Sodium beta-alumina thin films as gate dielectrics for AlGaN/GaN metal–insulator–semiconductor high-electron-mobility transistors*

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Sodium beta-alumina (SBA) is deposited on AlGaN/GaN by using a co-deposition process with sodium and Al_2O_3 as the precursors. The X-ray diffraction (XRD) spectrum reveals that the deposited thin film is amorphous. The binding energy and composition of the deposited thin film, obtained from the X-ray photoelectron spectroscopy (XPS) measurement, are consistent with those of SBA. The dielectric constant of the SBA thin film is about 50. Each of the capacitance–voltage characteristics obtained at five different frequencies shows a high-quality interface between SBA and AlGaN. The interface trap density of metal–insulator–semiconductor high-electron-mobility transistor (MISHEMT) is measured to be $(3.5\sim9.5)\times10^{10}$ cm$^{-2}\cdot$eV^{-1} by the conductance method. The fixed charge density of SBA dielectric is on the order of 2.7×10^{12} cm^{-2}. Compared with the AlGaN/GaN metal–semiconductor heterostructure high-electron-mobility transistor (MESHEMT), the AlGaN/GaN MISHEMT usually has a threshold voltage that shifts negatively. However, the threshold voltage of the AlGaN/GaN MISHEMT using SBA as the gate dielectric shifts positively from −5.5 V to −3.5 V. From XPS results, the surface valence-band maximum (VBM-E_F) of AlGaN is found to decrease from 2.56 eV to 2.25 eV after the SBA thin film deposition. The possible reasons why the threshold voltage of AlGaN/GaN MISHEMT with the SBA gate dielectric shifts positively are the influence of SBA on surface valence-band maximum (VBM-E_F), the reduction of interface traps and the effects of sodium ions, and/or the fixed charges in SBA on the two-dimensional electron gas (2DEG).

Keywords: sodium beta-alumina, AlGaN/GaN, MESHEMT, MISHEMT

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1. Introduction

Semiconductors and gate dielectrics are two field-effect transistor (FET) material components. Over the past few years, the material science community has paid much attention to the development of gate insulators for GaN-based semiconductors. Various high dielectric constant (HK) insulators, such as Al_2O_3,[1−7] HfO_2,[1,3,8−11] ZrO_2,[9,12,13] Si_3N_4,[14,15] and organic dielectric,[16] have been used for GaN-based metal–insulator–semiconductor high-electron-mobility transistors (MISHEMTs).

Sodium beta-alumina (SBA) has an unusual crystal structure, its structure has two-dimensional alternating thin layers of aluminium oxide (about 1.13 nm) and sodium ions. The sandwich structure of SBA dictates the motion of the sodium ions, i.e., they can move freely only in the direction parallel to the lattice plane. In the direction normal to the plane, however, the motion of the sodium ions is restricted to a range of a few angstroms by the adjacent alumina layers. Consequently, SBA has a very high relative permittivity.[17] Pal *et al.*[18] used the SBA thin films as HK gate dielectrics for transparent field-effect transistors. And they concluded that the SBA thin film is a good candidate of HK gate dielectric.

In this paper, we use the SBA thin film as the gate dielectric of an AlGaN/GaN MISHEMT. A high-quality interface between SBA and AlGaN is obtained. The interface trap density of the AlGaN/GaN MISHEMT and the fixed charges in SBA are estimated. Usually, the threshold voltage of the AlGaN/GaN MISHEMT shifts negatively compared with that of the AlGaN/GaN metal–semiconductor heterostructure high-electron-mobility transistor (MESHEMT). However, the threshold volt-

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age of the AlGaN/GaN MISHEMT with the SBA thin film as gate dielectric positively shifts from −5.5 V to −3.5 V. The possible reasons for the unusual shift are the influence of SBA on the surface valence-band maximum (VBM-E_F), the reduction of interface traps and the effects of sodium ions and/or the fixed charges in SBA on the two-dimensional electron gas (2DEG).

2. Experiment

The schematic illustrations of the AlGaN/GaN MESHEMT and the MISHEMT are shown in Fig. 1. Each of the AlGaN/GaN epilayers is grown by metal–organic chemical vapour deposition (MOCVD) and consists of a 2-μm GaN buffer layer and a 30-nm undoped $Al_{0.25}Ga_{0.75}N$ layer on a sapphire substrate. The SBA is grown on AlGaN and Pt/Si using co-deposition by oxide molecular beam epitaxy (MBE) with sodium and Al_2O_3 as the precursors. The sodium and Al_2O_3 precursors are evaporated by using thermal evaporation and electron beam evaporation respectively. The wafer is divided into two parts. One part is for the AlGaN/GaN MISHEMT, and the other is for the MESHEMT.

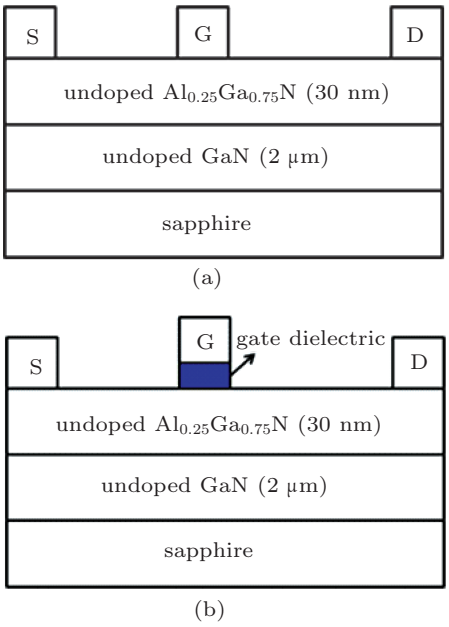


Fig. 1. (color online) Schematic illustrations of (a) MESHEMT and (b) MISHEMT.

The devices each with a gate width of 100 μm and gate length of 3 μm are fabricated by conventional GaN-based FET fabrication steps. Ohmic contact is prepared by electron beam to evaporate a multilayered Ti/Al/Ni/Au (30 nm/80 nm/30 nm/50 nm) in sequence, followed by a rapid thermal annealing at 825 °C for 30 s in an N_2 ambient. After that, the SBA or Al_2O_3 layer is deposited on a gate place. Then the Ni/Au (100 nm/50 nm) contact is deposited to form Schottky contact by electron beam evaporation. An MESHFET without SBA thin film is prepared in the procedure the same as the device processing procedure of the remaining part of the wafer, except the step for the deposition of the gate dielectric.

The composition of thin film is determined by XPS, which is used for obtaining the evolution of valence-band maximum (VBM-E_F) after SBA has been deposited on AlGaN. The capacitance and device performance are measured at room temperature by using Agilent 4294A and Agilent 4155B semiconductor parameter analyzer for dc characteristics respectively.

3. Results and discussion

X-ray diffraction (XRD) spectrum reveals that the deposited thin film is amorphous. The Na 1s and Al 2p core level XPS spectra of the as-deposited SBA are shown in Figs. 2(a) and 2(b) respectively. As shown in Fig. 2(a), the Na 1s XPS binding energy spectrum shows a peak at about 1071.4 eV. It is in good agreement with the standard value 1071.7 eV,

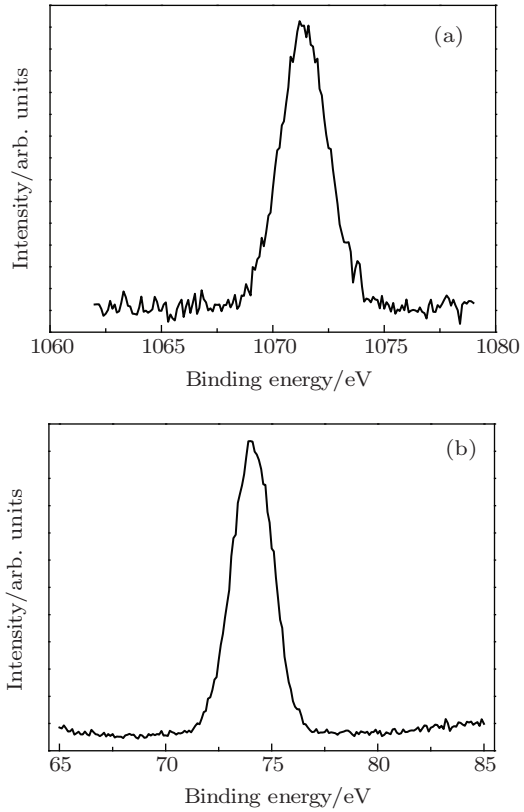


Fig. 2. The X-ray photoelectron spectroscopy (XPS) spectra of (a) Na 1s and (b) Al 2p.

indicating that Na is in its Na^+ state. Using the same method, we can determine Al in its Al^{3+} state shown in Fig. 2(b). The atomic ratio of Na:Al is found to be about 1:11 by integrating the areas of the peaks. Thus it indicates that the deposited thin film is consistent with sodium beta-alumina.

Capacitance–voltage (C–V) measurement is carried out on a metal–insulator–metal structure for SBA at a high frequency (1 MHz). The oxide capacitance C is measured to be 201 pF for 70-nm SBA. The dielectric constant $\varepsilon_{\rm OX}$ of SBA is estimated to be 50 using the following equation:

$$C = \frac{\varepsilon_0 \varepsilon_{\rm OX} A}{d_{\rm OX}}, \tag{1}$$

where ε_0 is the vacuum permittivity; the capacitor area, A, is 3.14×10^{-4} cm^2; $d_{\rm OX}$ is the thickness of SBA. The estimated dielectric constant is significantly higher than that of Al_2O_3 (9), which is caused by sodium ions, and it is also higher than those of some other inorganic high-k materials such as HfO_2 (25) and ZrO_2 (25). It demonstrates that the motion of sodium ions is restricted by the unusual structure and SBA can be a candidate for gate insulator dielectric for its high permittivity. The SBA thin film deposited as the gate dielectrics shows a good capacitance character on the metal–insulator–semiconductor structure in Fig. 3. Based on Eq. (1) and the following equation:

$$\frac{1}{C_{\rm MISHENT}} = \frac{1}{C_{\rm MESHEMT}} + \frac{1}{C_{\rm OX}}, \tag{2}$$

where $C_{\rm MISHEMT}$ is the gate capacitance of MISHEMT with SBA gate dielectric; $C_{\rm MESHEMT}$ is the gate capacitance of MESHEMT; $C_{\rm OX}$ is the capacitance contributed by gate dielectrics. The gate area, A, is 7700 μm^2, by which the thickness of SBA thin film can be estimated to be about 11.4 nm.

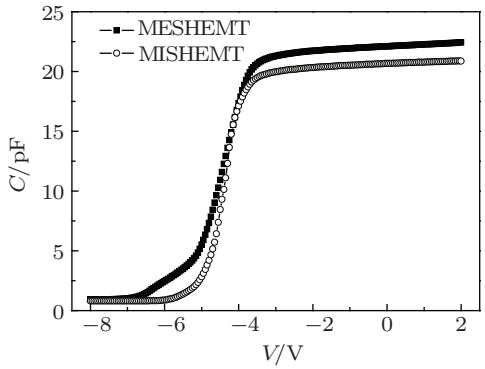


Fig. 3. Capacitance–voltage characteristics of the MESHEMT and MISHEMT.

C–V characteristics of the MISHEMT obtained at five different frequencies varying from 100 Hz to 1 MHz are shown in Fig. 4, each of which displays a weak frequency dispersion from the depletion to accumulation, and a high-quality interface between SBA and AlGaN. In addition, the capacitance is significantly dependent on the frequency at accumulation, which is attributed to the interface trap density ($D_{\rm it}$) and the fixed charge in the SBA.

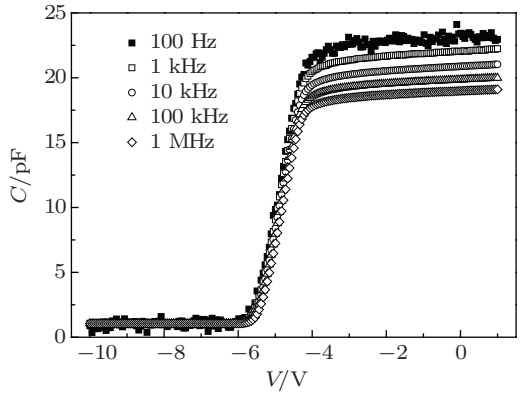


Fig. 4. Frequency-dependent C–V characteristics of the AlGaN/GaN MISHEMT.

The values of $D_{\rm it}$ of the MESHEMT and MISHEMT are calculated to be $(0.5\sim1.5)\times10^{11}$ cm$^{-2}\cdot$eV^{-1} and $(3.5\sim9.5)\times10^{10}$ cm$^{-2}\cdot$eV^{-1}, respectively, by the conductance method.[19] After +5-V gate voltage and 10-min treatment at 120 °C, the C–V characteristics of the MISHEMT are measured. The flat band voltage ($V_{\rm FB}$) shift is approximately 0.18 V, and the fixed charge density is estimated to be on the order of 2.7×10^{12} cm^{-2} for the SBA dielectric.

Compared with the AlGaN/GaN MESHEMT, the threshold voltage of AlGaN/GaN MISHEMT has a threshold voltage that usually shifts negatively. For example, the threshold voltage of AlGaN/GaN MISHEMT with Al_2O_3 gate dielectric shifts from −5.5 V to −7.5 V compared with that of the MESHEMT at $V_{\rm DS} = 10$ V as shown in Fig. 5. However, when SBA is deposited as the gate dielectric, the threshold voltage of the MISHEMT shifts positively from −5.5 V to −3.5 V at $V_{\rm DS} = 10$ V as shown in Fig. 5. We conclude that the causation for the unusual change of threshold voltage is the introduction of sodium ions. The possible reason is the influence on the surface potential after SBA has been deposited on AlGaN.

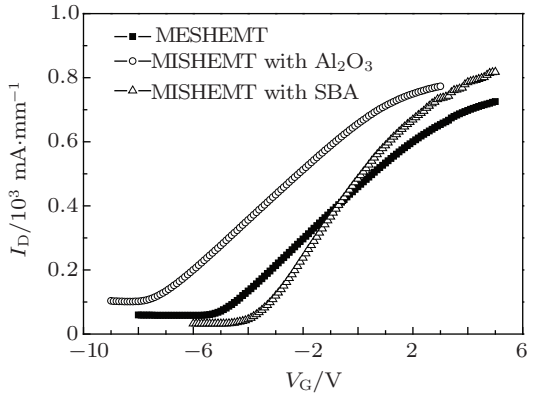


Fig. 5. Comparison of threshold voltage between MESHEMT and MISHEMT at $V_{DS} = 10$ V.

Modified from a generally used formula by taking into account the effects of charge polarization, surface and buffer traps, the threshold voltage of the undoped AlGaN/GaN devices can be expressed as[20]

$$V_{th} = \frac{\phi_B}{e} - \frac{d\sigma}{\varepsilon} - \frac{\Delta E_C}{e} + \frac{E_{f0}}{e} - \frac{e d N_{st}}{\varepsilon} - \frac{e N_b}{C_b}, \quad (3)$$

where ϕ_B is the metal–semiconductor Schottky barrier height; d is the GaN barrier-layer thickness; σ is the density of 2DEG at the barrier–AlGaN/GaN interface; ε is the dielectric constant of AlGaN; ΔE_C is the conduction-band offset at the AlGaN/GaN heterojunction; E_{f0} is the difference in energy between the intrinsic Fermi level and the conduction band edge of the GaN channel; N_{st} is the net-charged surface traps per unit area; N_b is the effective net-charged buffer traps per unit area; C_b is the effective buffer-to-channel capacitance per unit area. When SBA is deposited as the gate dielectric, the N_{st} is reduced and the sodium ions and/or the fixed charge reduce the density of 2DEG (σ), which can positively shift the threthold voltage. Additionally, the SBA also affects ϕ_B.

To further understand the effect, the XPS measurement is performed, and the obtained results are shown in Fig. 6. The VBM-E_F decreases from 2.56 eV to 2.25 eV after SBA has been deposited on AlGaN, suggesting that the surface potential has increased as the result of SBA effect. Assuming that the band gap of AlGaN does not change, the surface potential of AlGaN increases about 0.31 eV. Therefore, the result of XPS measurement displays the increase in surface potential of AlGaN/GaN heterostructure. A possible reason for this increase is that the sodium ions induce the acceptor-like stats, or eliminate the donor-like surface stats.[21] These factors could push the Fermi level closer to the valence band, which causes the 2DEG under the dielectric oxide decrease, and then the threshold voltage moves closer to zero.

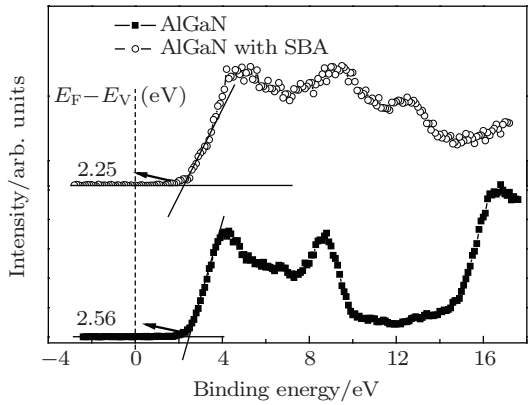


Fig. 6. Comparison of valence-band spectrum of AlGaN with and without SBA.

4. Conclusion

In this paper, we studied the sodium beta-alumina (SBA) thin films as the gate dielectric for AlGaN/GaN MISHEMT. The dielectric constant of SBA thin film is approximately 50; the interface trap density of the AlGaN/GaN MISHEMT is about $(3.5\sim9.5)\times10^{10}$ cm^{-2}eV^{-1}; and the fixed charges in SBA thin film is on the order of 2.7×10^{12} cm^{-2}. Conventionally, the threshold voltage of AlGaN/GaN MISHEMT shifts negatively compared with that of the MESHEMT. However, the threshold voltage of AlGaN/GaN MISHEMT with SBA as gate dielectric exhibits an unusual positive shift from −5.5 V to −3.5 V. The surface VBM-E_F decreases from 2.56 eV to 2.25 eV after the SBA deposition on AlGaN. The possible reasons for the positive shift of threshold voltage are the influence of SBA on the surface valence-band maximum (VBM-E_F), and effects of the reduction of interface traps and the effects of sodium ions and/or the fixed charges in SBA on the two-dimensional electron gas (2DEG).

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