Influence of temperature on strain-induced polarization Coulomb field scattering in AlN/GaN heterostructure field-effect transistors*

Lü Yuan-Jie(吕元杰)[a], Feng Zhi-Hong(冯志红)[a]†, Lin Zhao-Jun(林兆军)[b], Guo Hong-Yu(郭红雨)[a], Gu Guo-Dong(顾国栋)[a], Yin Jia-Yun(尹甲运)[a], Wang Yuan-Gang(王元刚)[a], Xu Peng(徐 鹏)[a], Song Xu-Bo(宋旭波)[a], and Cai Shu-Jun(蔡树军)[a]

[a] *National Key Laboratory of Application Specific Integrated Circuit (ASIC), Hebei Semiconductor Research Institute, Shijiazhuang* 050051, *China*
[b] *School of Physics, Shandong University, Jinan* 250100, *China*

(Received 24 October 2013; revised manuscript received 14 January 2014; published online 22 May 2014)

Electron mobility scattering mechanism in AlN/GaN heterostuctures is investigated by temperature-dependent Hall measurement, and it is found that longitudinal optical phonon scattering dominates electron mobility near room temperature while the interface roughness scattering becomes the dominant carrier scattering mechanism at low temperatures (∼100 K). Based on measured current–voltage characteristics of prepared rectangular AlN/GaN heterostructure field-effect transistor under different temperatures, the temperature-dependent variation of electron mobility under different gate biases is investigated. The polarization Coulomb field (PCF) scattering is found to become an important carrier scattering mechanism after device processing under different temperatures. Moreover, it is found that the PCF scattering is not generated from the thermal stresses, but from the piezoelectric contribution induced by the electrical field in the thin AlN barrier layer. This is attributed to the large lattice mismatch between the extreme thinner AlN barrier layer and GaN, giving rise to a stronger converse piezoelectric effect.

Keywords: AlN/GaN, electron mobility, polarization Coulomb field scattering, polarization

PACS: 71.55.Eq, 72.20.Fr, 72.10.–d, 77.22.Ej **DOI:** 10.1088/1674-1056/23/7/077105

1. Introduction

GaN-based materials offer significant potential for high-frequency/high-power heterostructure field-effect transistors (HFETs) due to their high electron velocity and high critical field. Owing to the wide band gap and large polarization effect, AlN/GaN heterostructures offer great advantages for vertical device scaling for high frequency operation.[1–3] The scattering mechanisms affect the electron mobility of the two-dimensional electron gas (2DEG), which is crucial to the ultimate performance of an $Al_xGa_{1-x}N$/GaN HFET.[4,5] Many groups have investigated the scattering mechanisms in the AlN/GaN heterostructure material using a temperature-dependent Hall measurement. It has been found that longitudinal optical (LO) phonon scattering dominates the 2DEG electron mobility nearby room temperature, while interface roughness scattering becomes the dominant carrier scattering mechanism at low temperatures (∼100 K).[6,7] Moreover, according to our former results,[8] the polarization Coulomb field (PCF) scattering related to the strain variation in the barrier layer has an enhanced influence on the 2DEG electron mobility in the AlN/GaN HFET after device processing, which is attributed to the large lattice mismatch between the extreme thin AlN barrier layer and the GaN layer. However, little attention has been paid to the influence of temperature on the PCF scattering in the AlN/GaN HFET devices. Since the strained AlN/GaN heterostructure has become a popular material for the main-stream gallium nitride based devices for microwave and digital circuit applications, it is essential to understand the effect of temperature on the PCF scattering in the AlN/GaN HFET devices. In this letter, temperature-dependent Hall measurement is performed to investigate the electron mobility scattering mechanism in AlN/GaN heterostructure. Moreover, rectangular AlN/GaN HFET is fabricated. Based on measured current–voltage (I–V) characteristics under different temperatures (300 K, 350 K, 400 K, and 450 K), temperature-dependent variation of electron mobility under different gate biases is calculated, and the influence of temperature on the PCF scattering in the AlN/GaN HFET devices is further investigated.

2. Experiment

The AlN/GaN heterostructure employed in this work is epitaxially grown by metal organic chemical vapor deposition (MOCVD) on a (0001) sapphire substrate. The AlN/GaN heterostructure consists of a low-temperature nucleation layer, followed by a 2-μm S. I. GaN, a 3-nm AlN barrier layer, and a 2-nm S. I. GaN cap. Hall measurements indicate a sheet carrier density of around 1.03×10^{13} cm^{-2} and an electron mobility of 1760 cm^2/V·s at room temperature. For device processing, mesa isolation was performed using Cl_2/BCl_3 re-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61306113 and 11174182).
†Corresponding author. E-mail: blueledviet@yahoo.com.cn
© 2014 Chinese Physical Society and IOP Publishing Ltd

active ion etching, and the source and drain Ohmic contacts were formed by depositing Si/Ti/Al/Ni/Au using e-beam evaporation and lift-off. The source and drain regions are rectangular, with a width of 100 μm and a length of 50 μm, and the space between the source and drain is 100 μm. These contacts were annealed in a rapid thermal annealing system, and with transmission line method patterns, the specific resistivity of the source and drain Ohmic contacts was measured to be 5.1×10^{-5} Ω·cm^2. To form the gate, Ni/Au (50 nm/200 nm) Schottky contact was then deposited in the space between the source and drain Ohmic contacts by e-beam evaporation. The Ni/Au rectangular Schottky contact was symmetrically placed in the middle between the source and drain, and the size was 20/100 μm (length/width). Capacitance–voltage (*C*–*V*) measurements were performed using an Agilent B1520A at 1 MHz, and the *I*–*V* measurements for AlN/GaN HFET were performed using Keithley 4200 semiconductor parameter analyzer under temperatures of 300 K, 350 K, 400 K, and 450 K, respectively.

3. Results and discussion

Figure 1(a) shows the temperature-dependent Hall measurement of AlN/GaN heterostructure material as a function of temperature (100–450 K). At high temperatures, the mobility decreases abruptly with increasing temperature while it becomes independent of temperature at low temperatures (∼100 K). The sheet carrier density can be accepted to be independent of temperature. According to the results of Cao *et al.*,[7] the scattering mechanisms that affect the 2DEG electron mobility in AlN/GaN heterostructures mainly include LO phonon scattering, acoustic phonon scattering, and interface roughness scattering.[9] By fitting the measured curve of mobility versus temperature with related equations, it is found that LO phonon scattering dominates the 2DEG electron mobility around room temperature, while interface roughness scattering becomes the dominant carrier scattering mechanism at low temperature (< 100 K). The above results are consistent with those of Cao *et al.*, and the calculation details can refer to Ref. [7].

Figure 2 shows the *C*–*V* curve of the Ni Schottky contact for the AlN/GaN HFET. The *C*–*V* measurement was obtained using the source contact and the Ni Schottky contact. The 2DEG electron density (n_{2D}) under different gate biases can be obtained by integrating the measured *C*–*V* curves,[10] and the calculated results are displayed in the inset. Considering the Schottky contact area error between design and fabrication, there is about ±1% error in the calculated 2DEG electron density.

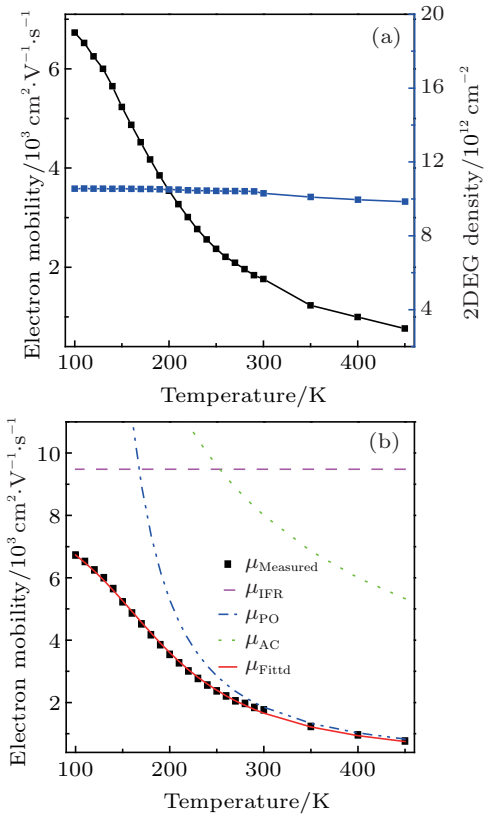


Fig. 1. (color online) Temperature-dependent Hall measurement (a) and calculated mobility versus temperature (b) for AlN/GaN heterostructure.

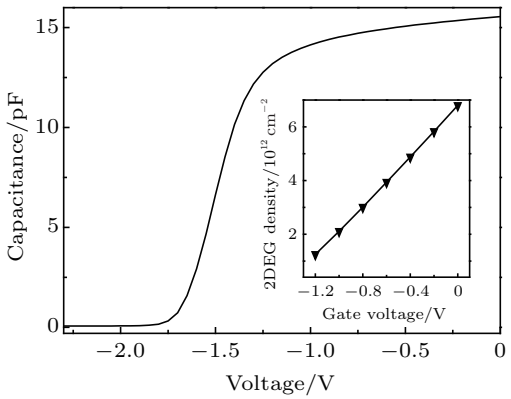


Fig. 2. Measured *C*–*V* curve and the calculated 2DEG electron density n_{2D} (inset) under different gate biases at room temperature for the prepared AlN/GaN HFET.

For rectangular devices, the electron drift mobility of 2DEG under the gate area in strained AlN/GaN HFET can be calculated by[4,11]

$$\mu_n = \frac{I_{DS} L_G}{q n_{2D} W [V_{DS} - I_{DS}(R_D + R_S + R_{Ohm})]}, \quad (1)$$

$$R_D = \frac{L_{GD}}{q n_{2D0} \mu_{n0} W}, \quad (2)$$

$$R_S = \frac{L_{GS}}{q n_{2D0} \mu_{n0} W}, \quad (3)$$

where R_S is the channel resistance between gate and source contacts, R_D is the channel resistance between gate and drain

contacts, $R_{\rm Ohm}$ is the Ohmic resistance of source and drain contacts, $L_{\rm G}$ is the gate length, $L_{\rm GD}$ is the space between gate and drain contacts, $L_{\rm GS}$ is the space between gate and source contacts, $n_{\rm 2D0}$ is the 2DEG electron density under zero gate bias, μ_{n0} is the electron drift mobility under zero gate bias, and W is the gate width. The other parameters used in the calculation are the same as those in Zhao's calculation.[4]

Figure 3 shows the I–V characteristics for the rectangular AlN/GaN HFET measured at 300, 350, 400, and 450 K, respectively. During the calculation of the electron mobility with Eq. (1), the values of the measured current $I_{\rm DS}$ with a source-drain voltage of 100 mV at different gate biases are used. Since the sheet carrier density is almost independent of temperature (Fig. 1), the 2DEG electron density at 300 K is used for the mobility calculation at different temperature. Furthermore, with transmission line method patterns, the Ohmic resistances of source and drain contacts ($R_{\rm Ohm}$) at 300, 350, 400, and 450 K are measured to be 4.5, 5.3, 6.6 and 8.4 Ω, respectively. With the related data substituted into Eq. (1), the electron mobility of the 2DEG under the gate area for the rectangular AlN/GaN HFET devices are calculated and shown in Fig. 4.

As seen from Fig. 1, the LO phonon scattering and the interface roughness scattering dominates the 2DEG electron mobility in AlN/GaN heterostructure material. However, for both LO phonon scattering and the interface roughness scattering, the mobility decreases with increasing electron density (or forward gate bias).[4,11] Thus, the LO phonon scattering and interface roughness scattering cannot explain the variation of the mobility with gate bias (Fig. 4). According to our former results, the device processing results in nonuniform polarization charge distribution in the AlN barrier layer, which induces an elastic scattering potential on the 2DEG electron mobility.[8,11] The elastic scattering potential corresponds to the polarization charge density variation which sets up a polarization Coulomb field that scatters 2DEG electrons. For PCF scattering, the electron mobility rises with increasing electron density. Thus, the PCF scattering becomes dominant in the AlN/GaN device after device processing, resulting in a monotonic decrease for the mobility of the 2DEG electrons with reverse gate bias. However, the electron mobility decreases more slowly at higher temperatures. This happens because that the LO phonon scattering and interface roughness scattering are enhanced with increasing temperature, and this counteracts the influence of PCF scattering.

Figure 5 shows the curves of electron mobility versus temperature for AlN/GaN material and prepared AlN/GaN HFET at different gate biases. Compared to that of AlN/GaN materials, with increasing temperature the electron mobility decreases more slowly after device processing. Moreover, at a larger reverse gate bias, the electron mobility decreases more slowly with increasing temperature. This is mainly attributed to the PCF scattering induced by the device processing, which

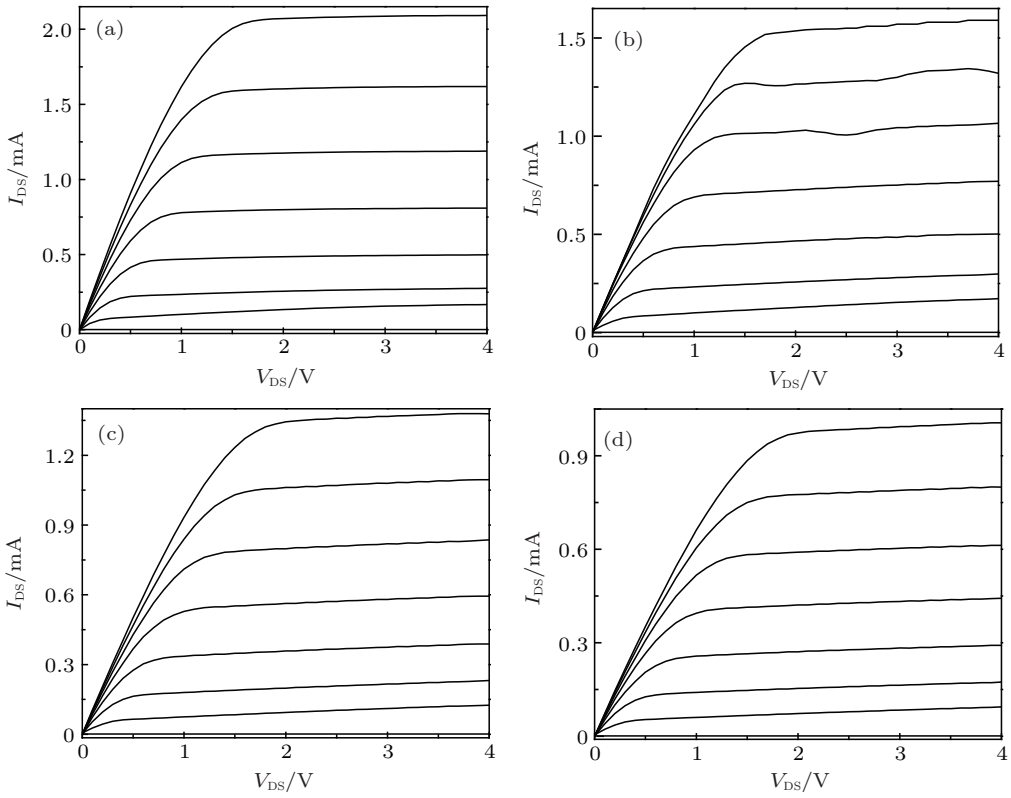


Fig. 3. Measured I–V curves at 300 K (a), 350 K (b), 400 K (c), and 450 K (d) for the prepared sample. $V_{\rm G}$ ranges from 0 to −1.4 V, with a step of −0.2 V.

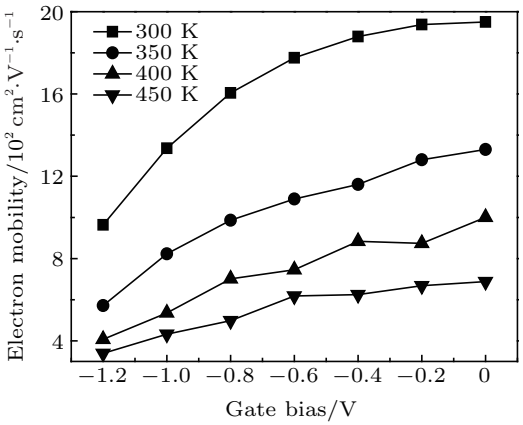


Fig. 4. Relationship between electron mobility of 2DEG and applied gate bias at 300 K, 350 K, 400 K, and 450 K for the prepared sample.

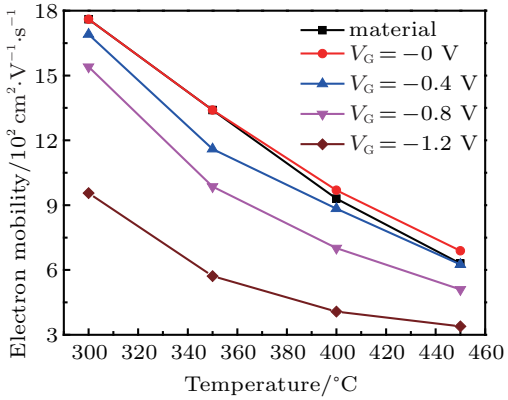


Fig. 5. (color online) Variation of electron mobility versus temperature at different gate biases for AlN/GaN material and prepared AlN/GaN HFET.

counteracts the influence of LO phonon scattering and interface roughness scattering. In addition, with the converse piezoelectric effect, the gate bias will further aggravate strain variation of the thin AlN barrier layer. Due to the large lattice mismatch between AlN and GaN, the critical thickness of the AlN barrier layer in the AlN/GaN heterostructures is very small. Since there are only several atom layers in the extremely thin AlN barrier layer (∼3 nm) for the AlN/GaN HFETs, there will be a strong electrical field when applying a gate bias in the thin AlN barrier layer. As a result, increasing reverse gate bias augments the variation of the piezoelectric polarization charges in the thin AlN barrier layer under the Schottky contact. Since the elastic scattering potential of the polarization Coulomb field is proportional to the nonuniform polarization, increasing the reverse gate bias results in a stronger PCF scattering in the 2DEG electrons. Moreover, as the 2DEG density decreases, the electrostatic shielding for the polarization charges is weakened, and PCF scattering increases. As a result, the influence of PCF scattering is enhanced by further increasing the reverse gate bias, and thus the electron mobility decreases more slowly under higher reverse gate bias with increasing temperature. By thermoelectroelastic simulations, Ancona *et al.* demonstrated that high temperature can induce thermal stress.[12] Since the temperature is even in the channel under low drain bias, the induced thermal stress will not induce nonuniform polarization charge distribution in the AlN barrier layer. Thus, the PCF scattering is not generated from thermal stresses, but comes from the piezoelectric contribution induced by the electrical field in the thin AlN barrier layer.

4. Summary

In summary, AlN/GaN heterostructure was epitaxially grown by MOCVD on a sapphire substrate. By using a temperature-dependent Hall measurement, it is found that LO phonon scattering dominates the electron mobility in AlN/GaN heterostructure near room temperature, while interface roughness scattering becomes the dominant carrier scattering mechanism at low temperatures (∼100 K). Furthermore, rectangular AlN/GaN HFET was fabricated, and the *I*–*V* characteristics under different temperatures (300, 350, 400, and 450 K) were measured. Based on the calculated temperature-dependent electron mobility under different gate biases, PCF scattering is found to be very important under different temperatures after device processing. It is also found that the PCF scattering is not generated from the thermal stresses, but from the piezoelectric contribution induced by the electrical field in the thin AlN barrier layer. This happens mainly because the large lattice mismatch between the extreme thinner AlN barrier layer and GaN gives rise to a strong converse piezoelectric effect.

References

[1] Medjdoub F, Zegaoui M, Ducatteaux D, Rolland N and Rolland P A 2011 *IEEE Electron Dev. Lett.* **32** 874
[2] Ji D, Liu B, Lu Y W, Zou M and Fan B L 2012 *Chin. Phys. B* **21** 067201
[3] Shinohara K, Regan D, Corrion A, Brown D, Tang Y, Wong J, Candia G, Schmitz A, Fung H, Kim S and Micovic M 2012 *IEDM Tech. Dig.* **27** 617
[4] Zhao J Z, Lin Z J, Corrigan T D, Wang Z, You Z D and Wang Z G 2007 *Appl. Phys. Lett.* **91** 173507
[5] Lü Y J, Feng Z H, Cai S J, Dun S B, Liu B, Yin J Y, Zhang X W, Fang Y L, Lin Z J, Meng L G and Luan C B 2013 *Chin. Phys. B* **22** 067104
[6] Pandey S, Cavalcoli D, Minj A, Fraboni B, Cavallini A, Skuridina D, Vogt P and Kneissl M 2012 *Acta Mater.* **60** 3176
[7] Cao Y and Jena D 2007 *Appl. Phys. Lett.* **90** 182112
[8] Lü Y J, Feng Z H, Han T T, Dun S B, Gu G D, Yin J Y, Sheng B C, Liu B, Fang Y L, Cai S J, Lin Z J, Luan C B and Yang Q H 2013 *Appl. Phys. Lett.* **103** 113502
[9] Ridley B K, Foutz B E and Eastman L F 2000 *Phys. Rev. B* **61** 16862
[10] Lü Y J, Lin Z J, Zhang Y, Meng L G, Cao Z F, Luan C B, Chen H and Wang Z G 2011 *Chin. Phys. B* **20** 047105
[11] Lü Y J, Lin Z J, Zhang Y, Meng L M, Luan C B, Cao Z F, Chen H and Wang Z G 2011 *Appl. Phys. Lett.* **98** 123512
[12] Ancona M G 2012 *IEDM Tech. Dig.* **13** 315