Electron mobility in the linear region of an AlGaN/AlN/GaN heterostructure field-effect transistor*

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We simulate the current–voltage (I–V) characteristics of AlGaN/AlN/GaN heterostructure field-effect transistors (HFETs) with different gate lengths using the quasi-two-dimensional (quasi-2D) model. The calculation results obtained using the modified mobility model are found to accord well with the experimental data. By analyzing the variation of the electron mobility for the two-dimensional electron gas (2DEG) with the electric field in the linear region of the AlGaN/AlN/GaN HFET I–V output characteristics, it is found that the polarization Coulomb field scattering still plays an important role in the electron mobility of AlGaN/AlN/GaN HFETs at the higher drain voltage and channel electric field. As drain voltage and channel electric field increase, the 2DEG density reduces and the polarization Coulomb field scattering increases, as a result, the 2DEG electron mobility decreases.

Keywords: AlGaN/AlN/GaN heterostructure field-effect transistors, quasi-two-dimensional model, the polarization Coulomb field scattering, the two-dimensional electron gas mobility

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1. Introduction

AlGaN/GaN heterostructure field-effect transistors (HFETs) have been a research hotspot in the field of semiconductor electronic devices due to their excellent characteristics, such as high transconductances, high saturation currents, and high cut-off frequencies. The two-dimensional electron gas (2DEG) electron mobility is an important parameter which directly affects the frequency characteristics and the power characteristics in AlGaN/GaN HFETs. In the previous studies it was found that the polarization Coulomb field scattering has an important influence on the electron mobility of the 2DEG for both AlGaN/GaN HFETs and AlGaN/AlN/GaN HFETs,[1,2] but those studies were restricted to the low-field mobility for the 2DEG electrons with the drain to source bias being 0.1 V, while the further researches have not been conducted on the variation of the electron mobility with both the drain voltage and the channel electric field in the linear region of the AlGaN/AlN/GaN HFET current–voltage (I–V) output characteristic curve. The aim of this paper is to study the variation of the 2DEG electron mobility with the drain voltage and the channel electric field in the linear region, and analyze the influence of the polarization Coulomb field scattering on the 2DEG electron mobility in the linear region.

2. Experiment

The heterostructure layer employed in this paper was grown by molecular beam epitaxy (MBE) on a (0001) sapphire substrate. The heterostructure layer consisted of a 40-nm AlN nucleation layer, followed by a 3-μm undoped GaN layer, a 0.5-nm AlN insert layer, and finally a 22.5-nm undoped $Al_{0.28}Ga_{0.72}N$ layer. The measured 2DEG sheet density and Hall-mobility at room temperature are 1.1×10^{13} cm^{-2} and 1800 cm^2/V·s, respectively. The source and drain Ohmic contacts were formed by depositing Ti/Al/Ni/Au on heterostructure material using e-beam evaporation and lift-off techniques. These contacts were annealed at 800 °C for 60 s in a rapid thermal annealing system. The gate Schottky contacts was formed by depositing Ni/Au on heterostructure material using e-beam evaporation and the lift-off techniques. For the devices, the values of length/width of the source and drain were all 50 μm/100 μm, the spaces between the source and drain were all 100 μm, and the gate sizes, i.e., the values of length/width were 80 μm/100 μm, 60 μm/100 μm, 40 μm/100 μm, and 20 μm/100 μm. The C–V characteristics of the AlGaN/AlN/GaN HFETs were measured using an Aglient B5120A at 1000 kHz, and the I–V characteristics were measured using an Aglient B1500A.

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3. Calculation and analysis

Figure 1 shows the measured *C*–*V* characteristic curves of the AlGaN/AlN/GaN HFETs for the different gate lengths at room temperature, the gate lengths for samples a, b, c, and d are 80 μm, 60 μm, 40 μm, and 20 μm, respectively.

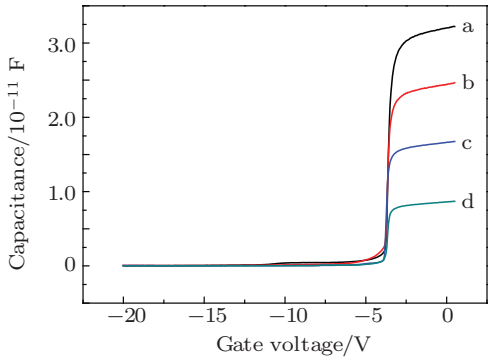


Fig. 1. (color online) Measured *C*–*V* curves for samples a, b, c, and d at room temperature.

The values of two-dimensional electron gas sheet density at different gate biases can be obtained by integrating the *C*–*V* curves[1]

$$n_{2D}(V) = \frac{Q}{qS} = \frac{\int_{V_t}^{V} C\,\mathrm{d}V}{qS}, \tag{1}$$

where C is the gate-to-drain capacitance, V the gate bias, q the electron charge, S the Schottky contact area, V_t the threshold voltage which can be obtained from the differential of the *C*–*V* curve.[3] The threshold voltages for samples a, b, c, and d are −3.65 V, −3.65 V, −3.75 V, and −3.65 V, respectively.

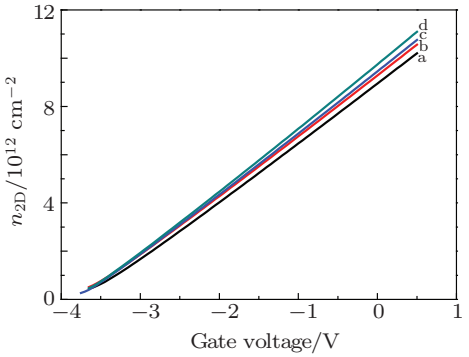


Fig. 2. (color online) Plots of 2DEG sheet density versus gate bias.

As shown in Fig. 2, the relationships between the two-dimensional electron gas sheet density and gate bias are all approximately linear, so we can obtain the two-dimensional electron gas sheet density through the following linear fitting expression

$$n_{2D}(V) = B^{*}V + a, \tag{2}$$

where B and a are fitting parameters, whose values are shown in Table 1.

Table 1. Fitting parameters of 2DEG sheet density for samples a, b, c, and d.

sample	B/cm$^{-2}\cdot$V^{-1}	a/cm^{-2}
a	2.40542×10^{12}	8.90151×10^{12}
b	2.45831×10^{12}	9.24725×10^{12}
c	2.50865×10^{12}	9.41416×10^{12}
d	2.59008×10^{12}	9.70114×10^{12}

The *I*–*V* characteristic calculation of the AlGaN/AlN/GaN HFET is based on a quasi-2D model,[4–6] as shown in Fig. 3.

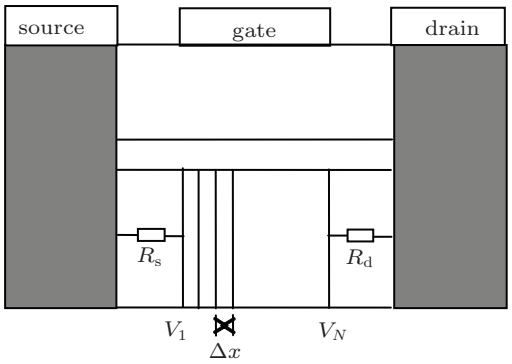


Fig. 3. Quasi-2D model used in the AlGaN/AlN/GaN HFET.

The channel is divided into N equal parts, the length of each equal part is

$$\Delta x = L_g/N, \tag{3}$$

where L_g is the gate length.

The voltages at the source and drain ends of the channel are given, respectively, by

$$V_1 = V_s + I_{ds}R_s, \tag{4}$$

$$V_N = V_{ds} - I_{ds}R_d, \tag{5}$$

where R_s and R_d are the source contact resistance and drain contact resistance, respectively. The low-field mobility of the AlGaN/AlN/GaN HFET is given by[2]

$$\mu_{low} = \frac{I_{ds}L_g}{qn_{2D}W[V_{ds} - I_{ds}(R_d + R_s)]}, \tag{6}$$

$$R_s = \frac{L_{gs}}{qn_{2D0}\mu_{n0}W}, \tag{7}$$

$$R_d = \frac{L_{gd}}{qn_{2D0}\mu_{n0}W}, \tag{8}$$

where L_{gd} is the space between gate and drain, L_{gs} the space between gate and source, n_{2D0} the 2DEG sheet density at zero gate bias, and μ_{n0} the electron mobility at zero gate bias.

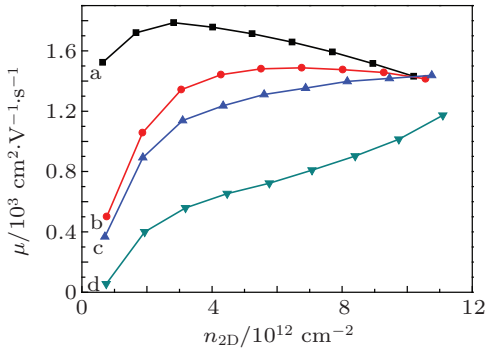


Fig. 4. (color online) Variations of low-field mobility with 2DEG sheet density at room temperature.

The relationships between the 2DEG electron low-field mobility and the 2DEG sheet density, when the drain–source voltage is 0.1 V at room temperature, are shown in Fig. 4. To obtain the values of electron mobility at different channel positions, a polynominal fit to the curves is used, and expressed as

$$\mu_{i,\mathrm{low}} = A + B_1 n_i + B_2 n_i^2 + B_3 n_i^3 + B_4 n_i^4 + B_5 n_i^5, \tag{9}$$

where A, B_1, B_2, B_3, B_4, and B_5 are all fitting parameters, whose values are shown in Table 2.

Table 2. Fitting parameters of low-field mobility for samples a, b, c, and d.

Sample	A/cm^2·V^{-1}·s^{-1}	$B_1/10^{-10}$ cm^4·V^{-1}·s^{-1}	$B_2/10^{-22}$ cm^6·V^{-1}·s^{-1}	$B_3/10^{-35}$ cm^8·V^{-1}·s^{-1}	$B_4/10^{-48}$ cm^{10}·V^{-1}·s^{-1}	$B_5/10^{-62}$ cm^{12}·V^{-1}·s^{-1}
a	1281.14511	4.7024	–1.59566	2.45932	–1.86624	5.48553
b	–156.29354	10.5026	–2.72409	3.56283	–2.32637	5.96335
c	–192.57935	9.66619	–2.71309	3.96354	–2.85795	8.02423
d	–331.8085	6.38586	–1.80169	2.6992	–1.96219	5.63094

The two-dimensional electron gas sheet density in Eq. (9) can be obtained from Eq. (2) as follows:

$$n_i = B(V_\mathrm{g} - V_i) + a. \tag{10}$$

Considering the influence of the electric field on the electron mobility, we modify the mobility model based on the low-field mobility as follows:[7]

$$\mu_i = \frac{\mu_{i,\mathrm{low}}}{\left[1 + \left(\dfrac{\mu_{i,\mathrm{low}} E_i}{v_\mathrm{sat}}\right)^r\right]^{1/r}}, \tag{11}$$

where E_i is the channel electric field, v_sat the electron saturation drift velocity, whose value is 2.576×10^7 cm/s,[8] r is the fitting parameter, whose values are shown in Table 3.

Table 3. Fitting parameters for samples a, b, c, and d at different gate biases.

Sample	$V_\mathrm{g} = 0.5$ V	$V_\mathrm{g} = 0$ V	$V_\mathrm{g} = -0.5$ V	$V_\mathrm{g} = -1.0$ V	$V_\mathrm{g} = -1.5$ V	$V_\mathrm{g} = -2.0$ V
a	1	0.9	0.8	0.68	0.6	0.55
b	1	1	1	1	1	1
c	1	1	1	1	1	1
d	0.46	0.48	0.5	0.55	0.6	0.6

The carrier drift velocity and the channel electric field at the i-th section, respectively, are

$$v_i = I_\mathrm{ds}/qWn_i, \tag{12}$$

$$E_i = v_i/\mu_i. \tag{13}$$

Once the drain–source current is given, the 2DEG sheet density n_i, the carrier drift velocity v_i, the electron mobility μ_i and the channel electric field E_i at the i-th section can be obtained according to Eqs. (9)–(13). The channel voltage at the next point is

$$V_{i+1} = V_i + E_i \Delta x. \tag{14}$$

According to Eq. (5), V_ds is finally obtained from V_N.

The calculated I–V characteristics for samples a, b, c, and d using the above formulas are shown in Fig. 5, and it can be seen that the calculation results and the experimental data are in good agreement.

Figure 5 shows that the modified mobility model used in the calculation is correct. Through the above calculation we can obtain the values of 2DEG sheet density, the electric field strength, the channel voltage, and the electron mobility at different channel positions under direct current bias. Because the channel voltages are different at different positions, the values of 2DEG sheet density and the channel electric field are also different, so the electron mobility of the 2DEG is no longer a constant. Considering that the drain end of the channel first pinches off with the increase of drain voltage, the study is focused on the variation of the 2DEG electron mobility at the channel position of the drain end. Figure 6 shows the variations of the 2DEG electron mobility with drain voltage at the drain end for samples a, b, c, and d when the gate bias is zero.

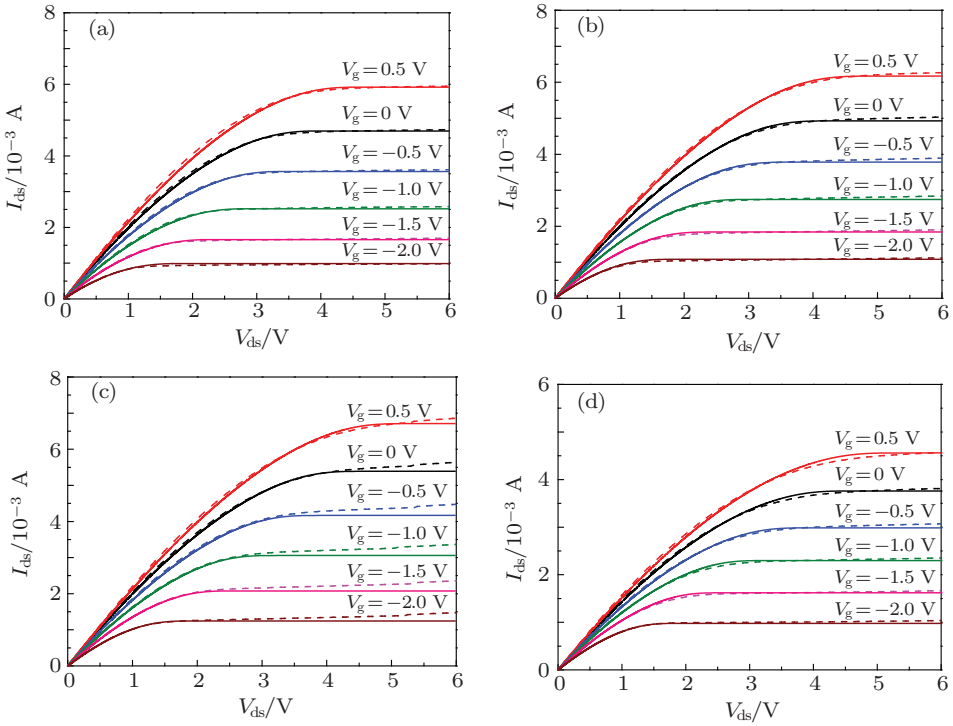


Fig. 5. (color online) Comparisons between the calculated *I*–*V* characteristics (solid lines) and the experimental results (dashed lines) for $L_g = 80$ μm (a), 60 μm (b), 40 μm (c), and 20 μm (d).

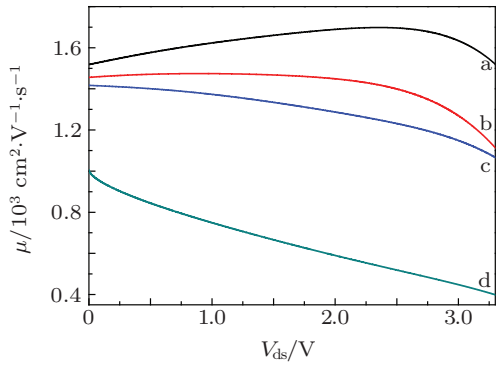


Fig. 6. (color online) Variations of 2DEG electron mobility with drain voltage at zero-gate-bias.

As shown in Fig. 6, in the 2DEG electron mobility for sample a there appears a peak, the electron mobility for sample b is first almost unchanged, and then drops with the increase of drain voltage, the values of electron mobility for samples c and d always reduce with the increase of drain voltage. These results can be explained using the polarization Coulomb field scattering. When the Schottky contact metals are deposited on AlGaN/AlN/GaN heterostructures, the strain of AlGaN barrier layer under the Schottky gate metals changes, and the polarizations are different in the gated region and ungated region. In addition, with the converse piezoelectric effect, the gate biases will induce the strain variation of the AlGaN barrier layer under the gate metals. As a result, the polarization charge density underneath the gate metals will be changed by the gate bias electric field. Moreover, because the transverse diffusion of drain/source Ohmic contact metal atoms can form a large concentration gradient along the strained AlGaN barrier layer, the polarization charges at the AlGaN/AlN/GaN interfaces which are closed to the Ohmic contact metals are distributed irregularly. With all the above reasons, there will appear a polarization charge density variation at the AlGaN/AlN/GaN interfaces, thereby establishing a polarization Coulomb field that scatters the 2DEG electrons.[1,2,9,10]

There are three main kinds of scattering mechanisms that affect the electron mobility of the 2DEG,[1,2] i.e., longitudinal optical (LO) phonon scattering, interface roughness scattering, and polarization Coulomb field scattering. It is found that for the polarization Coulomb field scattering, the electron mobility rises with the increase of the 2DEG sheet density, but decreases for the LO phonon scattering and the interface roughness scattering. For sample a, the gate length is largest and so the polarization Coulomb field scattering is weakest. With low drain voltage, the 2DEG sheet density is high enough so that the polarization Coulomb field scattering is shielded, so the LO phonon scattering and the interface roughness scattering play a dominant role. The 2DEG sheet density decreases with the increase of drain voltage, which results in the increase of the electron mobility. When the drain voltage continues to increase and the 2DEG sheet density continues to decrease, the shielding effect weakens, and then the polarization Coulomb field scattering begins to be dominant. Therefore, the electron mobility drops with the increase of the drain voltage. For sample b, the gate length is smaller than that of sample a and the gradient of the polarization charge density is larger than that

of sample a. When the drain voltage is small, the LO phonon scattering, the interface roughness scattering and the polarization Coulomb field scattering work together, so the mobility variation is not obvious. As the drain voltage continues to increase, the polarization Coulomb field scattering becomes stronger and stronger, which leads to the drop of the electron mobility in turn. For samples c and d, their gate lengths are small and the gradients of the polarization charge density are relatively large, the polarization Coulomb field scattering is always dominant. As the drain voltage increases, the 2DEG sheet density reduces, as a result, the electron mobility drops. Considering that the gate length of sample d is smaller than that of sample c, the gradient of the polarization charge density in sample d is larger than that in sample c, hence the change in electron mobility of sample d is larger than that of sample c.

Figure 7 shows the variations of electron mobility with electric field at the drain end of the channel when the drain voltage gradually increases to pinch-off voltage.

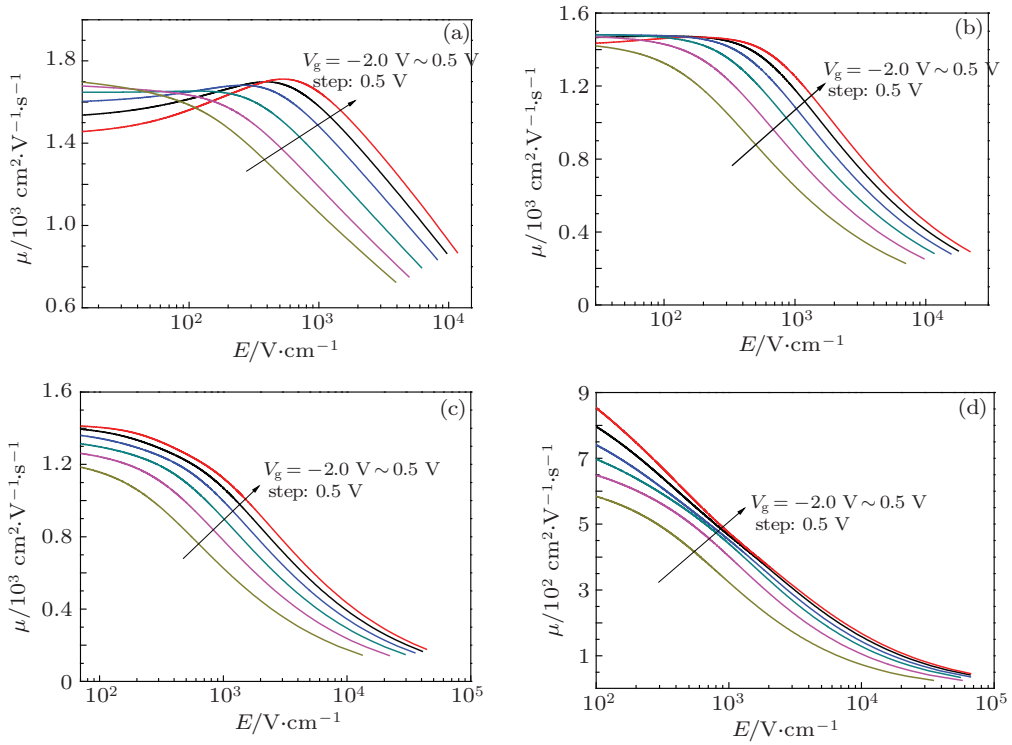


Fig. 7. (color online) Variations of electron mobility variation with electric field at the drain end of the channel for $L_g = 80$ μm (a), 60 μm (b), 40 μm (c), and 20 μm (d).

For samples a and b, their gate lengths are larger and the gradients of the polarization charge density are relatively small, so the polarization Coulomb field scattering is weaker. At higher gate bias, the 2DEG sheet density is higher and the polarization Coulomb field scattering is shielded, so the LO phonon scattering and the interface roughness scattering are dominant. The 2DEG sheet density decreases with the increase of electric field strength, which results in the increase of the electron mobility. When the electric field continues to increase, the 2DEG sheet density decreases and the shielding effect weakens. Then the polarization Coulomb field scattering begins to work and therefore the electron mobility drops. At the lower gate bias, the 2DEG sheet density is lower, the shielding from the polarization Coulomb field is weaker and the polarization Coulomb field scattering is the main scattering mechanism, so the electron mobility decreases with the increase of the electric field strength.

For samples c and d, their gate lengths are smaller and the gradients of the polarization charge density are relatively large, the polarization Coulomb field scattering is always dominant at different gate biases. The 2DEG sheet density decreases with the increase of the electric field strength, which weakens the shielding from the polarization Coulomb field, so the electron mobility decreases. As to the same sample, the 2DEG sheet density increases with the gate bias, and so the electron mobility rises.

The above analysis shows that the polarization Coulomb field scattering has an important influence on 2DEG electron mobility in the linear region of each of the AlGaN/AlN/GaN HFET output characteristic curves, especially for the small gate length devices (samples c and d). When the polarization Coulomb field scattering is the dominant carrier scattering mechanism in the AlGaN/AlN/GaN HFET, as drain voltage and channel electric field increase, the 2DEG sheet den-

sity decreases, and the polarization Coulomb field scattering increases, as a result, the 2DEG electron mobility reduces.

4. Conclusion

In this paper we simulate the current–voltage characteristics of the AlGaN/AlN/GaN HFETs using quasi-2D model, and modify the mobility model based on the low-field mobility. It is found that the calculation results accord well with the experimental data. We analyze the variation of the 2DEG electron mobility with the channel electric field in the linear region, and find that the polarization Coulomb field scattering still plays an important role in the electron mobility of the 2DEG in AlGaN/AlN/GaN HFET at a higher drain voltage and channel electric field. The 2DEG electron mobility decreases with the increases of the drain voltage and the channel electrical field, which is attributed to the polarization Coulomb field scattering. As the drain voltage and the channel electric field increase, the 2DEG sheet density decreases, and the polarization Coulomb field scattering increases, as a result, the 2DEG electron mobility reduces.

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