Low-resistance Ohmic contact on polarization-doped AlGaN/GaN heterojunction*

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High electronic density is achieved by polarization doping without an impurity dopant in graded AlGaN films. Low specific contact resistance is studied on the polarization-doped AlGaN/GaN heterojunctions by using the transmission line method (TLM). The sheet density of polarization-doped AlGaN/GaN heterojunction is 6×10^{14} cm^{-2} at room temperature. The linearly graded material structure is demonstrated by X-ray diffraction. The carrier concentration and mobility are characterized by a temperature-dependent Hall measurement. Multiple-layer metal (Ti/Al/Ti/Au) is deposited and annealed at 650 °C to realize the Ohmic contacts on the graded AlGaN/GaN heterojunctions.

Keywords: polarization, AlGaN, carrier concentration, Ohmic contact

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1. Introduction

Group III nitrides, such as GaN, AlN, and InN, have attracted considerable attention due to their applications in high-power electronic and optoelectronic devices.[1–3] The wurtzite (WZ) GaN-based structure grown along the c axis is found to have a large strain-induced piezoelectric (PZ) field.[4] In addition to the high PZ polarization, a large spontaneous (SP) polarization is expected to be present in WZ GaN-based semiconductors.[5] It is now widely recognized that built-in electric fields due to polarization-induced charges play an important role in the electrical and optical properties of nitride heterostructures grown along the c axis. Much work has been done on revealing the nature of the high two-dimensional (2D) electron densities in the nominally undoped AlGaN/GaN structures.[6–11] The large interface charge density in this system is correlated to the spontaneous and piezoelectric polarization, resulting in a high electric field in the AlGaN barrier layer. Instead of a sharp heterojunction, an interesting phenomenon occurs if the junction is graded. The polarization of AlGaN is larger than that of GaN, and keeps increasing as the Al composition increases, leading to a polarization 'bulk' charge given by $\rho = \nabla \cdot \boldsymbol{P}(r)$. The graded AlGaN layer on Ga-face GaN results in a net positive polarization charge in the graded layer. This polarization charge is fixed and it attracts carriers from available sources of charge (the surface, remote dopants, etc.). Therefore, a three-dimensional electron slab (3DES) is formed.[4,12–16]

The performance of a device fabricated from GaN and relevant compound is strongly affected by the resistance caused by the electrical contact. To avoid excessive heating, which results in failure of the device, specific contact resistances on the order of less than 10^{-3} Ω·cm^2 for light-emitting diode (LED) and less than 10^{-4} Ω·cm^2 for laser diode are required. It has, however, been shown that for the n-type side-up vertical LED, poor n-type Ohmic property is one of the major barriers to the attainment of high external quantum efficiency.[17–20] It has been reported that n-Ohmic contact to Ga-face GaN could be easily formed using either Ti- or vanadium-based scheme.[21,22] However, very there are few reports on n-Ohmic contacts of $Al_xGa_{1-x}N$, especially when $x \geq 0.3$ can be found. In the present work, low resistance Ohmic contact is achieved on linearly graded polarization-doped AlGaN. Furthermore, to the best of our knowledge, there are only a few studies on n-type Ohmic contact of polarization-doped AlGaN.

2. Experimental details

All of the samples used in this work were grown on sapphire substrates with 3-μm-thick GaN template, which had previously been grown by using metal–organic chemical-vapor deposition (MOCVD). The growth was done in an MBE system equipped with In, Al, Ga, Si, Mg, and a radio-frequency (RF) nitrogen plasma source, which enabled the growth of InN, GaN, AlN, and the corresponding ternary alloys. The grown heterojunction structures are shown in the inset of Fig. 1. Under the gallium-rich condition, a 100-nm-thick Ga-face unintentionally doped GaN buffer layer was grown along the polar c (0001) axis. On the top of buffer layer, 100-nm-thick linearly graded $Al_xGa_{1-x}N$ was prepared by varying Al composition from 0% to 10%, 30%, and 50%, separately, and the obtained samples are named samples A,

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B and C, respectively. A Philips X'pert X-ray diffraction instrument was used to characterize the graded nitride samples. The transmission line method (TLM) was used to investigate the specific contact resistance. The samples were first etched with reactive ion etching (RIE) by using Cl_2 as an etchant to form mesa structures. Before metallization, the samples were etched in a HCl:DI water (1:2) solution to remove the native oxide layer on the surface. Multiple metal layers of Ti (25 nm)/Al(100 nm)/Ti (50 nm)/Au (100 nm) were deposited onto the samples at a pressure of 10^{-6} Torr (1 Torr = 1.33322×10^2 Pa). All of the samples were annealed by using the rapid thermal annealing process (RTP) since it is able to change film-to-film or film-to-wafer substrate interfaces, activate dopants, repair damage from ion implantation, densify deposited films, and change states of grown films.

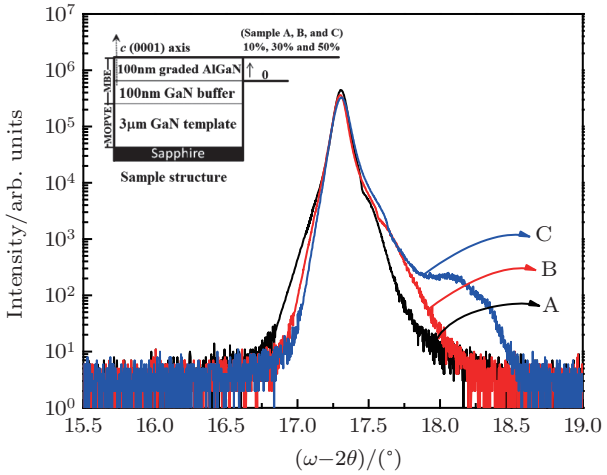


Fig. 1. (color online) X-ray diffraction data for linearly graded AlGaN samples A, B, and C around the GaN (0002) peak and the epitaxial layer structure (inset).

3. Results and discussion

As shown in Fig. 1, the dependence of Al composition in the graded AlGaN layer on aluminum flux is mapped out with X-ray diffraction analysis (0002). The result indicates that the shoulder is broadened as the Al composition becomes higher in the sample. As shown in Fig. 2(a), the graded layer is grown on a Ga-face that is unintentionally doped on the GaN buffer along the [0001] direction. Positive polarization charges are created in the region where the Al composition is graded gradually, thereby resulting in the change in Al composition and thus the change in polarization.[16] The positive polarization charges can be calculated with $\rho_\pi = -\nabla \cdot \boldsymbol{P}$, where ρ_π is the fixed polarization charge, $\boldsymbol{P}$ is the total polarization combining piezoelectric polarization with spontaneous polarization. These charges do not make any direct contribution to the electrical transport in the crystal. However, they are neutralized by free electrons that are attracted from the semiconductor surroundings, and 3DES is formed in this way.[16] The band diagram and carrier concentration of sample B, calculated by self-consistently solving Schrödinger and Poisson's equation, are shown in Fig. 2(b).[23] In the absence of impurities, the band diagram shows that the high concentration (∼10^{18} cm^{-3}) electrons are induced in the graded region. This will be confirmed by the experimental results.

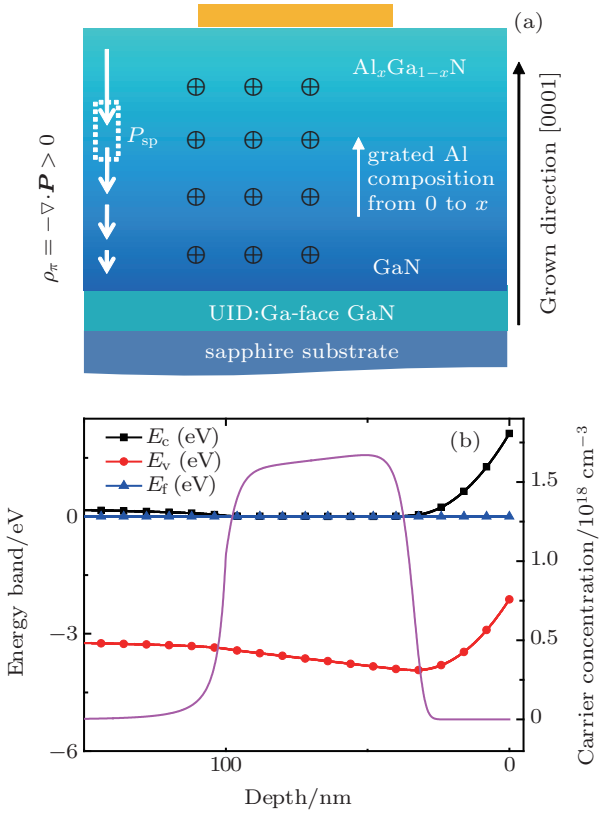


Fig. 2. (color online) (a) Schematic plot of growth direction of grading layer and polarization charges; (b) band diagram of graded AlGaN layers.

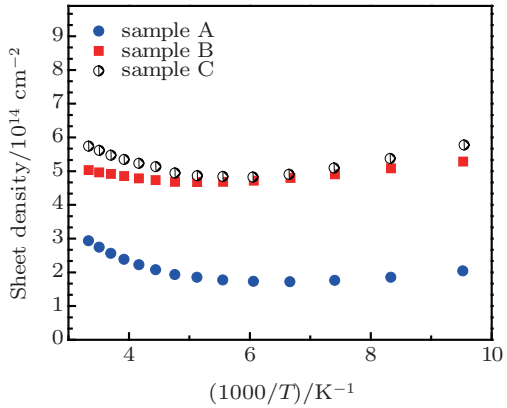


Fig. 3. (color online) Temperature-dependences of carrier concentration Hall measurements for linearly graded AlGaN samples A, B, and C.

Figure 3 shows the temperature-dependent Hall measurements for all the three samples. Before the Hall measurements, the Ohmic contacts are demonstrated by linear *I*–*V* curve. From the Hall measurements, the carrier concentration n_{2D} of sample C (linearly graded $Al_{0.5}Ga_{0.5}N$) is $\sim 6 \times 10^{14}$ cm^{-2} at room temperature. The carrier concentration n_{2D} of sample A (linearly graded $Al_{0.1}Ga_{0.9}N$) is

$\sim 3 \times 10^{14}$ cm^{-2}, also at room temperature. The doping density can be adjusted by controlling the Al composition, or changing the thickness of the graded layer. If the graded layer thickness z_0 is smaller than the thermal de-Broglie wavelength ($\lambda_{\rm dB} = 2\pi\hbar/\sqrt{2m^* k_{\rm B} T} \approx 17$ nm) for non-degenerate carriers, the free-electron gas is quantized in the z direction and causes a quasi-two-dimensional electron gas (2DEG). For slabs of graded regions ($z_0 \gg \lambda_{\rm dB}$), the electron gas is three-dimensional (3D). The concentration of 3DES can be calculated by $\rho = n_{\rm 2D}/d \approx 10^{19}$ cm^{-3}, where ρ is the concentration of 3DES and d is the thickness of the Al composition grading layer.[16] It is very well understood that the principle of polarization-induced doping in a graded AlGaN material system is totally different from the traditional shallow "hydrogenic" technique. Previous studies have indicated that the unintentionally doped GaN template functions as a reservoir of free electrons, thus more free electrons are available for the polarization charge field.[24,25] However, this factor is not included in the calculated models, Therefore, the polarization-induced sheet density in the present work is much higher than the value (10^{12} cm^{-2} and/or low 10^{13} cm^{-2} range) obtained by calculating and using semi-insulating GaN as substrate.[4,26] This clearly shows that high Al composition can enhance the carrier concentration. However, a higher Al composition also causes a larger lattice mismatch between the graded layer and GaN template, which can degenerate the free-electrons.[27] This explains the insignificant increase of the sheet density when the Al composition is enhanced from 0.3 to 0.5. The electronic density of 3DES generated by this technique does not depend on temperature (not frozen out). Because the carriers are induced by the polarization charges, they require no impurity incorporation, and thus exhibit virtually no freezing out at cryogenic temperatures as opposed to thermally ionized carriers in shallow, donor-doped layers.[28] In addition, because ionized impurity scattering is absent, polarization-induced 3D electron gases indicate higher conductivity than impurity-doped layer with a comparable carrier concentration. However, the removal of ionized impurity scattering results in higher mobility. In impurity-doped GaN, thermally activated carriers are frozen out due to lower energy and less effective screening of electrons caused by lowering temperature. This leads to the severe scattering of ionized impurities, and the lowering of mobility. As shown in the Hall measurements, the mobility of the polarization-induced electrons is not as high as expected. The most likely reason for the low mobility is that the polarization-induced high density electrons in the graded AlGaN layer causes low mobility, as can be seen from Fig. 4. Meanwhile, it is different from the scenario of the donor-doped carriers where the mobile 3DES is not frozen out at low temperatures. The conductivity of the polarization-induced 3DES in linearly graded AlGaN is easily controlled by changing the grading aluminum composition for the same thickness, or by changing the thickness for same grading Al composition. This is very useful for designing the high-conductivity layers required in many device structures.

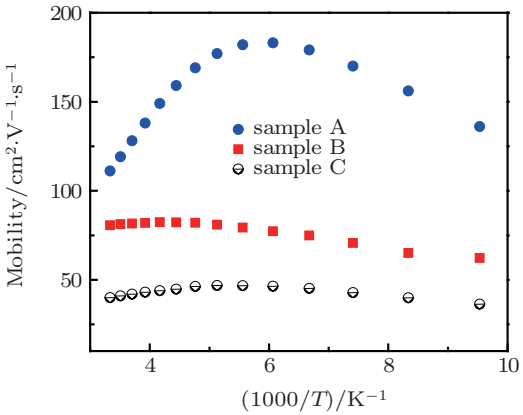


Fig. 4. (color online) Temperature-dependences of mobility Hall measurements for linearly graded AlGaN samples A, B, and C.

For the device application, it is imperative to successfully implement low-resistance Ohmic contacts to an n-type graded AlGaN/GaN heterojunction. The transmission line method (TLM) has been widely used for Ohmic-contact analysis of device characterization because of its simplicity and accuracy. The TLM method employs an etched mesa, and metal-contact pads are subsequently deposited on the top of the mesa as shown in the inset of Fig. 5. As shown in Fig. 6, the current–voltage (I–V) measurements of all three samples indicate that Ohmic contacts are obtained after 60-second annealing at 650 °C. It is worthwhile studying the dependence of the Ohmic contact on temperature. With the highest electron sheet density, sample C is annealed at 600 °C and 700 °C for 60 seconds, separately. However, the nonlinear I–V curves indicate that non-Ohmic contacts are obtained when the annealing temperatures are below and above 650 °C. At an annealing temperature of 650 °C, N out-diffuses from the GaN lattice to form TiN and N vacancies without decomposing the crystal structure. The interfacial region thus becomes heavily doped, thereby producing the configuration needed for tunneling contacts. A thin TiN layer at the interface between the metal contact and GaN has been observed by TEM.[29] At a lower annealing temperature (600 °C), heavy doping is not produced in the interfacial region because not enough TiN and N vacancies are formed. Thus, the Ohmic contact cannot be realized at 600 °C in this work. The Ti/Al bilayer turns into the film highly resistive due to the formed Al_2O_3 coating at higher annealing temperature (700 °C), resulting in the increase in contact resistance. Generally, the Ni layer is used between Al and Au to prevent the contacts from oxidizing during alloying. A Ti/Au over layer is used on the top of standard Ti/Al metallization. As a result, the Ti and Al layers strengthen the mutual reactions to produce Ti_xAl_{1-x} alloys. The Ti_xAl_{1-x} alloy produces low resistance at the interface. Furthermore, the Ti_xAl_{1-x} alloy ties up excess Al atoms, preventing it from

balling up. Therefore, the contacts become thermally stable and the roughening of the metal film is reduced.

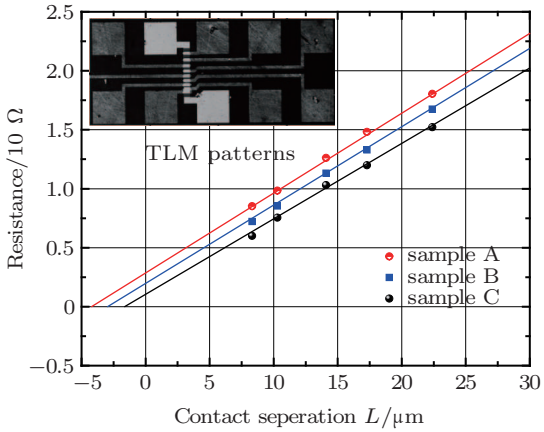


Fig. 5. (color online) Contact resistances versus contact separation for linearly graded AlGaN samples A, B, and C, measured by the transmission line method (TLM).

From the I–V measurements, TLM analysis can be realized as shown in Fig. 5, the x-intercept is twice the transfer length (L_t); that is, $2L_t$. The y-intercept gives twice the contact resistance (R_c); that is, $2R_c$. The specific contact resistance (ρ_c) or called contact resistivity and the semiconductor sheet resistance (R_{sh}) are calculated (Fig. 5) from linear fitting to the measured data by using the extrapolated L_t, and R_c by using $(\rho_c) = (L_t)^2 R_{sh}$ and $R_{sh} = R_c W/L_t$. Here, the value of electrode length W is 30 μm, and the values of L_t and R_c can be obtained from Fig. 5 (as shown in Table 1). Besides being annealed at 650 °C for 60 seconds, different pieces of samples obtained under the same growth condition are also annealed at 650 °C for 30 and 90 seconds, respectively. The specific contact resistances for all the samples are shown in Table 1. The specific contact resistance decreases with the increase of Al composition in the linearly graded AlGaN heterojunction. The reason is shown from the Hall measurements; that is, higher grading Al composition in graded AlGaN leads to high carrier concentration. It is easily understood that the value of specific contact resistance for all the samples is inversely proportional to the Al composition in graded AlGaN. Meanwhile, the specific contact resistance is also changed with annealing time. For all the samples annealed at 650 °C for 60 seconds, the values of specific contact resistance are all smaller than those for the samples annealed at 650 °C for 30 and 90 seconds. In the rapid annealing process, the formation of TiN occurs at the interface and results in a shallow N-deficient AlGaN layer, which increases the doping level close to the interface and thereby leads to Ohmic contact. For 30-second annealing samples, the annealing time is not long enough to complete the formation of TiN at the interface and results in a higher specific contact resistance than for 60-second annealing samples. As the annealing time is increased to 90 seconds, the multiple metal layers tend to ball up and thus result in a rough surface. Meanwhile, it is possible to oxidize the Al surface for a longer annealing time, most likely forming sapphire. As a result, a coating of the low conductive sapphire formed on the Al layer leads to an increase in specific contact resistance. The final layer Au is used to reduce sheet resistance and avoid the oxidation during the high-temperature annealing that is necessary to achieve low specific contact resistance.

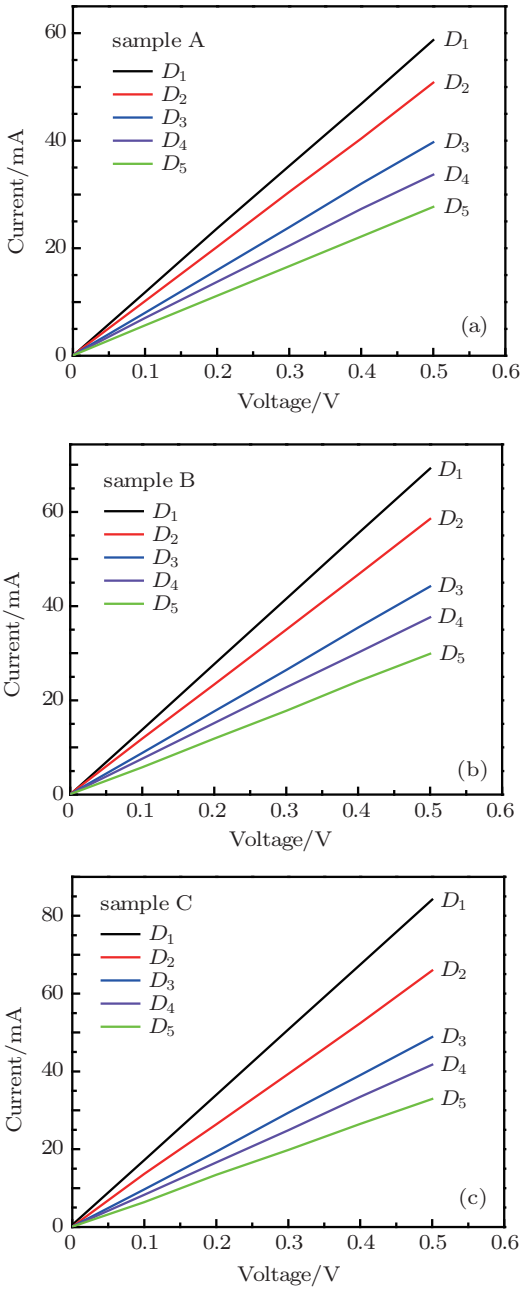


Fig. 6. (color online) Current–voltage characteristics for linearly graded AlGaN samples A, B, and C annealed at 650 °C for 60 seconds and different distances between two contacts: $D_1 = 8.5$ μm, $D_2 = 10.5$ μm, $D_3 = 14$ μm, $D_4 = 17.5$ μm, and $D_5 = 22.5$ μm.

However, it has been reported that annealing at high temperatures will cause the degradation in device performance (e.g. the deterioration of edge acuity of electrical contact and the relaxation of AlGaN/GaN heterostructure).[30] Another exciting finding in this work is that we achieve very low resistance Ohmic contact (1.2×10^{-7} Ω·cm^2) at a relatively low an-

nealing temperature 650 °C, which is conducible to the devices free from electrical degradation.

Table 1. Values of transfer length (L_t), contact resistance (R_c), and specific contact resistance (ρ_c) for graded AlGaN/GaN heterojunctions. The subscripts 30, 60 and 90 refer to 30-, 60- and 90-second annealing at 650 °C.

	Sample A	Sample B	Sample C
L_{t30}/μm	3.91	2.83	1.93
L_{t60}/μm	2.04	1.48	0.81
L_{t90}/μm	3.73	2.64	1.86
R_{c30}/Ω	2.76	2.05	1.92
R_{c60}/Ω	1.53	1.12	0.56
R_{c90}/Ω	2.64	1.84	1.22
$\rho_{c30}/10^{-6}$ Ω·cm^2	3.25	1.76	1.14
$\rho_{c60}/10^{-6}$ Ω·cm^2	0.90	0.46	0.12
$\rho_{c90}/10^{-6}$ Ω· cm^2	2.96	1.45	0.64

4. Conclusion

For the potential device application, low-resistance Ohmic contacts to all the polarization-doped AlGaN/GaN heterojunctions are demonstrated. The polarization in linearly graded AlGaN/GaN heterojunction can induce high-concentration (n_{2D} up to 6×10^{14} cm^{-2}) 3D electron slabs. This is an attractive technique to change the traditional donor-doped GaN-based materials. It is also observed that there is no carrier frozen out in polarization charges in the AlGaN/GaN semiconductor system.

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