Influence of annealed ohmic contact metals on electron mobility of strained AlGaN/GaN heterostructures*

Zhao Jianzhi(赵建芝)[1], Lin Zhaojun(林兆军)[1,†], Corrigan T D[2], Zhang Yu(张宇)[1], Li Huijun(李惠军)[3], and Wang Zhanguo(王占国)[4]

(1 School of Physics, Shandong University, Jinan 250100, China)
(2 Department of Physics, University of Maryland, College Park, Maryland 20740, USA)
(3 School of Information Science and Engineering, Shandong University, Jinan 250100, China)
(4 Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China)

Abstract: The influence of annealed ohmic contact metals on the electron mobility of a two dimensional electron gas (2DEG) is investigated on ungated AlGaN/GaN heterostructures and AlGaN/GaN heterostructure field effect transistors (AlGaN/GaN HFETs). Current–voltage (*I*–*V*) characteristics for ungated AlGaN/GaN heterostructures and capacitance–voltage (*C*–*V*) characteristics for AlGaN/GaN HFETs are obtained, and the electron mobility for the ungated AlGaN/GaN heterostructure is calculated. It is found that the electron mobility of the 2DEG for the ungated AlGaN/GaN heterostructure is decreased by more than 50% compared with the electron mobility of Hall measurements. We propose that defects are introduced into the AlGaN barrier layer and the strain of the AlGaN barrier layer is changed during the annealing process of the source and drain, causing the decrease in the electron mobility.

Key words: AlGaN/GaN heterostructure; anneal; ohmic contact metals; 2DEG; electron mobility
DOI: 10.1088/1674-4926/30/10/102003 **PACC:** 7280E **EEACC:** 2520D; 2560B

1. Introduction

AlGaN/GaN HFETs have been the subject of intense investigation due to their importance in microwave and high temperature/high power applications[1,2]. It has been shown that annealed ohmic contact metals have an influence on the polarization of the AlGaN barrier layer[3]. To date we have not seen any reports of whether annealed ohmic contact metals have an influence on the mobility of the 2DEG or not. Because the mobility of the 2DEG is crucial to the ultimate performance of AlGaN/GaN HFETs, and, during the device processing, ohmic contact metals are annealed to form source and drain ohmic contacts, it is important to investigate the influence of annealed ohmic contact metals on electron mobility of the 2DEG in strained AlGaN/GaN heterostructures. In this work, the influence of annealed ohmic contact metals on electron mobility of the 2DEG was investigated using Hall measurement results, *I*–*V* characteristics for ungated AlGaN/GaN heterostructures and *C*–*V* characteristics for AlGaN/GaN HFETs.

2. Experiment

The AlGaN/GaN heterostructure layer employed in this study was epitaxially grown by metal organic chemical vapor deposition (MOCVD) on a (0001) sapphire substrate. The structure consisted of a 40 nm AlN nucleation layer, followed by a 3 μm undoped GaN layer and a 21.5 nm thick undoped $Al_{0.3}Ga_{0.7}N$ layer. Hall measurements indicated a sheet carrier density of around 1.36×10^{13} cm^{-2} and an electron mobility of 1200 cm^2/(V·s) at room temperature. For the ungated AlGaN/GaN heterostructure, the source and drain ohmic contacts were formed by depositing Ti/Al/Mo/Au using e-beam evaporation and lift-off. As shown in Fig. 1(a), the source region was circular with a diameter of 100 μm and the drain was a ring with an inside diameter of 300 μm and an outside diameter of 420 μm. These contacts were annealed at 850 °C for 30 s in a rapid thermal annealing system. Using transmission line method patterns, the specific resistivity of the source and drain ohmic contacts was measured to be 2×10^{-5} Ω·cm^2. For the AlGaN/GaN HFET (see Fig. 1(b)), a Ni/Au (60 nm/200 nm) ring Schottky contact with an inside diameter of 180 μm and an outside diameter of 220 μm was deposited in the space of the source and drain by e-beam evaporation. *C*–*V* measurements for the AlGaN/GaN HFET were performed at room

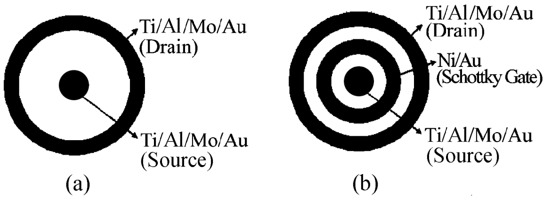

Fig. 1. Structure diagram of (a) ungated AlGaN/GaN heterostructures and (b) AlGaN/GaN HFETs.

---

* Project supported by the National Natural Science Foundation of China (No. 10774090) and the State Key Development Program for Basic Research of China (No. 2007CB936602).

† Corresponding author. Email: linzj@sdu.edu.cn

Received 1 November 2008, revised manuscript received 4 June 2009

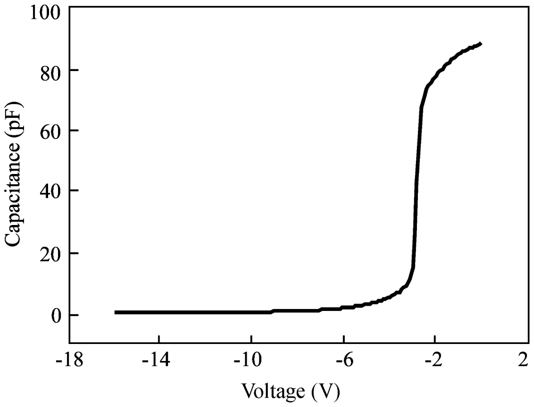

Fig. 2. Measured *C–V* curve at room temperature for the AlGaN/GaN HFET.

temperature using an Agilent 4284A at 10 kHz frequency. *I–V* measurements for the ungated AlGaN/GaN heterostructure were performed at room temperature using an Agilent 4156C semiconductor parameter analyzer.

3. Results and discussion

Figure 2 shows the *C–V* curve of the AlGaN/GaN HFET (see Fig. 1(b)), which was obtained using the source contact and the Ni Schottky contact. Integrating the *C–V* data yields the charge within the 2DEG versus voltage, and the threshold voltage is then determined to be –2.8 V by linear extrapolation[4]. The 2DEG sheet carrier concentration under the Ni Schottky contact can be calculated by[5]

$$n_{2D} = \int_{V_T}^{0} \frac{C\mathrm{d}V}{Sq}, \tag{1}$$

where C is the measured capacitance between the source ohmic contact and the Ni Schottky contact, V_T is the threshold voltage, q is the electron charge and S is the Ni Schottky contact area. It should be indicated that the 2DEG density calculated by Eq. (1) corresponds to the gate at zero bias. However, the difference between the 2DEG density calculated by Eq. (1) and the 2DEG density of the AlGaN/GaN HFET with floating gate could be neglected due to the fact that there is no external bias between the source and the gate. Therefore, the calculated result yields a sheet carrier concentration of 1.12×10^{13} cm^{-2} for the AlGaN/GaN HFET. The electron drift mobility of the 2DEG in the ungated AlGaN/GaN heterostructure (see Fig. 1(a)) was calculated as[5]

$$\mu_n = \frac{I_{DS} \ln \frac{r_2}{r_1}}{2\pi q n_{2D} V_{DS}}, \tag{2}$$

where n_{2D} is the 2DEG electron density, I_{DS} is the current flowing from drain to source in the linear region of the ungated AlGaN/GaN heterostructure, V_{DS} is the applied low voltage between drain and source, and r_1 and r_2 are the centric radius and the inner radius of the ring ohmic contact. The *I–V* characteristic for the ungated AlGaN/GaN heterostructure was measured and is shown in Fig. 3. The value

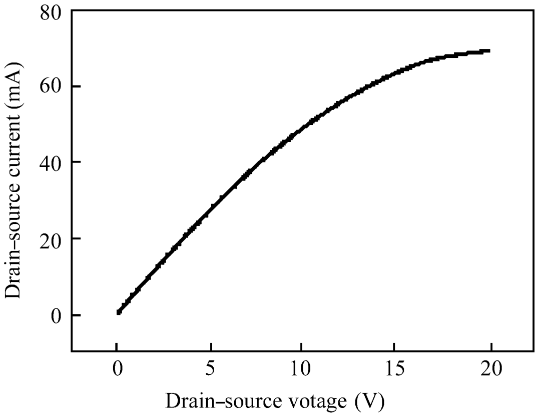

Fig. 3. Measured *I–V* curve at room temperature for the ungated AlGaN/GaN heterostructure.

of 0.5728 mA, which is the measured current I_{DS} with a source–drain voltage of 100 mV, is used to calculate the electron mobility of the 2DEG.

The annealed ohmic contact metals weaken the polarization of the AlGaN barrier layer and the weakened polarization decreases the 2DEG electron density in the channel[3]. As a consequence, the 2DEG electron density of the ungated AlGaN/GaN heterostructure is less than the original Hall measurement result. Furthermore, when the Ni Schottky contact is deposited on the strained AlGaN/GaN heterostructure, some 2DEG electrons under the Ni Schottky contact are extracted to the void surface donor states[6]. Therefore, the 2DEG electron density of the ungated AlGaN/GaN heterostructure (Fig. 1(a)) is more than that of the AlGaN/GaN HFET (Fig. 1(b)). As a result, the value of the 2DEG electron density for the ungated AlGaN/GaN heterostructure is less than 1.36×10^{13} cm^{-2} and is larger than 1.12×10^{13} cm^{-2}. In addition, the 2DEG density of the ungated AlGaN/GaN heterostructure is uniform along the channel without external bias due to the diffusion of 2DEG electrons[6] and the influence of the 100 mV source–drain bias on the distribution on 2DEG electrons can be neglected. Therefore, using Eq. (2) and the values of the 2DEG electron density obtained by the Hall measurement (1.36×10^{13} cm^{-2}) and that of the AlGaN/GaN HFET obtained by Eq. (1) (1.12×10^{13} cm^{-2}), respectively, we determine the electron drift mobility of the 2DEG in the ungated AlGaN/GaN heterostructure to be between 460 and 560 cm^2/(V·s).

The Fermi level of the AlGaN/GaN heterostructure employed here is above the conduction band in the triangular quantum well and the electrons in the 2DEG channel are a degenerate system. For highly degenerate semiconductors, Hall mobility is the same as the electron drift mobility[7], and therefore the Hall measurement results here are approximately the same as the real 2DEG density and the electron drift mobility of our AlGaN/GaN heterostructure. In fact, it has been reported that the electron drift mobility calculated from *I–V* characteristics is comparable with Hall mobility for an AlGaN/GaN heterostructure[8, 9].

However, in this work, comparing the calculated results (460–560 cm^2/(V·s)) of the ungated AlGaN/GaN heterostructure with the electron mobility obtained by Hall measurements (1200 $\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$), it is found that the value of the 2DEG density of the ungated AlGaN/GaN heterostructure shows only a small change compared with that of the Hall measurement, but the electron mobility is reduced by more than 50%. This can be attributed to the annealing process of the source and drain. During the annealing process, atoms from the ohmic contact metals diffuse into the AlGaN barrier layer and some defects are introduced into the barrier layer[3]. Because of defect scattering, the 2DEG electron mobility is decreased compared with the Hall measurement result. Furthermore, the strain of the AlGaN barrier layer is changed[3] with the annealing of the source and drain ohmic contacts, and the transverse influence distance is about 10 μm; therefore, the polarization charge density is different between the regions near and far away from the ohmic contacts in the AlGaN barrier layer. As a result, there will be a gradient of polarization charge density along the channel at the interface of AlGaN and GaN near the source and drain ohmic contacts, respectively, which greatly degrades the 2DEG electron mobility[5]. In addition, the existence of polarization charge density gradient and the uniform 2DEG density along the channel result in different surface potential along the channel. Further research should be undertaken into the relationship between the strain of the AlGaN barrier layer caused by the annealing of the source and drain ohmic contacts and the 2DEG electron mobility.

4. Conclusion

The influence of annealed ohmic contact metals on electron mobility of the 2DEG has been investigated on an ungated AlGaN/GaN heterostructure and an AlGaN/GaN HFET. Using Hall measurement results, *I*–*V* characteristics for the ungated AlGaN/GaN heterostructure and *C*–*V* characteristics for the AlGaN/GaN HFET, it is found that the electron mobility of the 2DEG for the ungated AlGaN/GaN heterostructure is decreased by more than 50% compared with the electron mobility of the Hall measurements. During the annealing process of source and drain ohmic contacts, some defects are introduced into the AlGaN barrier layer and the strain of the AlGaN barrier layer is changed, resulting in the decrease of the 2DEG electron mobility.

References

[1] Palacios T, Chakraborty A, Rajan S, et al. High-power AlGaN/GaN HEMTs for Ka-band applications. IEEE Electron Device Lett, 2005, 26: 781

[2] Kohn E, Daumiller I, Kunze M, et al. Transient characteristics of GaN-based heterostructure field-effect transistors. IEEE Trans Microw Theory Tech, 2003, 51: 634

[3] Lin Z J, Lu W, Lee J, et al. Influence of annealed ohmic contact metals on polarization of AlGaN barrier layer. Electron Lett, 2003, 39: 1412

[4] Schaadt D M, Miller E J, Yu E T, et al. Lateral variations in threshold voltage of an $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$/GaN heterostructure field-effect transistor measured by scanning capacitance spectroscopy. Appl Phys Lett, 2001, 78: 88

[5] Zhao J Z, Lin Z J, Corrigan T D, et al. Electron mobility related to scattering caused by the strain variation of AlGaN barrier layer in strained AlGaN/GaN heterostructures. Appl Phys Lett, 2007, 91: 173507

[6] Lin Z J, Lu W. Influence of Ni Schottky contact area on two-dimensional electron-gas sheet carrier concentration of strained AlGaN/GaN heterostructures. J Appl Phys, 2006, 99: 014504

[7] Liu E K, Zhu B S, Luo J S, et al. Semiconductor physics. Beijing: National Defense Industry Press, 2005 (in Chinese)

[8] Dang X T, Asbeck P M, Yu E T, et al. Measurement of drift mobility in AlGaN/GaN heterostructure field-effect transistor. Appl Phys Lett, 1999, 74: 3890

[9] Redwing J M, Tischler M A, Flynn J S, et al. Two-dimensional electron gas properties of AlGaN/GaN heterostructures grown on 6H-SiC and sapphire substrates. Appl Phys Lett, 1996, 69: 963