{Schottky}$, R_S, R_D, n_{2DEG} for samples 1, 2, 3, 4 and R'_S, R'_D, u'_{2DEG} for samples 5, 6, 7, 8 were calculated (see Table 1). From Table 1, it can be seen that the drain series resistance in samples 1, 2, 3, 4 is much lower than that in the control group, and the 2DEG electron mobility in the channel between gate contacts and drain contacts is much higher than that in the control group. An INCAx-sight 7421 energy dispersive spectroscopy (EDS) analysis system with an accelerating voltage of 15 kV was used to investigate the influence of annealing the Ohmic contacts on the strained AlGaN barrier layer. We chose 3 tiny regions between gate contacts and drain contacts to make elements content analysis for samples 5, 6, 7, 8, respectively. Figures 6(a), 6(b), and 6(c) show results of

elements content analysis in the objective regions for sample 6. It was found that there are Ohmic contact metal atoms (Ti, Au) near the drain, which means the transverse diffusion of metal atoms has happened and there are also lots of oxygen atoms near the drain which were brought in during rapid thermal annealing. Ti, Au, and oxygen atoms are not found in the middle of the gate–drain region or near the gate. So there is obvious strain variation in the AlGaN barrier layer between the gate contact and the drain contact that is caused by the transverse diffusion of metal atoms and the lead-in oxygen defects. SEM-EDS analysis for other samples showed the same results as for sample 6.

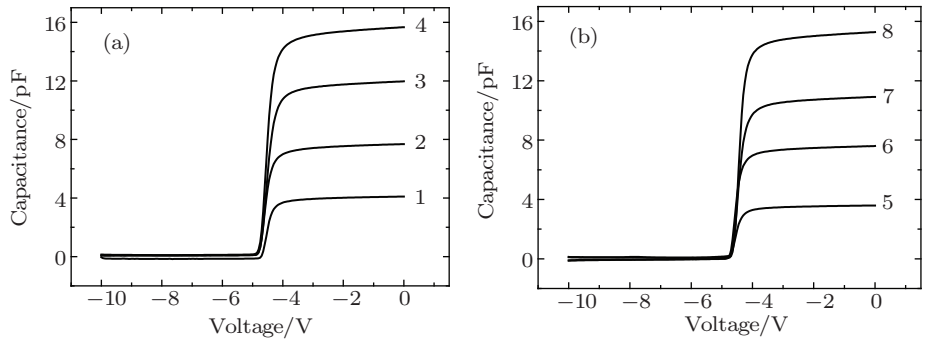


Fig. 2. The measured *C–V* curves at room temperature for samples 1, 2, 3, 4 (a), and samples 5, 6, 7, 8 (b).

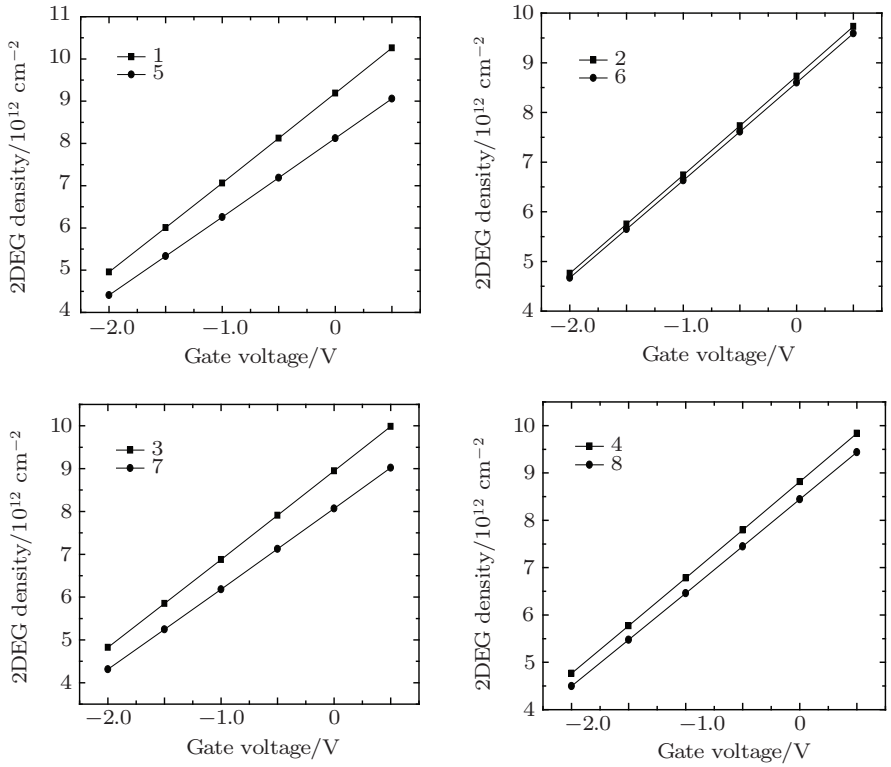


Fig. 3. The calculated 2DEG electron density under different gate biases at room temperature for samples 1, 2, 3, 4 and 5, 6, 7, 8.

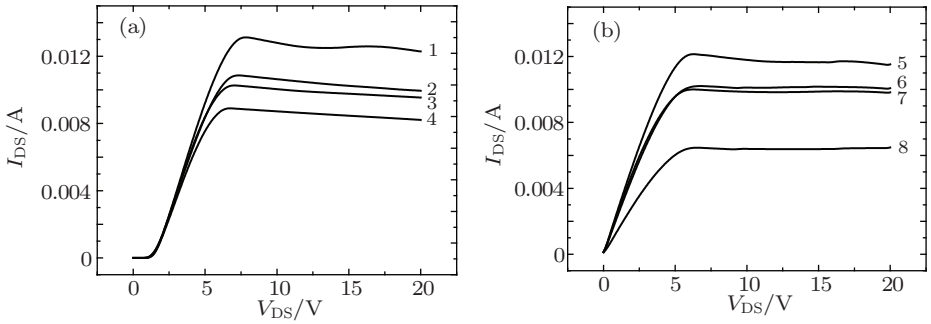


Fig. 4. The measured *I–V* curves under zero gate bias at room temperature for samples 1, 2, 3, 4 (a), and samples 5, 6, 7, 8 (b).

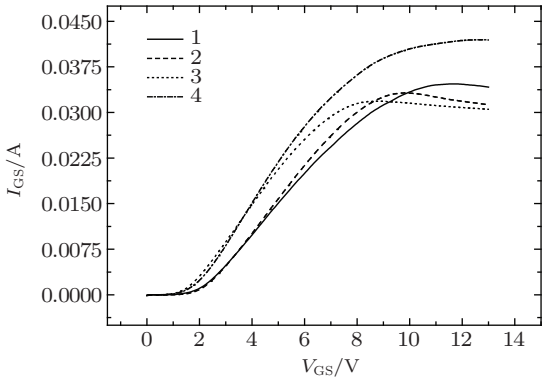


Fig. 5. The measured *I*–*V* curves between gate contacts and source contacts at room temperature for samples 1, 2, 3, 4.

Because Schottky drain AlGaN/AlN/GaN HFETs and the control group had the same sizes and were fabricated on the same material, the apparent difference between n_{2DEG} and u'_{2DEG} is attributed to the different influence of Ohmic drain contacts and Schottky drain contacts on the strained AlGaN barrier layer. For conventional AlGaN/AlN/GaN HFETs, drain Ohmic contacts were formed through rapid thermal annealing, which resulted in transverse diffusion of metal atoms toward gate contacts. The diffusion of metal atoms contributes to the strain variation in the AlGaN barrier between gate contacts and drain contacts, and leads to strong polarization Coulomb field scattering in this region. Also, oxygen defects were created in the AlGaN barrier layer near drain Ohmic contacts and also contributes to the strain variation in the AlGaN barrier layer. However, for Schottky drain AlGaN/AlN/GaN HFETs, drain contacts were formed without rapid thermal annealing. Compared with Ohmic drain contacts, the deposition of Schottky drain contacts had much less effect on the strained AlGaN barrier layer, and led to weaker polarization Coulomb field scatter with interface polarization charges distributed more regularly in the gate–drain region. From Table 1, we also can see the large difference between R_S and R_D in Schottky drain AlGaN/AlN/GaN HFET devices, and this demonstrates that the Ohmic contacts have a stronger influence on the strained AlGaN barrier layer than the Schottky contacts have.

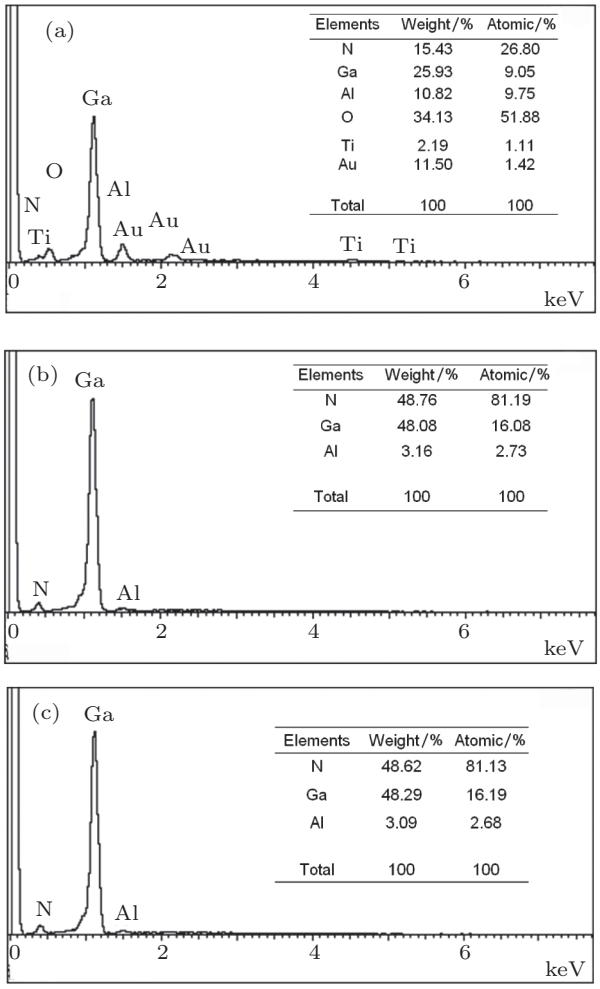


Fig. 6. Results of EDS analysis for the objective region with 1 μm from the drain contact (a), in the middle of the gate–drain region (b), and with 1 μm from the gate contact (c) at room temperature for sample 6.

Table 1. The calculated parameters for samples 1, 2, 3, 4 and samples 5, 6, 7, 8.

	$R_{Schottky}$/Ω	R_S/Ω	R_D/Ω	u_{2DEG}/(cm^2/V·s)		$R'_D(R'_S)$/Ω	u'_{2DEG}/(cm^2/V·s)
1	72.8	145.8	77.5	2108	5	164.8	1120
2	78.0	106.2	74.8	1722	6	149.4	876
3	73.7	72.3	48.3	1806	7	114.5	812
4	80.2	33.4	28.4	1570	8	46.5	990

4. Summary and conclusion

In summary, Schottky drain AlGaN/AlN/GaN HFETs with different gate contact areas were both fabricated along with conventional AlGaN/AlN/GaN HFETs of the same size as control. For Schottky drain AlGaN/AlN/GaN HFETs, the drain series resistance is much lower and the 2DEG electron mobility in the gate–drain channel is much higher than those of the control group, and this is attributed to the different influence of Ohmic contacts and Schottky contacts on the strained AlGaN barrier layer. Compared with the Schottky drain AlGaN/AlN/GaN HFETs, the annealing of drain Ohmic contacts causes significant strain variation in the AlGaN barrier layer and gives rise to strong polarization Coulomb scattering between gate contacts and drain contacts in the conventional AlGaN/AlN/GaN HFETs. Ohmic contacts are an

important source of polarization Coulomb field scattering in AlGaN/AlN/GaN HFET devices. For Schottky drain AlGaN/AlN/GaN HFETs, the strain in the AlGaN barrier layer is distributed more regularly and the polarization Coulomb scattering in the gate–drain region is weaker. The decrease of the drain series resistance based on the use of Schottky metallization in the drain contact is useful in improving the high-frequency performance of AlGaN/GaN HFETs.

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