Influence of Ni Schottky contact thickness on two-dimensional electron-gas sheet carrier concentration of strained $Al_{0.3}Ga_{0.7}N/GaN$ heterostructures*

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Abstract: Ni/Au Schottky contacts with thicknesses of either 50 Å/50 Å or 600 Å/2000 Å were deposited on strained $Al_{0.3}Ga_{0.7}N/GaN$ heterostructures. Using the measured C–V curves and I–V characteristics at room temperature, the calculated density of the two-dimensional electron-gas (2DEG) of the 600 Å/2000 Å thick Ni/Au Schottky contact is about 9.13×10^{12} cm^{-2} and that of the 50 Å/50 Å thick Ni/Au Schottky contact is only about 4.77×10^{12} cm^{-2}. The saturated current increases from 60.88 to 86.34 mA at a bias of 20 V as the thickness of the Ni/Au Schottky contact increases from 50 Å/50 Å to 600 Å/2000 Å. By self-consistently solving Schrodinger's and Poisson's equations, the polarization charge sheet density of the two samples was calculated, and the calculated results show that the polarization in the AlGaN barrier layer for the thick Ni/Au Schottky contact is stronger than the thin one. Thus, we attribute the results to the increased biaxial tensile stress in the $Al_{0.3}Ga_{0.7}N$ barrier layer induced by the 600 Å/2000 Å thick Ni/Au Schottky contact.

Key words: AlGaN/GaN heterostructure; Schottky contact thicknesses; two dimensional electron gas; tensile stress
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1. Introduction

AlGaN/GaN heterostructure field-effect transistors (HFETs) have attracted intense interest for applications in the areas of high temperature, high power and microwave frequencies[1,2]. It has been shown that the polarization and surface states of the AlGaN barrier layer can exert a substantial influence on the concentration and distribution of free carriers in strained AlGaN/GaN heterostructures[3,4]. For high-frequency AlGaN/GaN HFETs, the distances between the gate and source as well as the gate and drain are very small. Schottky gate metals occupy much of the area of AlGaN/GaN HFETs. Previous work has showed that the area of Ni Schottky contacts affects the surface states of the AlGaN barrier layer and 2DEG sheet carrier concentrations[5], and different Schottky gate metals or different areas of the same Schottky gate metal can influence the strain of the AlGaN barrier layer[6]. However, little attention has been paid to the effect of Ni/Au Schottky contact thickness on 2DEG sheet carrier concentrations in strained AlGaN/GaN heterostructures. In this paper, Ni/Au Schottky contacts with two different thicknesses were deposited on strained $Al_{0.3}Ga_{0.7}N/GaN$ heterostructures. Using the measured capacitance–voltage (C–V) and current–voltage (I–V) characteristics of the Ni/Au Schottky contacts, we investigate the relationship between the thickness of the Ni/Au Schottky contacts and the 2DEG sheet carrier concentrations in strained $Al_{0.3}Ga_{0.7}N/GaN$ heterostructures.

2. Experiment

$Al_{0.3}Ga_{0.7}N/GaN$ heterostructures were epitaxially grown on (0001) sapphire substrate using metal-organic chemical vapor deposition (MOCVD). The structure consists 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 indicate 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 device processing, Ohmic contacts were formed by depositing Ti/Al/Mo/Au using e-beam evaporation and lift-off. These contacts were annealed at 850 °C for 30 s in a rapid thermal annealing (RTA) system. Ni/Au circular Schottky contacts with a diameter of 120 μm were then deposited by e-beam evaporation, and the thicknesses of the Schottky contacts were 50 Å/50 Å (Ni/Au) and 600 Å/2000 Å . The separation between the Ohmic contact metals and the circular Schottky contact metals is 40 μm. Figure 1 shows the device structure schematically. C–V measurements were performed at room temperature using an Agilent 4284A at 100 kHz frequency.

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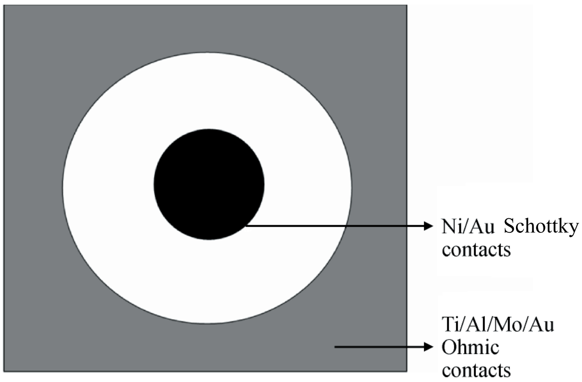

Fig. 1. Schematic diagram of the AlGaN/GaN device structure.

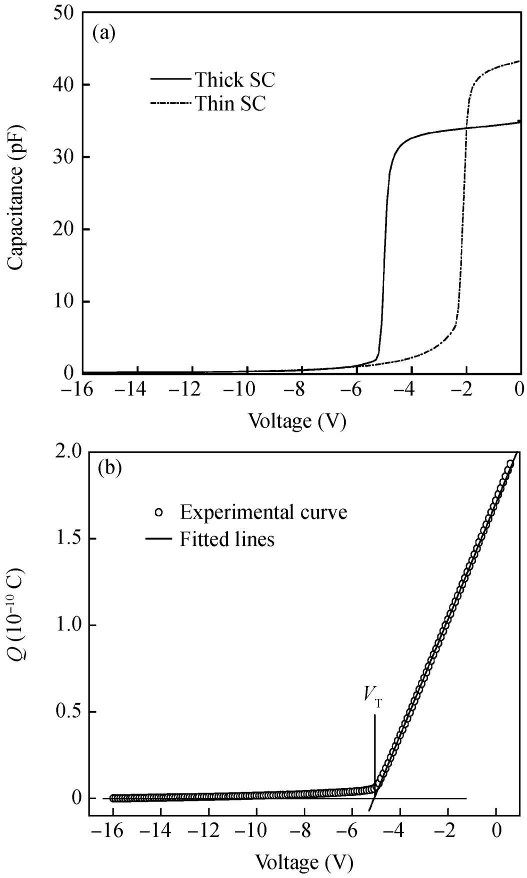

Fig. 2. (a) Measured C–V curves at room temperature for different Ni/Au Schottky contact thicknesses on AlGaN/GaN heterostructures. (b) Charge Q in the two-dimensional channel of the AlGaN/GaN heterostructures, obtained by C–V integration of the 600 Å/2000 Å thick Ni/Au Schottky contact in (a).

I–V measurements were performed at room temperature using an Agilent 4156C semiconductor parameter analyzer.

3. Results and discussion

The C–V curves of the Ni/Au Schottky contacts with the two different thicknesses are shown in Fig. 2(a). Integrating the C–V data yields the charge within the 2DEG versus voltage, and the threshold voltage for different Ni/Au Schottky contact thicknesses can be obtained by linear extrapolation[7].

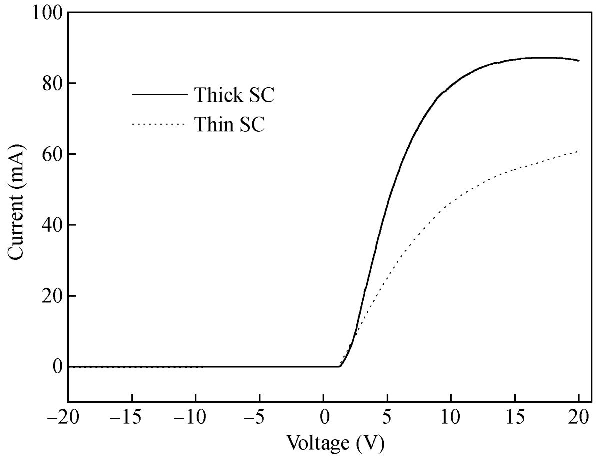

Fig. 3. Measured I–V curves at room temperature for different Ni/Au Schottky contact thicknesses on AlGaN/GaN heterostructures.

The threshold voltage is –2.1 V for the 50 Å/50 Å thick Ni/Au Schottky contact and –5.0 V for the 600 Å/2000 Å thick Ni/Au Schottky contact. The 2DEG sheet carrier concentration under different Ni/Au Schottky contact thicknesses can be calculated by[8]

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

where C is the measured capacitance between the Ohmic contact and the Ni/Au Schottky contact, V_T is the threshold voltage, q is the electron charge, and S is the Ni/Au Schottky contact area.

The calculated result yields a sheet carrier concentration of 4.77×10^{12} cm^{-2} for the thin Ni/Au Schottky contact sample and 9.13×10^{12} cm^{-2} for the thicker one. The 2DEG sheet carrier concentration for the 600 Å/2000 Å thick Ni Schottky contact is nearly twice of that for the 50 Å/50 Å Ni/Au Schottky contact. This can be confirmed by the I–V measurements between the Ohmic contact and Ni/Au Schottky contact. Figure 3 shows the measured I–V curves for the two different Ni/Au Schottky contact thicknesses, in which the solid line represents the I–V measurement with the 600 Å/2000 Å thick Ni/Au Schottky contact and the dot line the 50 Å/50 Å thick Ni/Au Schottky contact. It is indicated that the value of the saturated current at a bias of 20 V for the 600 Å/2000 Å thick Ni/Au Schottky contact is 86.34 mA and that for the 50 Å/50 Å thick Ni/Au Schottky contact is 60.88 mA. The saturated current is related to the 2DEG sheet carrier concentrations. A higher 2DEG sheet carrier concentration corresponds to a higher saturation current[9, 10], and so the I–V measurement result is consistent with that of the C–V measurements. We attribute the higher sheet carrier concentration for the thicker Schottky contacts to the influence of the Ni/Au Schottky contact thickness on the strain of the $Al_{0.3}Ga_{0.7}N$ barrier layer. It has been reported that the biaxial tensile stress applied to the AlGaN layer increases as the Si_3N_4 passivation layer thickness increases, leading to an increase of the 2DEG density confined at the AlGaN/GaN heterointerface[11]. In our samples, Ni/Au Schottky contacts occupy much of the area of the devices. The total thickness of the thicker Ni/Au Schottky contact is 2600

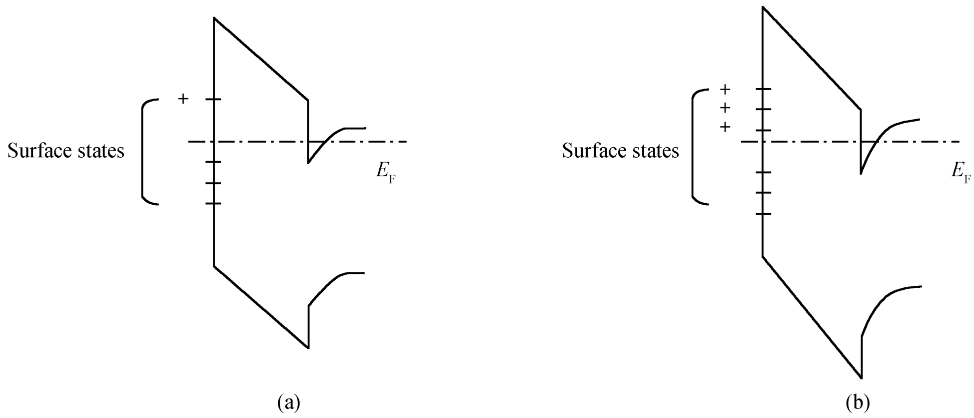

Fig. 4. Schematic energy band diagram for (a) the 50 Å/50 Å thick Ni/Au Schottky contact and (b) the 600 Å/2000 Å thick Ni/Au Schottky contact on AlGaN/GaN heterostructures.

Å, and we believe that it will also exert an external biaxial tensile stress on the $Al_{0.3}Ga_{0.7}N$ barrier layer leading to an increase of the piezoelectric polarization in the $Al_{0.3}Ga_{0.7}N$ barrier layer. The total thickness of the thinner Ni/Au Schottky contact thickness is only 100 Å, and therefore its influence on the strain of the AlGaN barrier layer can be neglected. As a result, the polarization in the AlGaN barrier layer for the 2600 Å thick Ni/Au Schottky contact is much higher than the thin one. This can be confirmed by analysis of the measured C–V curves (Fig. 2(a)). The base structure for the measured capacitance is a parallel plate capacitor, and the capacitance value (C) can be determined by[12]

$$C = S\frac{\varepsilon_0\varepsilon_r}{d}, \tag{2}$$

where d is the width of the AlGaN barrier layer, ε_0 is the vacuum dielectric constant, and ε_r is the dielectric constant of the AlGaN barrier layer. The capacitance values for the 600 Å/2000 Å and 50 Å/50 Å thick Ni/Au Schottky contacts at zero bias are 34.8 pF and 43.3 pF, respectively (Fig. 2(a)), and the area of the Ni/Au Schottky contact is 1.1304×10^{-4} cm^{-2}. With the width d of the AlGaN barrier layer taken as 21.5 nm, the dielectric constants of the AlGaN barrier layer for the thick and thin Ni/Au Schottky contacts are calculated with Eq. (2), and the calculated values (ε_r) are 7.4739 and 9.3032, respectively. It has been shown that a smaller dielectric constant of the AlGaN barrier layer corresponds to the stronger polarization of the AlGaN barrier layer[3], which indicates that the polarization of the AlGaN barrier layer for the thick Ni/Au Schottky contact is stronger than that of the thin Ni/Au Schottky contact. Furthermore, the value of the polarization charge sheet density for AlGaN barrier layers can also be calculated. First, with the known 2DEG electronic density (n_{2D}) and the measured $I-V$ characteristics, the Schottky barrier heights for the Ni/Au Schottky contacts are calculated by self-consistently solving Schrodinger's and Poisson's equations[6,13], and the obtained barrier heights for the 600 Å/2000 Å and 50 Å/50 Å Ni/Au Schottky contacts are 1.5 eV and 1.41 eV, respectively. The polarization charge sheet density for AlGaN barrier layers can be obtained by[14]

$$n_{2D}(x) = \sigma(x)/e - [\varepsilon_0\varepsilon_r(x)/de^2][e\Phi_b(x) + E_F(x) - \Delta E_c(x)], \tag{3}$$

where x is the Al content, σ is the polarization charge sheet density, $e\Phi_b$ is the Schottky barrier height, E_F is the Fermi level with respect to the GaN conduction band-edge energy, ΔE_c is the conduction band offset at the AlGaN/GaN interface, and e is the electron charge. The Fermi level $E_F(x)$ is determined by calculating the barrier heights, and the values of $E_F(x)$ for the thick and thin Ni/Au Schottky contacts are 0.304 eV and 0.195 eV, respectively. The band offset, ΔE_c, is determined by[15]

$$\Delta E_c = 0.7[E_g(x) - E_g(0)], \tag{4}$$

where the band gap of AlGaN, $E_g(x)$, is given by[16]

$$E_g(x) = 6.13x + 3.42(1-x) - x(1-x). \tag{5}$$

If x is taken as 0.3, $\Delta E_c(x)$ is calculated to be 0.42 eV using Eqs. (4) and (5). Applying the known parameters to Eq. (3), the calculated polarization charge sheet density for the thick and thin Ni/Au Schottky contacts are 1.18×10^{13} cm^{-2} and 7.6×10^{12} cm^{-2}, respectively. Therefore, the conclusion can be drawn that the polarization in the AlGaN barrier layer for the thick Ni/Au Schottky contact is stronger than the thin one.

The polarization electric field in the $Al_{0.3}Ga_{0.7}N$ barrier layer depends on the polarization. When the polarization is weak, the polarization electric field in the $Al_{0.3}Ga_{0.7}N$ barrier layer is also weak. In this case, fewer donor states have an energy above the Fermi level, as is shown in Fig. 4, and fewer surface donor electrons are ionized to go into the $Al_{0.3}Ga_{0.7}N$/GaN interface and form the 2DEG. This is the reason why there is less 2DEG sheet carrier concentration for the 50 Å/50 Å thick Ni/Au Schottky contact. With higher polarization electric field, the 2DEG electron density confined at the AlGaN/GaN interface is much larger for the 600 Å/2000 Å thick Ni/Au Schottky contact.

4. Conclusion

In conclusion, the 2DEG density of the $Al_{0.3}Ga_{0.7}N$/GaN heterostructure increases as the Ni/Au Schottky contact thickness increases, and the measured I–V results are consistent with the calculated 2DEG density. We attribute the results to the increased biaxial tensile stress in the $Al_{0.3}Ga_{0.7}N$ barrier layer introduced by the thick Ni/Au Schottky contact.

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