Influence of the AlGaN barrier thickness on polarization Coulomb field scattering in an AlGaN/AlN/GaN heterostructure field-effect transistor*

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In this study rectangular AlGaN/AlN/GaN heterostructure field-effect transistors (HFETs) with 22-nm and 12-nm AlGaN barrier layers are fabricated, respectively. Using the measured capacitance–voltage and current–voltage characteristics of the prepared devices with different Schottky areas, it is found that after processing the device, the polarization Coulomb field (PCF) scattering is induced and has an important influence on the two-dimensional electron gas electron mobility. Moreover, the influence of PCF scattering on the electron mobility is enhanced by reducing the AlGaN barrier thickness. This leads to the quite different variation of the electron mobility with gate bias when compared with the AlGaN barrier thickness. This mainly happens because the thinner AlGaN barrier layer suffers from a much stronger electrical field when applying a gate bias, which gives rise to a stronger converse piezoelectric effect.

Keywords: AlGaN/AlN/GaN, barrier layer thickness, electron mobility, polarization Coulomb field scattering

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1. Introduction

Owing to the high electron velocity and high critical field, the AlGaN/GaN heterostructure field-effect transistor (HFET) is excellent in high-voltage and high-power operations at microwave/sub-microwave frequencies, and it has been a subject of intense investigation.[1,2] Great progress in AlGaN/GaN HFET performance has been achieved during the last few years. A recorded power-gain cutoff frequency ($f_{\max}$) of 300 GHz has been achieved on a gate-recessed AlGaN/GaN HFET.[3] Improvements in AlGaN/GaN HFET technology have also allowed the demonstration of high-power broadband solid state power amplifiers (PA) from L-band to W-band, which will enable the development of the next generation of high data rate communication systems, phased array radars, and active imagers.[4] The scattering mechanism affects the electron mobility of the two-dimensional electron gas (2DEG), which is crucial to the ultimate performance of an AlGaN/GaN HFETs. It has been demonstrated that the polarization Coulomb field (PCF) scattering related to the strain variation in the AlGaN barrier layer has a great influence on the 2DEG electron mobility in the conventional AlGaN/AlN/GaN HFET, especially for a device with a small ratio of gate length to drain-to-source distance.[5,6] However, the AlGaN barrier layer thickness is usually about 22 nm in the conventional AlGaN/AlN/GaN HFET. Zhao *et al.*[7] have investigated the effects of rapid thermal annealing on the PCF scattering in the AlGaN/AlN/GaN heterostructure with 17-nm AlGaN barrier layer, but they did not compare the influences of different AlGaN barrier thicknesses on PCF scattering. The role that PCF scattering plays in the AlGaN/AlN/GaN HFET device with thin barrier layer (12 nm) has not been investigated. Moreover, to further improve the frequency performance, it is necessary to reduce the gate length as well as the AlGaN barrier thickness in order to suppress the short channel effect. Thus, it is of great importance to investigate the influence of the AlGaN barrier thickness on PCF scattering in AlGaN/AlN/GaN HFET. In this paper, rectangular AlGaN/AlN/GaN HFETs with different AlGaN barrier thickness values (22 nm and 12 nm) are fabricated. Based on the measured current–voltage (I–V) and capacitance–voltage (C–V) characteristics, the electron mobility under the gate area for the prepared devices are calculated. It is found that the variation of the electron mobility with gate bias is quite different from with AlGaN barrier thickness. The influence of the PCF scattering on the 2DEG electron mobility in AlGaN/AlN/GaN HFET with thinner barrier layer is found to be enhanced when compared with that with a thicker barrier layer.

2. Experiment

The AlGaN/AlN/GaN heterostructures with different AlGaN barrier thickness values employed in this work were epitaxially grown by metal organic chemical vapor deposition

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(MOCVD) on (0001) sapphire substrates. One epitaxial structure consisted of a 22-nm undoped $Al_{0.21}Ga_{0.79}N$ barrier layer, a 1-nm AlN layer, a 2-μm undoped GaN layer, and a 200-nm low-temperature AlN nuclear layer. This structure produced a 2DEG with a total charge density of 8.6×10^{12} cm^{-2} and electron mobility of 2170 cm^2/V·s as measured by using van der Pauw structure at room temperature. The other structure consisted of a 12-nm undoped $Al_{0.3}Ga_{0.7}N$ barrier layer, a 1-nm AlN layer, a 2-μm undoped GaN layer, and a 200-nm low-temperature AlN nuclear layer. This structure produced a 2DEG with a total charge density of 9.61×10^{12} cm^{-2} and an electron mobility of 2070 cm^2/V·s, as measured by using van der Pauw structure at room temperature. Since the electron density decreases with a reduction in the thickness of the AlGaN barrier layer, a higher aluminum mole fraction (30%) in the 12-nm AlGaN barrier layer was chosen to give a comparable sheet resistance. Uniform device processing is performed on the two heterostructures. Mesa isolation was performed using a Cl_2/BCl_3 plasma-based dry etch. Source and drain Ohmic contact of Ti/Al/Ni/Au were formed by e-beam evaporation and lift-off. The source and drain regions were rectangular (100-μm wide and 50-μm long), and the spacing between the source and drain was 100 μm. A rapid thermal annealing was taken to form a good Ohmic contact at 850 °C for 30 s under nitrogen atmosphere. Using the patterns obtained by transmission line method (TLM), the Ohmic contact resistances were typically measured to be 0.42 Ω·mm and 0.49 Ω·mm for the AlGaN/AlN/GaN heterostructures with 22-nm and 12-nm AlGaN barrier layers, respectively. To form the gate, Ni/Au (50 nm/200 nm) Schottky contacts of varying areas were then deposited in the space between the source and drain Ohmic contacts by e-beam evaporation. The Ni/Au rectangular Schottky contacts were symmetrically placed in the middle 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. *C*–*V* measurements were performed at room temperature by using an Agilent B1520A at 1 MHz, and the *I*–*V* measurements were performed at room temperature by 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 AlGaN/AlN/GaN HFETs with 22-nm and 12-nm AlGaN barrier layers, respectively. The *C*–*V* measurements are obtained by using the gate and source contact. The values of 2DEG electron density (n_{2D}) under the Ni Schottky contact at different gate biases can be obtained by integrating the measured *C*–*V* curves.[7] The calculated results are shown in Fig. 2. Considering the error of Schottky contact area between the fabrication and the design, there is about ±2% error in the calculated 2DEG electron density. It can be seen that with an increase in the Schottky contact area, the 2DEG densities decrease at the same gate bias in the AlGaN/AlN/GaN HFETs with

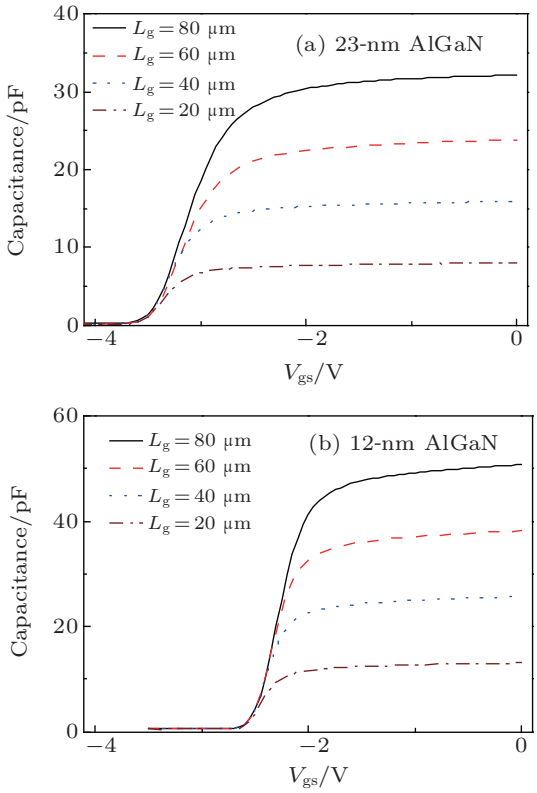


Fig. 1. (color online) Measured *C*–*V* curves with different gate lengths for the prepared AlGaN/AlN/GaN HFETs with 22 nm (a) and 12 nm (b) AlGaN barrier layers, respectively.

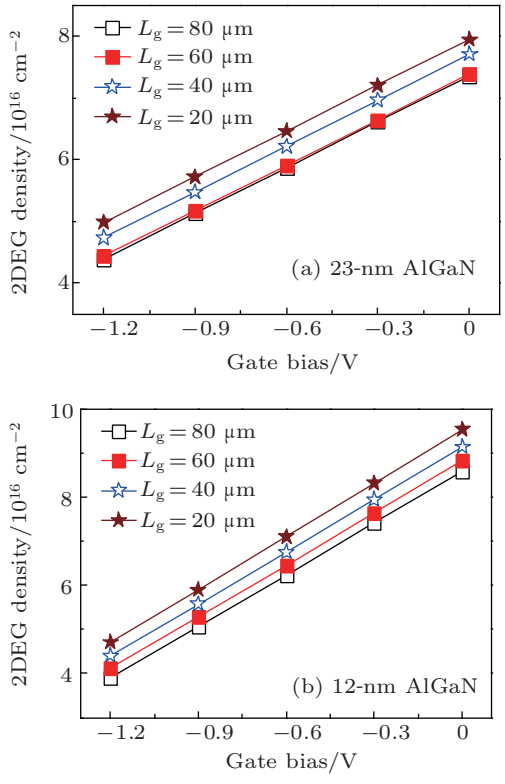


Fig. 2. (color online) Calculated 2DEG electron densities under different gate biases for the prepared AlGaN/AlN/GaN HFETs with 22 nm (a) and 12 nm (b) AlGaN barrier layers, respectively.

22-nm and 12-nm AlGaN barrier layers, respectively. This result is the same as the one that we have previously shown on strained AlGaN/AlN/GaN heterostructures.[5] For the details of the explanation for the variation of 2DEG density with Schottky contact area, readers can refer to Ref. [5].

For the rectangular devices, the electron mobility of the channel 2DEG under the gate area in the strained AlGaN/AlN/GaN HFET can be calculated from the following expression:[5]

$$\mu_{\rm n} = \frac{I_{\rm ds} L_{\rm g}}{q n_{\rm 2D} W [V_{\rm ds} - I_{\rm ds}(R_{\rm D} + R_{\rm s} + R_{\rm Ohm})]}, \tag{1}$$

$$R_{\rm D} = \frac{L_{\rm gd}}{q n_{\rm 2D0} \mu_{\rm n0} W}, \quad R_{\rm s} = \frac{L_{\rm gs}}{q n_{\rm 2D0} \mu_{\rm n0} W}, \tag{2}$$

where $R_{\rm d}$ is the channel resistance between drain and gate contacts, $R_{\rm s}$ is the channel resistance between source and gate contacts, $R_{\rm Ohm}$ is the Ohmic resistance of source and drain contacts, $L_{\rm gd}$ is the distance between the gate and drain, $L_{\rm gs}$ is the distance between the gate and source, $L_{\rm g}$ is the gate length, $n_{\rm 2D0}$ is the 2DEG electron density at zero gate bias, $\mu_{\rm n0}$ is the electron mobility at zero gate bias, and W is the gate width. Other parameters and the calculation used can be found from Zhao *et al.*'s calculation.[7]

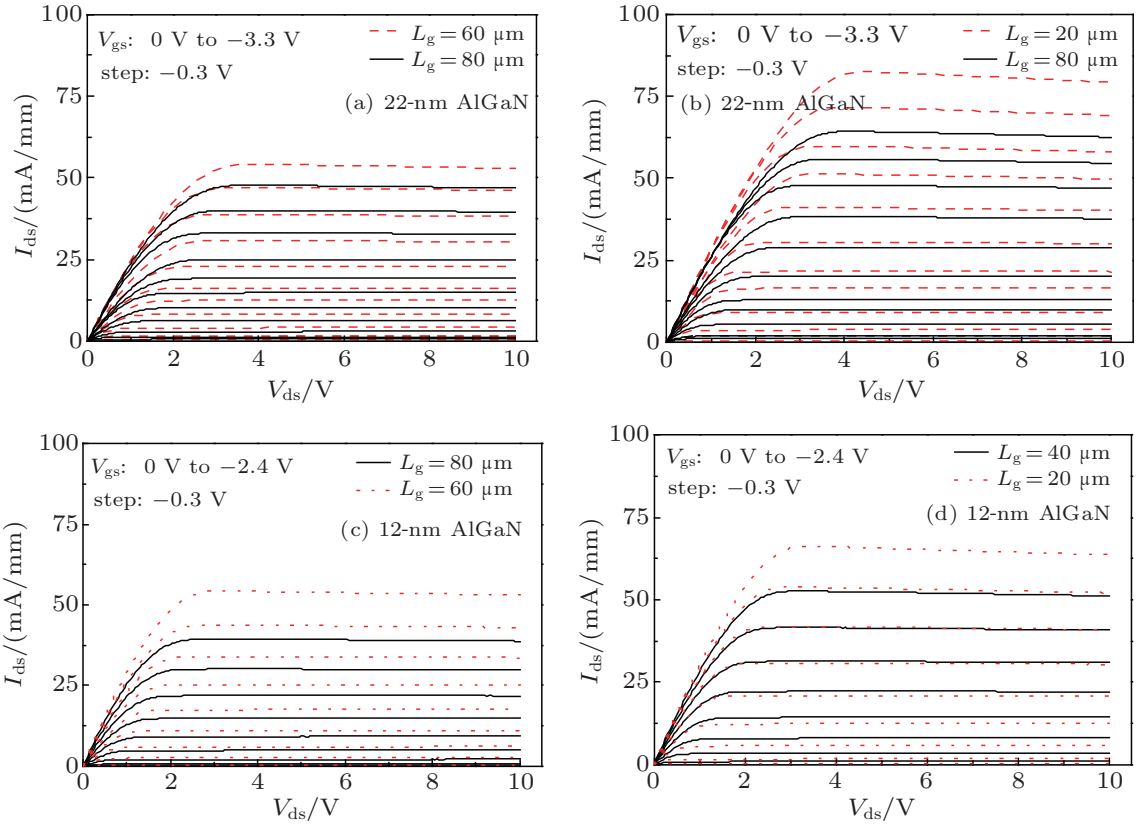


Fig. 3. (color online) Measured *I*–*V* curves with different gate lengths at room temperature for the prepared AlGaN/AlN/GaN HFETs with 22 nm ((a) and (b)) and 12 nm ((c) and (d)) AlGaN barrier layers, respectively.

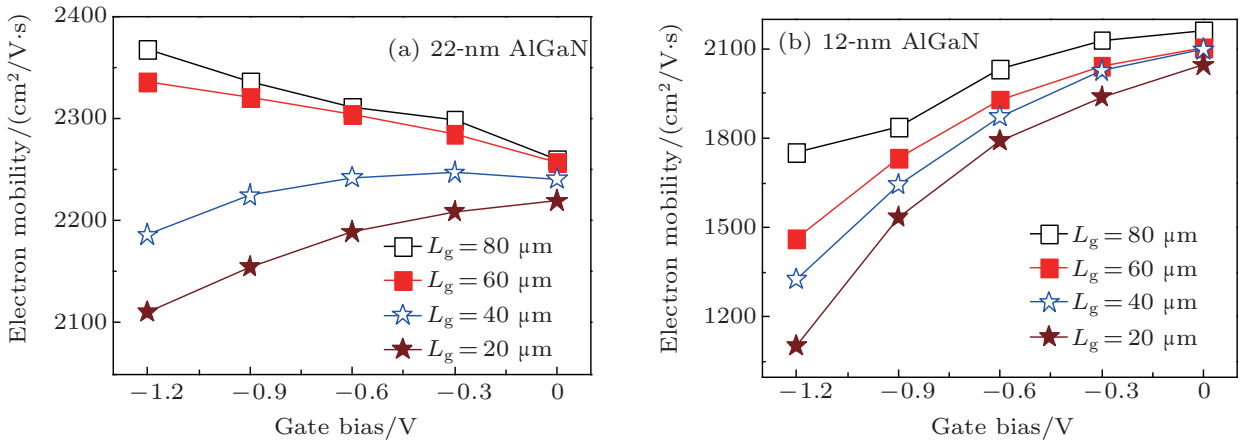


Fig. 4. (color online) Relationships between the electron mobility of the 2DEG and the applied gate bias at room temperature for the prepared AlGaN/AlN/GaN HFETs with 22 nm (a) and 12 nm (b) AlGaN barrier layers, respectively.

The *I*–*V* characteristics for the rectangular AlGaN/AlN/GaN HFETs with 22-nm and 12-nm AlGaN barrier layers are measured and shown in Fig. 3. For the calculation of the 2DEG electron mobility by using Eq. (1), the values of the current I_{ds} at source–drain bias of 100 mV under different gate voltages are used. By substituting the relevant data into Eq. (1), the 2DEG electron mobilities under the gate area for the rectangular AlGaN/AlN/GaN HFET devices with 22-nm and 12-nm AlGaN barrier layers are calculated and shown in Figs. 4(a) and 4(b), respectively. The variations of the electron mobility with gate bias are quite different when the AlGaN barrier thickness is changed. The difference can be explained as follows.

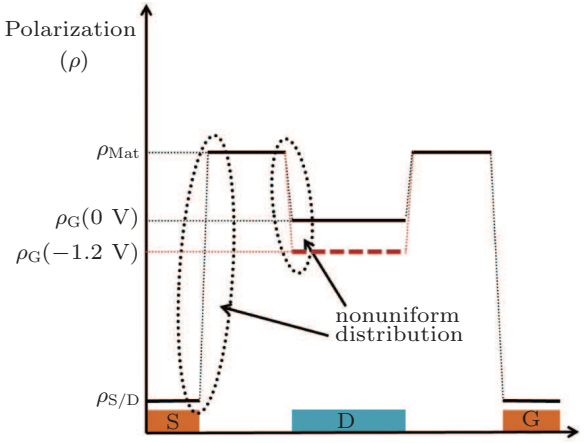


Fig. 5. (color online) Schematic diagram for the distribution of the polarization charge density in the AlGaN/AlN/GaN HFET.

It has been demonstrated that the scattering mechanism that affects the 2DEG electron mobility in the AlGaN/AlN/GaN heterostructure material is mainly due to polar–optical (PO) phonon scattering and interface roughness scattering.[5,7] In addition, PCF scattering related to the strain variation in the AlGaN barrier layer is induced after device processing and it has a significant influence on the 2DEG electron mobility in the conventional AlGaN/AlN/GaN HFET device.[5,7] As shown in Fig. 5, the Ohmic annealing causes the contact metal atoms to diffuse into the AlGaN barrier layer and this results in the reduction of the polarization charge density underneath the Ohmic contact.[8] In addition, the interaction between the atoms of the Schottky contact metals and the surface atoms of the AlGaN barrier layer also results in a reduction of the polarization charge density underneath the Schottky contact.[9] Moreover, due to the converse piezoelectric effect, the gate biases will further aggravate the strain variation of the AlGaN barrier layer. As shown in Fig. 5, ρ_{Mat} is the density of the polarization charges in the AlGaN/AlN/GaN heterostructure material. ρ_G is the polarization charge density underneath the gate metals, and $\rho_{S/D}$ is the density of the polarization charges underneath the Source/Drain contacts. The nonuniform polarization among ρ_{Mat}, ρ_G, and $\rho_{S/D}$ will induce a potential of elastic scattering on the 2DEG electron mobility, and the elastic scattering potential sets up a polarization Coulomb field that scatters 2DEG electrons. For both the interface roughness scattering and the PO phonon scattering, the mobility decreases with increasing electron density. However, for PCF scattering, the electron mobility increases with the increasing electron density.

Table 1. Extracted Schottky barrier heights and polarization charge densities under the Schottky contacts corresponding to different gate biases for the prepared AlGaN/AlN/GaN HFETs with 80-μm gate length.

		22-nm AlGaN	12-nm AlGaN
ϕ_b/eV		1.13	1.16
$\rho_{Mat}/10^{12}$ cm^{-2}		10.1	12.3
$\rho_G/10^{12}$ cm^{-2}	$V_G = 0$ V	8.15	9.97
	$V_G = -0.3$ V	8.07	9.62
	$V_G = -0.6$ V	7.99	9.41
	$V_G = -0.9$ V	7.91	9.12
	$V_G = -1.2$ V	7.81	8.89

Based on the measured *C*–*V* curves and the forward *I*–*V* characteristics of the gate and source contacts for the prepared AlGaN/AlN/GaN HFETs, the polarization charge densities under the gate contacts (ρ_G) corresponding to different gate voltages can be calculated by self-consistently solving Schrödinger's and Poisson's equations,[10] the results are listed in Table 1 The Schottky barrier height (ϕ_b) used for this calculation can also be calculated from the measured *C*–*V* curves and the forward *I*–*V* characteristics of the gate and source contacts by self-consistently solving Schrödinger's and Poisson's equations,[11] the results are also shown in Table 1. The details of the above calculation can be found in Refs. [10] and [11].

As seen from Table 1, the value of ρ_{Mat} is much larger than the value of ρ_G, which demonstrates the nonuniform polarization in the AlGaN barrier layer between the gate and gate-to-source (or drain) area. Moreover, the difference between ρ_G and ρ_{Mat} aggravates with the increasing the reverse gate bias, which indicates the enhancement of PCF scattering. Since the elastic PCF scattering potential is proportional to the difference between ρ_{Mat} and ρ_G, $\rho_{S/D}$, the electrons under the gate area are scattered by the polarization charges which correspond to $(\rho_{Mat} - \rho_{S/D})$ and $(\rho_{Mat} - \rho_G)$. With the shorter gate length, the space between the gate contact and the source (or drain) contacts is larger, and the canceling of mutual Coulomb forces between the polarization charges $(\rho_{Mat} - \rho_{S/D})$ and $(\rho_{Mat} - \rho_G)$ is much weaker. Moreover, since $(\rho_{Mat} - \rho_G)$ is closer to the channel electrons than $(\rho_{Mat} - -\rho_{S/D})$, the PCF scattering originating from $(\rho_{Mat} - \rho_G)$ is much stronger than that from $(\rho_{Mat} - \rho_{S/D})$. So the polarization charge $(\rho_{Mat} - \rho_G)$ has a greater influence on the electrons under the gate area with a smaller gate length.

As a result, in the AlGaN/AlN/GaN HFETs with 22-nm barrier layer, the PCF scattering is relatively weak for the sample with a large gate length (60 μm and 80 μm). The interface

roughness scattering and PO phonon scattering dominate the 2DEG electron mobility, leading to a monotonic decrease of electron mobility with increasing gate bias. For the sample with a short gate length (40 μm and 20 μm), the gradient of the polarization charge density is large, thus the PCF scattering is the dominant carrier scattering mechanism, which results in a monotonic increase of electron mobility with increasing gate voltage.

Since the critical thickness of the AlGaN layer on GaN is estimated to be relatively large (almost larger than 60 nm with 22% Al composition), the thickness of AlGaN barrier has little influence on the interface roughness in the AlGaN/AlN/GaN heterostructures.[12] However, the relative effect of interface roughness scattering increases as the Al composition increases.[13] For the interface roughness scattering, the mobility decreases with increasing electron density. However, as seen from Fig. 4, the mobility rises with increasing electron density in each of the samples with a 12-nm barrier layer. This demonstrates that the PCF scattering has a dominant effect on the electron mobility. The interface roughness scattering is even enhanced by increasing the Al composition in the sample with 12-nm barrier layer. As seen from Table 1, the disparity between ρ_{Mat} and ρ_{G} for the AlGaN/AlN/GaN HFETs with 12-nm barrier layer is much larger than that for the AlGaN/AlN/GaN HFETs with 22-nm barrier layer. This mainly happens because the thinner AlGaN barrier layer will suffer much stronger electrical field when applying a gate bias. Moreover, increasing the Al composition will induce larger piezoelectric polarization and further enhance the converse piezoelectric effect. Owing to the stronger converse piezoelectric effect, the variation of the piezoelectric polarization charges in the thin AlGaN barrier layer is much larger than that in the thick AlGaN barrier layer. As a result, the PCF scattering has a greater effect on the electron mobility of the 2DEG in the AlGaN/AlN/GaN HFETs with 12-nm barrier layer than that in the AlGaN/AlN/GaN HFETs with 22-nm barrier layer, which results in a monotonic increase for the mobility of the 2DEG electrons with increasing gate voltage. Moreover, the PCF scattering is enhanced for the AlGaN/AlN/GaN HFET with a shorter gate length, resulting in the drop of electron mobility with the reduction of the Schottky contact area at a given gate bias. Since the 2DEG density increases slightly as the gate length is reduced at a given gate bias, the interface roughness scattering and PO phonon scattering will also play a part in reducing the electron mobility.

To improve the frequency performance, it is necessary to reduce the device scale and the AlGaN barrier thickness in order to suppress the short channel effect. We think that the PCF scattering will still have a considerable influence on the electron mobility in nanoscale AlGaN/AlN/GaN HFETs. However, as the devices sizes are reduced down to the nanoscale, the precision of the obtained values for the electron density, R_{S} and R_{D} will have a greater influence on the calculated electron mobility of the channel 2DEG under the gate area. It is necessary to employ new methods to extract the values of R_{S} and R_{D} more accurately, such as small signal measurements. Moreover, a T-shaped gate is usually used in the nanoscale AlGaN/AlN/GaN HFETs. The different electric fields of the T-shaped gate will affect the nonuniform polarization in the AlGaN barrier layer, especially for the one between ρ_{G} and ρ_{Mat}. As a result, in comparison with large-scale HFET devices, there may be some differences in the effect of PCF scattering on the electron mobility in nanoscale AlGaN/AlN/GaN HFETs, which needs further study.

4. Conclusions

In this paper, rectangular AlGaN/AlN/GaN HFETs with 22-nm and 12-nm AlGaN barrier layers are fabricated, respectively. Using the measured I–V and C–V curves, the electron mobilities under the gate area for the prepared AlGaN/AlN/GaN HFET devices are calculated at different gate biases. The variation of the electron mobility with gate bias is found to be quite different from that with the AlGaN barrier thickness. In addition, the polarization charge densities under the Schottky contact (ρ_{G}), which correspond to different gate biases, are also calculated by self-consistently solving Schrödinger's and Poisson's equations. It is found that the disparity between ρ_{G} and ρ_{Mat} for the AlGaN/AlN/GaN HFET with 12-nm barrier layer is much larger than the one with 22-nm barrier layer, indicating that the influence of the PCF scattering on the 2DEG electron mobility in AlGaN/AlN/GaN HFETs is enhanced by reducing the barrier layer thickness.

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