Influence of the channel electric field distribution on the polarization Coulomb field scattering in $In_{0.18}Al_{0.82}N$/AlN/GaN heterostructure field-effect transistors*

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By making use of the quasi-two-dimensional (quasi-2D) model, the current–voltage (I–V) characteristics of $In_{0.18}Al_{0.82}N$/AlN/GaN heterostructure field-effect transistors (HFETs) with different gate lengths are simulated based on the measured capacitance–voltage (C–V) characteristics and I–V characteristics. By analyzing the variation of the electron mobility for the two-dimensional electron gas (2DEG) with electric field, it is found that the different polarization charge distributions generated by the different channel electric field distributions can result in different polarization Coulomb field scatterings. The difference between the electron mobilities primarily caused by the polarization Coulomb field scatterings can reach up to 1522.9 $cm^2/V{\cdot}s$ for the prepared $In_{0.18}Al_{0.82}N$/AlN/GaN HFETs. In addition, when the 2DEG sheet density is modulated by the drain–source bias, the electron mobility presents a peak with the variation of the 2DEG sheet density, the gate length is smaller, and the 2DEG sheet density corresponding to the peak point is higher.

Keywords: $In_{0.18}Al_{0.82}N$/AlN/GaN heterostructure field-effect transistors, channel electric field distribution, polarization Coulomb field scattering, two-dimensional electron gas mobility

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1. Introduction

Lattice-matched InAlN/GaN heterostructure field-effect transistors (HFETs), which were first proposed by Kuzmík, have aroused intense interest in recent years due to the fact that they promise to deliver high two-dimensional electron gas (2DEG), high current, and high power densities in devices.[1–4] The 2DEG electron mobility is crucial to the frequency characteristics and power characteristics of GaN-based HFET. In their previous research, Zhao *et al.*[5] and Lü *et al.*[6] found that the polarization Coulomb field scattering has an important influence on the 2DEG electron mobility for both AlGaN/GaN HFETs and AlGaN/AlN/GaN HFETs. For the InAlN/GaN heterostructure, when the indium composition of InAlN material is set to be 17%∼18%, the InAlN barrier layer is lattice-matched to GaN and there is no strain or piezoelectric polarization for the InAlN barrier layer. The polarization charge is, therefore, completely determined by spontaneous polarization and the reliability of the device will be significantly enhanced.[1,7] Consequently, a study of whether the polarization Coulomb field scattering plays an important role in the InAlN/GaN HFET is required. To improve the characteristics of the device and enhance the lateral transport properties of the 2DEG, some researchers have insert an ultrathin AlN layer between the InAlN barrier layer and the GaN buffer layer.[8,9] In 2012, Luan *et al.*[10] found that the Ohmic contact processing and the gate bias cause the irregular distribution of the polarization charges at the $In_{0.18}Al_{0.82}N$/AlN interface, which generates the polarization Coulomb field, and the polarization Coulomb field scattering have an important influence on the 2DEG electron mobility in both rectangular and circular $In_{0.18}Al_{0.82}N$/AlN/GaN HFETs, which is the same as in the AlGaN/AlN/GaN HFETs. However, the above studies were made at a low channel electric field (corresponding to $V_{ds} = 0.1$ V). In fact, different biases will be applied to the source and drain contacts when the devices are working, and the channel electric field distribution varies with the value of V_{ds}. Since the polarization Coulomb field scattering resulting from the uneven polarization charge distribution is an important carrier scattering mechanism in the GaN-based $In_{0.18}Al_{0.82}N$/AlN/GaN HFETs, while the polarization charge distribution is closely related to the channel electric field distribution, it is necessary to study the influence of the channel electric field distribution on the polarization Coulomb field scattering. In our previous research, we have found that the polarization Coulomb field scattering plays an important role in the electron mobility of AlGaN/AlN/GaN HFETs at higher drain voltage and channel electric field,[11] but the $In_{0.18}Al_{0.82}N$/AlN/GaN HFETs have not been studied. In this paper, with the prepared $In_{0.18}Al_{0.82}N$/AlN/GaN HFETs, the

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values of 2DEG electron mobility with different channel electric fields are calculated and the influence of the channel electric field distribution on the polarization Coulomb field scattering is studied.

2. Experiment

The heterostructure layer employed in this paper was grown by metal–organic chemical vapor deposition (MOCVD) on a (0001) sapphire substrate. It consisted of a 40-nm AlN buffer layer, followed by a 3-μm undoped GaN channel layer, a 1-nm AlN interlayer, and finally a 4-nm undoped $In_{0.18}Al_{0.82}N$ barrier layer. The measured 2DEG sheet density and Hall-mobility at room temperature are 1.23×10^{13} cm^{-2} and 1413 cm^2/V·s, respectively. For device processing, mesa isolation was performed using Cl_2/BCl_3 reactive ion etching, and the source and drain Ohmic contacts were formed by depositing Ti/Al/Ni/Au using e-beam evaporation and lift-off techniques. They were then annealed in a rapid thermal annealing system, and the specific resistivity of the Ohmic contact was measured to be 3×10^{-5} Ω.cm^2. The contact areas are both 50 μm×100 μm (length × width) and the drain-to-source distances are both 100 μm. To form the gate, Ni/Au Schottky contacts of varying areas each were deposited in the space between the source and drain Ohmic contact by e-beam evaporation. The Schottky contacts are symmetrically placed in the middle between the source and drain contacts, and the gate contact areas were 80 μm×100 μm (length × width), 40 μm×100 μm, and 20 μm×100 μm respectively, which are numbered as 1, 2, and 3, respectively. The *C*–*V* curves were measured at room temperature using Aglient B1520A at 1 MHz, and the *I*–*V* curves were measured at room temperature using Aglient B1500A.

3. Calculation and analysis

Figure 1(a) shows the *C*–*V* curves of the InAlN/AlN/GaN HFETs with different gate lengths at room temperature. The *C*–*V* curves were measured using the source contact and the gate Schottky contact. The 2DEG sheet densities under different gate bias voltages can be obtained by investigating the *C*–*V* curves[5,6] shown in Fig. 1(b).

The *I*–*V* characteristic calculations of InAlN/AlN/GaN HFETs are based on a quasi-2D model and the calculation process is the same as that described in Ref. [12]. Therefore, the 2DEG sheet density at *i* point is given by fitting the curves of Fig. 1(b) (expressed as Eq. (1)) and the drift velocity expression in Ref. [12] is replaced by Eqs. (2) and (3).

$$n_i = B(V_g - V_i) + a, \tag{1}$$

$$\mu_i = \mu_{1,i}\left[1 - \left(\frac{v_i}{v_{sat}}\right)^r\right]^s, \tag{2}$$

$$E_i = v_i/\mu_i, \tag{3}$$

where B and α are matching parameters; v_{sat} is the electron saturation drift velocity, whose value is 2.1×10^7 cm/s;[13] r and s are both curve fitting factors; $\mu_{1,i}$ is the fitting mobility at i point, which is obtained by fitting the relationship curve between the low field electron mobility at the drain end of the channel and the 2DEG sheet density and is given by

$$\mu_{1,i} = C + D_1\exp(-n_i/t_1) + D_2\exp(-n_i/t_2) + D_3\exp(-n_i/t_3), \tag{4}$$

with C, D_1, t_1, D_2, t_2, D_3, and t_3 being all fitting parameters.

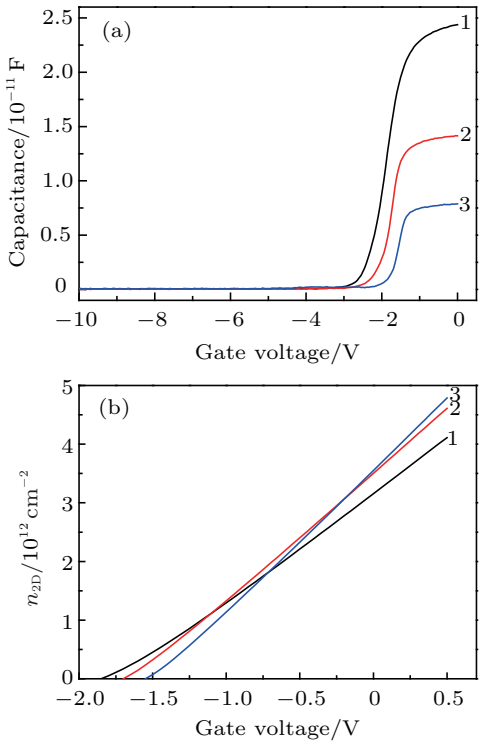


Fig. 1. (color online) (a) Measured *C*–*V* curves at room temperature for samples 1, 2, and 3, (b) plots of the 2DEG sheet density versus gate bias, obtained by integrating the *C*–*V* curves in panel (a).

So, once the drain–source current I_{ds} is given, we can calculate and obtain 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 point, and we then ultimately obtain V_{ds}.

Figure 2 gives the calculated *I*–*V* characteristics for the devices with different gate lengths, where the solid lines represent simulation curves and the dash lines denote the test curves. It can be seen that the calculation results accord well with the experimental data, which indicates that the calculation is correct.

Because the drain end of the channel first pinches off with the increase of drain–source voltage, our research has been focused on the variation of the 2DEG electron mobility at the drain end of the channel. Figure 3 shows the variations of the electron mobility with 2DEG sheet density, in which the solid lines represent the electron mobility values obtained by the

simulation calculation and the 2DEG sheet densities are modulated by the drain–source bias (corresponding to $V_{gs} = 0$), while the dash lines denote the low-field electron mobility values (calculated in accordance with Ref. [6]) and the 2DEG sheet densities are modulated by the gate–source bias (corresponding to $V_{ds} = 0.1$ V).

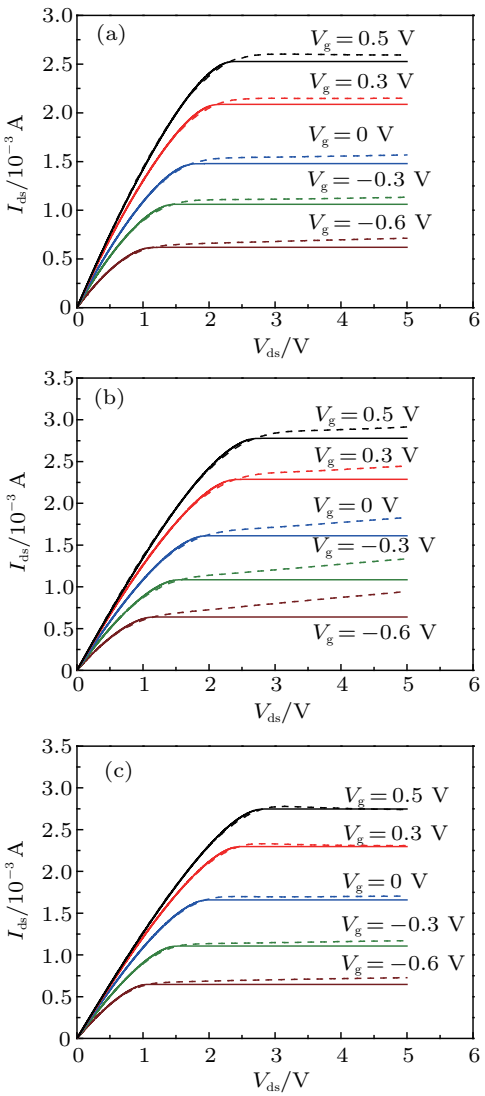


Fig. 2. (color online) Calculated *I*–*V* characteristics of samples 1 (a), 2 (b), and 3 (c).

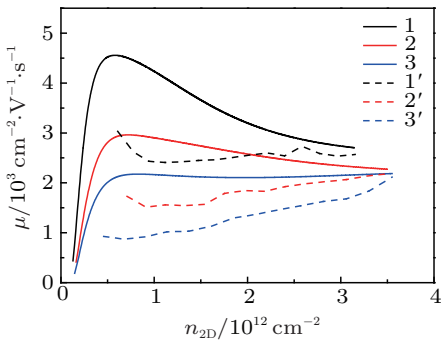


Fig. 3. (color online) Variations of the electron mobility with the 2DEG sheet density.

Figure 3 shows that, for the different samples, the electron mobility peaks correspond to different 2DEG sheet densities, the gate length is smaller, and the 2DEG sheet density is higher. As the 2DEG sheet density increases, the electron mobility difference between the solid lines and the dash lines decreases, and finally the electron mobility values tend to the same value. The electron mobility difference between the solid lines and the dash lines at the peak points can even reach up to 1522.9 cm^2/V·s (sample 1), 1241.1 cm^2/V·s (sample 2), and 1273.2 cm^2/V·s (sample 3), respectively.

From Ref. [10] it follows that the main scattering mechanisms in the $In_{0.18}Al_{0.82}N$/AlN/GaN HFETs are the same as those in the AlGaN/AlN/GaN HFETs, including the longitudinal optical (LO) phonon scattering, the interface roughness scattering, and the polarization Coulomb field scattering. Although there is no strain in the $In_{0.18}Al_{0.82}N$ barrier layer in the $In_{0.18}Al_{0.82}N$/AlN/GaN heterostructure, the thin AlN interlayer is strained due to the lattice-unmatched to GaN. Therefore, due to the converse piezoelectric effect, the change of the channel electric field (which is related to the drain–source biases and the gate–source biases) will induce the strain variation of the AlN interlayer in the $In_{0.18}Al_{0.82}N$/AlN/GaN heterostructure, which occurs in the AlGaN/AlN/GaN heterostructure.[14,15] The $In_{0.18}Al_{0.82}N$ barrier layer will then change following the strain variation of the AlN interlayer. As a result, the polarization charge density underneath gate metal will be changed by both the drain–source bias and the gate–source bias voltages. Consequently, the polarization charges at the $In_{0.18}Al_{0.82}N$/AlN interface are distributed irregularly. The difference between the nonuniform polarization with applied electrical field and the uniform polarization which corresponds to zero bias constitutes the elastic scattering potential and sets up a polarization Coulomb field that scatters 2DEG electrons.

Although the electron mobility decreases with the increase of 2DEG sheet density for LO phonon scattering and interface roughness scattering, the scenario is just the reverse for the polarization Coulomb field scattering.[5,6] For the 2DEG sheet density modulated by the drain–source bias, the polarization Coulomb field scattering is screened at higher 2DEG sheet density, and LO phonon scattering and interface roughness scattering predominate, so the electron mobility decreases with the increase of the 2DEG sheet density. When the 2DEG sheet density reduces to a certain value, the polarization Coulomb field scattering plays an important role, which leads to the rise of electron mobility with the increase of the 2DEG sheet density. As a result, the electron mobility curve presents a peak. The gate length of the device is smaller, the polarization charge density gradient is larger, and the polarization Coulomb field scattering is stronger, so the 2DEG sheet density corresponding to the peak point is higher.

Table 1 shows the channel electrical field distributions at the peak points and at the higher 2DEG sheet density. It is

shown that, at the peak point, the difference between the channel electrical field for the drain–source modulation and that for the gate–source modulation is large and the electron mobility difference is also obvious. While the channel electrical field distributions at the higher 2DEG sheet densities are nearly the same, the differences in electron mobility between them are small. For the interface roughness scattering, the electron mobility is mostly determined by the averaged distance of the 2DEG electrons from the AlN/GaN interface, and the averaged distance is largely affected by the 2DEG sheet density, thus the interface roughness scattering is mainly related to the 2DEG sheet density. Meanwhile, the LO phonon scattering is also mainly related to the 2DEG sheet density. According to the above analysis, corresponding to the same 2DEG sheet density, the electron mobility difference at the peak point does not predominantly result from the LO phonon scattering or from the interface roughness scattering. As a result, we can conclude that the electron mobility differences at the peak points are mainly caused by the polarization Coulomb field scattering. At this point, the conclusion can be made that the polarization Coulomb field scattering in the InAlN/AlN/GaN HFET is largely affected by the channel electrical field distribution.

Table 1. Channel electrical field distributions at the peak points and at higher 2DEG sheet density.

		Calculation results modulated by the drain–source bias (solid lines)				Calculation results modulated by the gate–source bias (dash lines)			
		$n_{2D}/10^{11}$ cm^{-2}	V_{ds}/V	V_{gs}/V	μ/cm$^2\cdot$V$^{-1}\cdot$s^{-1}	$n_{2D}/10^{11}$ cm^{-2}	V_{ds}/V	V_{gs}/V	μ/cm$^2\cdot$V$^{-1}\cdot$s^{-1}
At the	1	5.80557	1.541	0	4555.9	5.80557	0.1	−1.3287	3033
peak	2	7.2121	1.682	0	2961.7	7.2121	0.1	−1.2013	1720.6
points	3	8.272	1.667	0	2175.2	8.272	0.1	−1.0432	902
At the	1	29.654	0.111	0	2746.7	29.654	0.1	0	2567.9
higher 2DEG	2	32.849	0.143	0	2301	32.849	0.1	0	2184.7
sheet density	3	33.121	0.166	0	2171.7	33.121	0.1	0	2119.6

4. Conclusion

In this paper we simulate the *I*–*V* characteristics of the $In_{0.18}Al_{0.82}N$/AlN/GaN HFETs with different gate lengths using the quasi-2D model based on the test *C*–*V* characteristics and *I*–*V* characteristics. By analyzing the variation of the electron mobility with the 2DEG sheet density, it is found that the channel electric field distribution has an important influence on the polarization Coulomb field scattering in the $In_{0.18}Al_{0.82}N$/AlN/GaN HFET. When the 2DEG sheet density is modulated by the drain–source bias, the electron mobility presents a peak with the increase of the 2DEG sheet density. The gate length is smaller, the polarization Coulomb field scattering is stronger, and the 2DEG sheet density corresponding to the peak point is higher. Moreover, as the 2DEG sheet density increases, the electron mobility difference between the drain–source modulation and the gate–source modulation decreases, and finally the electron mobility values tend to the same value at higher 2DEG sheet densities. At the peak points, with the different channel electrical field distributions, the differences between the electron mobility values mostly caused by the polarization Coulomb field scattering can reach up to 1522.9 cm^2/V·s (sample 1), 1241.1 cm^2/V·s (sample 2), and 1273.2 cm^2/V·s (sample 3), respectively.

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