Influence of drain bias on the electron mobility in AlGaN/AlN/GaN heterostructure field-effect transistors*

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Using measured capacitance–voltage curves and current–voltage characteristics for the AlGaN/AlN/GaN heterostructure field-effect transistors with different gate lengths and drain-to-source distances, the influence of drain bias on the electron mobility is investigated. It is found that below the knee voltage the longitudinal optical (LO) phonon scattering and interface roughness scattering are dominant for the sample with a large ratio of gate length to drain-to-source distance (here 4/5), and the polarization Coulomb field scattering is dominant for the sample with a small ratio (here 1/5). However, the above polarization Coulomb field scattering is weakened in the sample with a small drain-to-source distance (here 20 μm) compared with the one with a large distance (here 100 μm). This is due to the induced strain in the AlGaN layer caused by the drain bias.

Keywords: AlGaN/GaN heterostructures, electron mobility, drain bias, electron scattering

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1. Introduction

Nitride two-dimensional electron gas (2DEG) channels are most promising for handling high-frequency and high-power signals.[1–4] The strained AlGaN/AlN/GaN heterostructure with a thin AlN interlayer has been a popular material structure for AlGaN/GaN heterostructure field-effect transistors (HFETs) due to the improved transport properties of the 2DEG and the electron mobility.[5,6] The main scattering mechanism that affects the electron mobility in the AlGaN/AlN/GaN HFETs has been studied with different Schottky areas in our previous reports.[7,8] However, the above research was performed with different gate biases in the case of low drain voltage (0.1 V). The influence of drain bias on the electron mobility has not been studied though the AlGaN/AlN/GaN HFETs are often used in high-voltage and high-power applications.[9] Thus, it is necessary to investigate the above influence in the AlGaN/AlN/GaN HFETs.

In this paper, with the fabricated rectangular AlGaN/AlN/GaN HFETs of different gate geometrical areas and drain-to-source distances, an average electron mobility in the channel under the Schottky gate is introduced and the influence of drain bias on the electron mobility is investigated.

2. Experiment

The heterostructure layer employed in this study is grown by molecular beam epitaxy (MBE) on a (0001) sapphire substrate. The structure consists of a 40-nm AlN nucleation layer, 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 is performed using Cl_2/BCl_3 reactive ion etching, and the source and drain Ohmic contacts with 100-μm wide and 50-μm long are formed by depositing Ti/Al/Ni/Au using e-beam evaporation and lift-off. Drain-to-source distances with 100 μm and 20 μm are prepared, respectively. These contacts are annealed in a rapid thermal annealing system, and patterned with transmission line method, the specific resistivity of Ohmic contact between the source and the drain is measured to be 5.9×10^{-5} Ω·cm^2. To form the gate, Ni/Au (60 nm/160 nm) Schottky contacts of varying areas are then deposited in the Ohmic contact space between the source and the drain by e-beam evaporation. The Schottky contact sizes in AlGaN/AlN/GaN HFETs with 100-μm drain-to-source distance are 20 μm/100 μm (length/width) and 80 μm/100μm which are denoted as 100-S (small area) and 100-L (large area). The Schottky contact sizes in Al-

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GaN/AlN/GaN HFETs with 20-μm drain-to-source distance are 4 μm/100 μm (length/width) and 16 μm/100 μm which are denoted as 20-S and 20-L, respectively. Capacitance–voltage (C–V) characteristics are measured at room temperature using an Agilent B1520A at 1000 kHz, and current–voltage (I–V) characteristics for the AlGaN/AlN/GaN HFETs are also measured at room temperature using an Agilent B1500A semiconductor parameter analyzer.

3. Calculation and analyses

Figures 1(a) and 1(b) show the C–V curves of the Ni Schottky contacts with different areas for the devices with drain-to-source distances of 100 μm and 20 μm, respectively. The C–V measurements are obtained using the source contact and the Ni Schottky contact. The difference in threshold voltage between sample 20-S and sample 20-L is due to the different strains under the Schottky contacts, caused by the different contact areas. By the integration of the measured C–V curves as shown in Fig. 1, the values of 2DEG electron density (n_{2D}) under different gate biases with different Ni Schottky contact areas can be obtained and are attached into Fig. 1.[10] The relationship between the 2DEG density and the gate bias is approximately linear as shown in Fig. 1. Fitting the linear relationship between the 2DEG density and the gate bias, the following formula is obtained

$$n_{2D}(U) = aU + b, \tag{1}$$

where a and b are the fitted constants, U is the voltage dropped on the AlGaN barrier layer under the gate area. The effect of the saturation velocity is dominant when $\alpha = \mu(V_{GS} - V_T)/(v_S L_G) \geq 1$, where μ is the field-effect mobility, V_{GS} the gate-to-source voltage, V_T the threshold voltage, v_S the electron saturation velocity, and L_G the gate length.[11] For our device, $\mu \sim 1800$ cm^2/V·s, $L_G \geq 4$ μm, $v_S \sim 2 \times 10^5$ m/s, $V_T \sim -4$ V, and for $V_{GS} = 0$ V, we have $\alpha < 0.9$. In this case, the electron drift mobility of the 2DEG in the strained AlGaN/AlN/GaN heterostructure is low field mobility.

For the rectangular device, the electron drift mobility of the 2DEG under the gate in the strained AlGaN/AlN/GaN heterostructure is calculated by the following formula:[7]

$$\int_{V_{GS}-I_{DS}R_S}^{V_{GS}-(V_{DS}-I_{DS}R_D)} n_{2D}(U)\,\mathrm{d}U = \frac{I_{DS}}{Wq}\int_{L_{GS}}^{L_G+L_{GS}} \frac{1}{\bar{\mu}_n}\,\mathrm{d}L, \tag{2}$$

where V_{GS} is the gate bias, V_{DS} the applied bias between drain and source, I_{DS} the current flowing from the drain to the source, q the electron charge, L_G the gate length, L_{GS} the space between the gate and source, and W the gate width. The drain bias causes the channel 2DEG density to be distributed irregularly, thereby leading to inconsistent electron mobility in the channel. For convenience, an average electron mobility $\bar{\mu}$ is used as shown in Eq. (2). Besides, in Eq. (2) R_D is the series resistance of the ungated gate–drain region and R_S is the series resistance of the ungated gate–source region, which can be given by

$$R_D = \frac{L_{GD}}{qn_{2D0}\mu_{n0}W}, \tag{3}$$

$$R_S = \frac{L_{GS}}{qn_{2D0}\mu_{n0}W}, \tag{4}$$

where n_{2D0} and μ_{n0} are the 2DEG electron density and electron mobility under zero gate bias, respectivrly and L_{GD} is the space between the gate and drain.

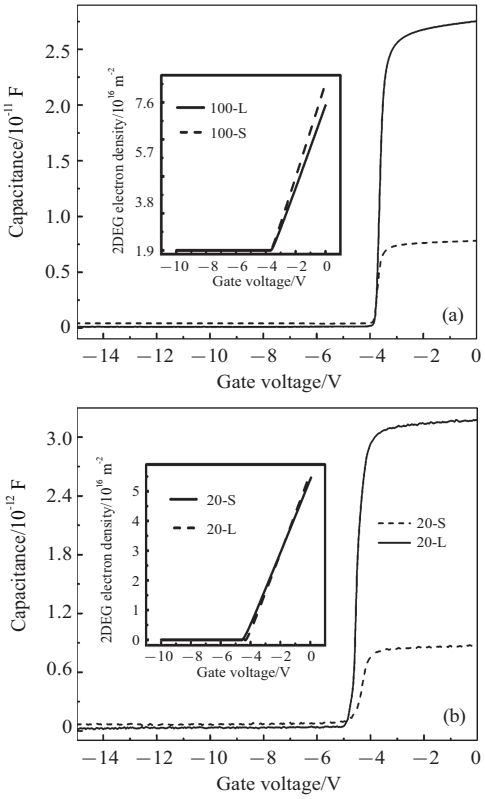


Fig. 1. Measured C–V curves at room temperature of the Ni Schottky contacts with different areas for the devices with drain-to-source distances of 100 μm (a) and 20 μm (b). The calculated 2DEG electron density n_{2D} under different gate biases are attached into the C–V curves, respectively.

Substituting Eq. (1) into Eq. (2), the following expression can be obtained:

$$\bar{\mu}_n = \frac{I_D L_G}{Wq\int_{V_{GS}-I_{DS}R_S}^{V_{GS}-(V_{DS}-I_{DS}R_D)} (aU+b)\,\mathrm{d}U}. \tag{5}$$

The I–V characteristics for the rectangular AlGaN/AlN/GaN HFETs with different drain-to-source distances are measured and shown in Fig. 2. With the relevant data substituted into Eq. (5), the average electron mobility of the 2DEG for the AlGaN/AlN/GaN HFET device can be calculated and the results are shown in Fig. 3. R_D and R_S affect the calculated values of the electron mobility. With drain bias increasing, the 2DEG density in the channel will decrease which leads to the slow increase of the values of R_D and R_S. However, according to our calculation the above effect will not change the variation trend of the average electron mobility.

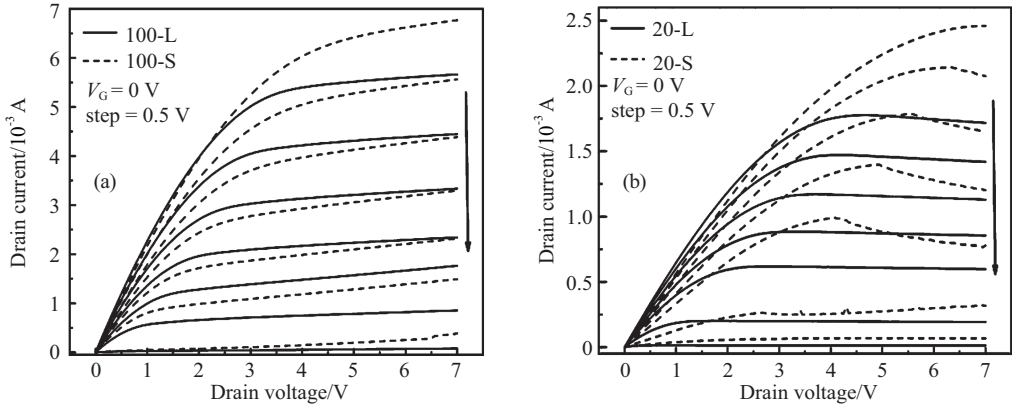


Fig. 2. Measured *I*–*V* curves at room temperature for samples with drain-to-source distances of 100 μm (a) and 20 μm (b).

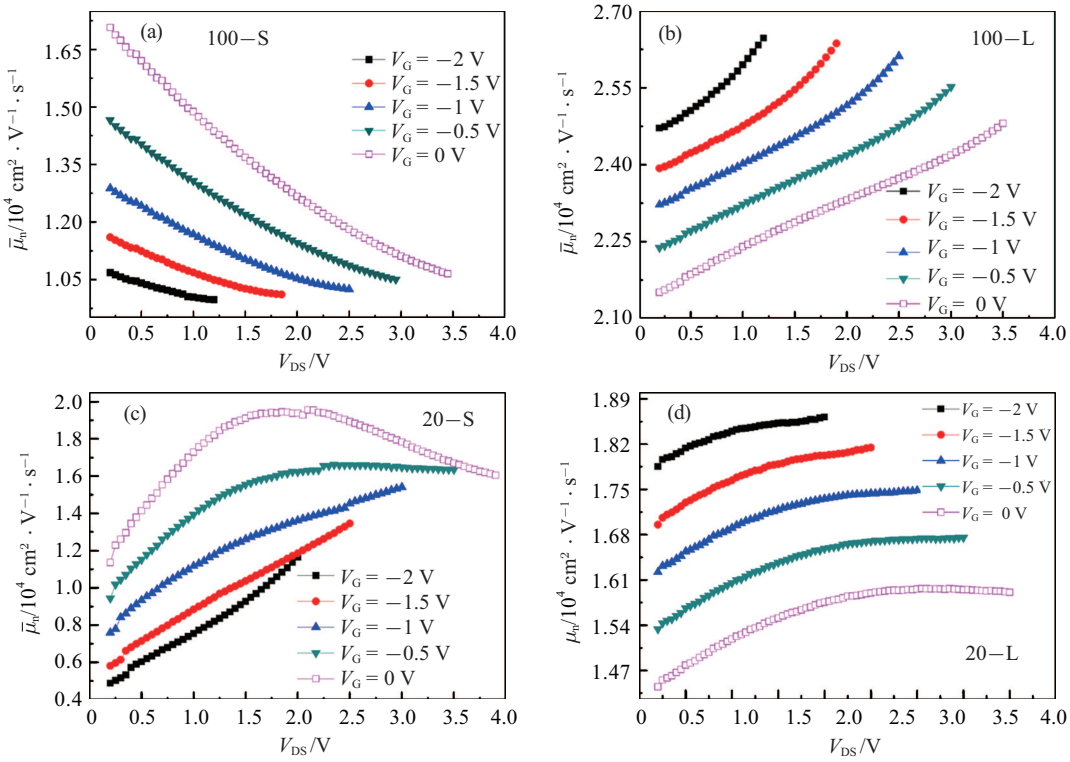


Fig. 3. (color online) The relationships between the electron mobility of the 2DEG and the applied drain bias at different gate voltages for samples with drain-to-source distances of 100 μm ((a), (b)) and 20 μm ((c), (d)), respectively.

According to our previous result,[7,8] there are mainly three kinds of important scattering mechanisms that influence the 2DEG electron drift mobility in an AlGaN/AlN/GaN HFET sample, and these scattering mechanisms are the longitudinal optical (LO) phonon scattering, the interface roughness scattering, and the polarization Coulomb field scattering caused by the irregular distributed polarization charges at the AlGaN/AlN interface. For the LO phonon scattering and the interface roughness scattering, the electron mobility decreases with electron density increasing,[12] but it rises for the polarization Coulomb field scattering.[7,10]

Our previous result shows that for devices with a large ratio of gate length to drain-to-source distance,[7,8] the gradient of the polarization charge density is relatively small, therefore, the scattering associated with a polarization Coulomb field is relatively weak. As a result, the LO phonon scattering and the interface roughness scattering dominate the 2DEG electron mobility. Thus, with drain voltage increasing, the 2DEG density decreases, leading to the monotonic increase for the mobility at a given gate bias for sample 100-L and 20-L (as shown in Fig. 3). At a given drain bias the monotonic decrease for the mobility with gate voltage increasing can also be explained. For the devices with a small ratio of gate length to drain-to-source distance, the gradient of the polarization charge density is large. Thus the polarization Coulomb field scattering is the dominant carrier scattering mechanism, which results in

the monotonic decrease for the mobility of the 2DEG electrons for 100-S at a given bias. However, for sample 20-S the electron mobility abnormally rises with drain voltage increasing. This can be explained as follows.

Before metal deposition, in a fully strained heterostructure the polarization charges are regularly distributed and hence cannot scatter electrons in GaN channel. After deposition, due to a partial strain relaxation in the AlGaN layer the polarization charges at the AlGaN/AlN interface are distributed irregularly.[13,14] Thus there an additional scattering potential will be induced in comparison with that in the ungated heterostructure. And the additional scattering mechanism corresponds to the polarization Coulomb field scattering. Once the drain bias is applied, the stress will be induced by the electric field in the access region.[15] Thus another additional scattering potential is formed which is opposite to the former scattering potential. When the drain-to-source distance is long (such as 100 μm), the stress induced by the electric field is small and the additional scattering potential in the access region can be ignored. However, for sample 20-S the additional scattering potential cannot be ignored and the total polarization Coulomb field scattering will be weaker, leading to an increase of the mobility at a given gate bias for sample 20-L (as shown in Fig. 3). The saturation or decrease of the electron mobility at high drain bias may be due to the hot electron effect. For sample 20-L at a given drain bias, the monotonic rise of the mobility with gate voltage increasing can be explained by the different polarization Coulomb field scattering potentials induced by the gate bias.

Besides, the calculated electron mobility of sample 100-L is much larger than that of the AlGaN/AlN/GaN heterostructure, measured by the Van der Pauw method (1800 $cm^2/V{\cdot}s$). This may be due to the change of the stress of AlGaN barrier layer induced by the deposited metal, which is different from the one of sample 100-S. And then the channel electron density is less than that of the AlGaN/AlN/GaN heterostructure (1.1×10^{13} cm^{-2}). With the increase of gate or drain bias, the channel electron density decreases more and the electron mobility increases due to the dominant scattering mechanisms of LO phonon scattering and the interface roughness scattering.

4. Conclusions

In this paper, rectangular AlGaN/AlN/GaN HFETs of different geometrical areas of gate and drain-to-source distances are prepared. With the measured *C*–*V* curves and the *I*–*V* characteristics of AlGaN/AlN/GaN HFETs, the influence of drain bias on the electron mobility in the channel under the Schottky gate is investigated. It is found that for the sample with a large ratio of gate length to drain-to-source distance (here 4/5) the LO phonon scattering and the interface roughness scattering are dominant, leading to the monotonic increase of the mobility with drain bias increasing. However, the influence of the drain bias on the electron mobility for the sample with a small ratio (here 1/5) varies with drain-to-source distance. The polarization Coulomb field scattering dominates the 2DEG electron mobility in the sample with a large drain-to-source distance (here 100 μm), however for the sample of 20 μm drain-to-source distance, the polarization Coulomb field scattering is weakened due to the induced strain in the AlGaN layer and leads to a monotonic increase of the mobility with drain bias increasing.

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