Significant performance enhancement in AlGaN/GaN high electron mobility transistor by high-κ organic dielectric*

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The electrical properties of AlGaN/GaN high electron mobility transistor (HEMT) with and without high-κ organic dielectrics are investigated. The maximum drain current $I_{\mathrm{D\ max}}$ and the maximum transconductance $g_{\mathrm{m\ max}}$ of the organic dielectric/AlGaN/GaN structure can be enhanced by 74.5%, and 73.7% compared with those of the bare AlGaN/GaN HEMT, respectively. Both the threshold voltage V_{T} and $g_{\mathrm{m\ max}}$ of the dielectric/AlGaN/GaN HEMT are strongly dielectric-constant-dependent. Our results suggest that it is promising to significantly improve the performance of the AlGaN/GaN HEMT by introducing the high-κ organic dielectric.

Keywords: AlGaN/GaN high electron mobility transistor, electrical property, organic dielectric

PACC: 7340N, 7360L, 7855K, 7790

1. Introduction

GaN is a promising semiconductor electronic material for applications in high-temperature, high-speed and high-power electronics due to its fundamental physical properties such as wide band gap and high mobility.[1] Excellent device performances have been demonstrated in the AlGaN/GaN high electron mobility transistor (HEMT) devices due to the two-dimensional electron gas (2DEG) because of the larger band gap energies of GaN and AlGaN.[2] The 2DEG formed at the AlGaN/GaN interface by spontaneous and piezoelectric polarization makes this structure particularly sensitive to change in surface strain or potential.[3] Many groups tried to integrate the ferroelectric with dielectric oxide on AlGaN/GaN structure as gate insulator to increase the polarization or change the surface strain and hence to improve the device performance. However, the interface of AlGaN/GaN was easily destroyed during the fabrication process due to the high temperature and/or the high oxygen partial pressure. Stolichnov *et al.*[4] suggested that the degradation of 2DEG was presumably provoked by the interdiffusions of PZT and AlGaN in high temperature which caused the defect formation in the AlGaN/GaN interface region. The passivation effects of the inorganic dielectric such as Al_2O_3, SiO_2, Si_3N_4, and SiON on the electrical properties of the AlGaN/GaN were intensively investigated.[5−7] The maximum drain current $I_{\mathrm{D\ max}}$ and the maximum transconductance $g_{\mathrm{m\ max}}$ could be enhanced by 25%,[6] and 8%,[7] respectively. In the present study, high-κ organic solution is selected as the dielectric of the AlGaN/GaN HEMT and the effects of the organic dielectric on the electrical properties are investigated. There are two obvious advantages: i) the high-κ organic dielectrics used in this study have a dielectric constant larger than 20, which is much higher than those of conventional inorganic dielectric passivants such as Al_2O_3 ($\varepsilon \sim 9$), SiO_2 ($\varepsilon \sim 3.9$), Si_3N_4 ($\varepsilon \sim 7.5$), and SiON (ε: $3.9 \sim 7.5$); ii) the organic dielectric can be simply dipped onto AlGaN/GaN

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at room temperature, which will not damage or degrade the AlGaN/GaN because of without any high-temperature and high-oxygen-pressure processes. Our results show that after introducing high-κ organic dielectric, the maximum drain current $I_{\mathrm{D\ max}}$ (74.5%) and transconductance $g_{\mathrm{m\ max}}$(73.7%) are greatly enhanced. And both the threshold voltage V_{T} and the maximum transconductance $g_{\mathrm{m\ max}}$ are strongly dielectric-constant-dependent.

2. Experiment

The AlGaN/GaN heterostructure consists of a 2-μm thick undoped GaN layer and a 20-nm thick undoped $Al_{0.25}Ga_{0.75}N$ layer grown by the metal organic chemical vapour deposition (MOCVD). The sheet carrier concentration was $\sim 1.3\times10^{13}$ cm^{-2} with a mobility of $\sim$1100 cm^2/Vs at room temperature by hall effect measurement. The AlGaN/GaN HEMT structures were fabricated via a standard process of photolithography, metallic electrode evaporation and lift-off. The source and drain electrodes of Ti/Al/Ti/Au (30/100/30/100 nm) were deposited by electron-beam evaporation, and then annealed at 850 °C in nitrogen atmosphere in a rapid thermal annealing system. Gate electrode of Ni/Au (100/30 nm) was deposited by electron-beam evaporation.

Figures 1(a) and 1(b) show the schematic structure and the optical image of the dielectric/AlGaN/GaN HEMT, respectively. The device dimensions are $W_{\mathrm{g}} = 150$ nm, $L_{\mathrm{g}} = 3$ nm, $L_{\mathrm{sd}} = 150$ μm, and $L_{\mathrm{sg}} = 10$ μm. The bare AlGaN/GaN HEMT with using the air as the dielectric ($\varepsilon = 1$) was used as the control sample. The organic dielectric was simply dipped onto the surface of the AlGaN/GaN HEMT at room temperature. The high-κ organic solutions used here with various dielectric constants are acetone ($\varepsilon = 20.7$), ethanol ($\varepsilon = 24.5$), dimethylformamide (DMF, $\varepsilon = 36.7$), and dimethylsulfoxide (DMSO, $\varepsilon = 47$). The electrical properties of the HEMT with and without the organic dielectrics were measured at room temperature by using an Agilent 4155B parameter analyzer. The measured procedures are explained as follows: measure the electrical properties of the bare HEMT; dip the high-κ organic dielectric onto the HEMT and measure the electrical properties again; clean the surface by acetone, ethanol, D.I. water carefully, and brow by dry N_2; dip another organic dielectric and measure it again.

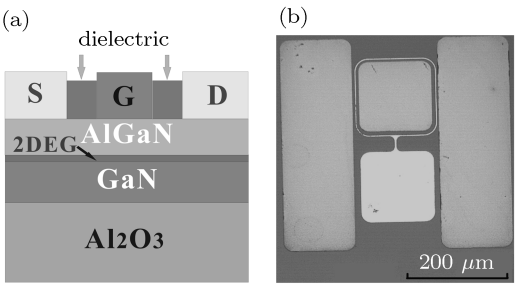


Fig. 1. Schematic structure of dielectric/AlGaN/GaN HEMT (a) and optical image of the HEMT (b).

3. Results and discussion

The I_{ds}–V_{ds} characteristics of the identical geometry AlGaN/GaN HEMTs with and without organic dielectrics were checked. As typical examples shown in Figs. 2(a) and 2(b) are the I_{ds}–V_{ds} characteristics of the bare AlGaN/GaN HEMT, and DMSO/AlGaN/GaN HEMT, respectively, where the V_{ds} varies from 0 to 20 V with V_{G} scanned from -5 V to -2 V in steps of 1 V. It is obvious that for a fixed gate voltage and V_{ds}, corresponding drain current I_{D} is significantly enhanced after introducing the DMSO dielectric. For example, the maximum drain current $I_{\mathrm{D\ max}}$ at $V_{\mathrm{g}} = -2$ V for DMSO/AlGaN/GaN HEMT (0.0825 A), is 74.5% higher than that of the bare HEMT (0.0477 A). One may doubt that the enhancement of the drain current comes from the leakage or horizontal conducting current due to the existence of the organic dielectric. In order to rule out this, we particularly measured the I–V characteristics of the organic solutions which had been dipped onto the bare insulating Al_2O_3 single crystalline substrate with the identical size of source and drain contacts. As shown in Fig. 3, the maximal current of the organic dielectric is $\sim10^{-6}$–10^{-5} A even under 20 V. One can find that $I_{\mathrm{D\ max}}$ of DMSO–HEMT at $V_{\mathrm{g}} = -2$ V (3.48×10^{-2} A), is 2964 times higher than that of the maximal current of DMSO at 20 V (1.174×10^{-5} A). One can conclude that the leakage or horizontal current originating directly from the organic dielectric can be neglected. And the enhancement should be an intrinsic feature of the dielectric/AlGaN/GaN HEMT structure itself. It should be noted that the enhancement in maximum drain current in this study is much higher than that of SiO_2 or Si_3N_4.[6,7] The enhancement mechanism will be discussed later.

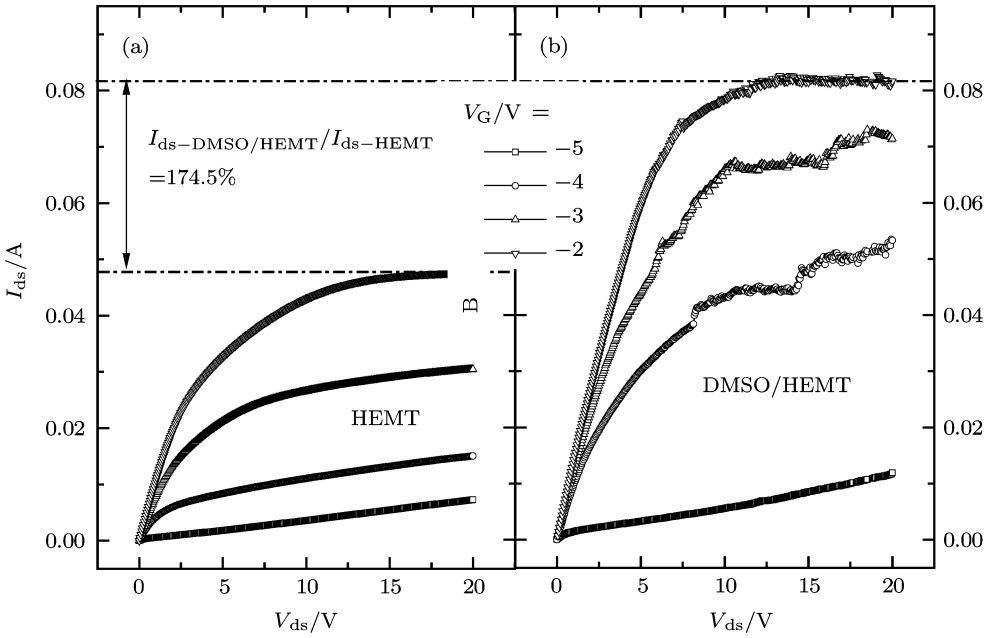


Fig. 2. I_{ds}–V_{ds} characteristics of AlGaN/GaN HEMT (a) and DMSO/AlGaN/GaN HEMT (b) with gate voltage V_g varying from –5 V∼–2 V.

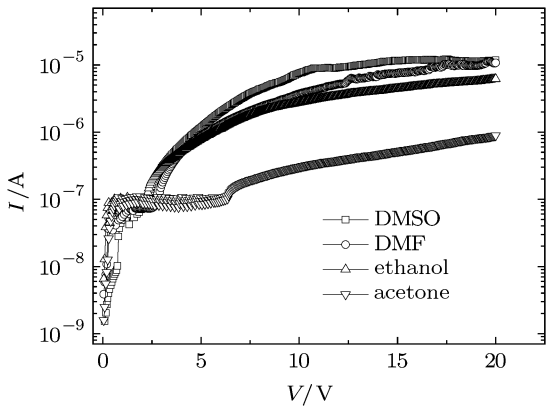


Fig. 3. *I*–*V* characteristics of organic dielectrics on bare Al_2O_3 substrate.

The transfer characteristics (I_{ds}–V_g) of the AlGaN/GaN HEMT with and without dielectrics were further investigated. Figure 4(a) shows the drain-source currents I_{ds} as a function of gate voltage V_G of the dielectric/AlGaN/GaN HEMT at a fixed V_{DS} = 10 V. It should be noted that the I_{ds} is larger than 150 mA/mm even when $V < V_T$. The imperfect quality of the gate caused by the lift-off process as shown in Fig. 1(b) should be responsible for it. We do not think that this will change the comparison results for samples with and without dielectrics. Figure 4(b) shows the dielectric constant dependence of threshold voltage V_T. It is clear that after introducing the organic dielectric, the V_T shifts toward higher voltages, which is similar to the scenarios of the passivants of SiO_2, Si_3N_4, and SiON.[6,7] Interestingly, the voltage V_T is strongly dependent on dielectric constant.

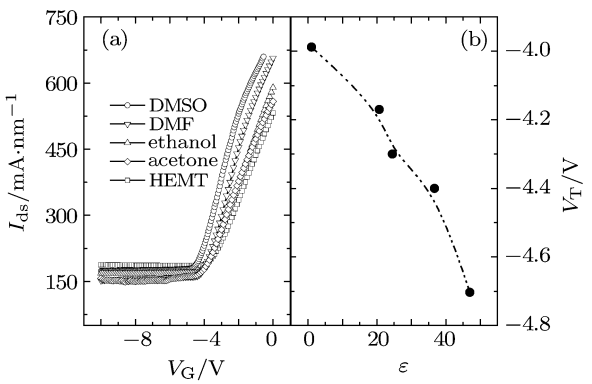


Fig. 4. The I_{ds}–V_g characteristics of the AlGaN/GaN HEMT with and without dielectric acetone, ethanol, DMF, and DMSO, under a fixed V_{ds} = 10 V (a), and the dielectric-constant dependence of the threshold voltage V_T (b).

The transconductance (g_m) can be calculated from the experimental I_{ds}–V_g characteristics. Figure 5(a) shows the transconductance g_m as a function of gate voltage for the AlGaN/GaN HEMT with and without dielectrics. The maximum transconductance $g_{m\ max}$ of the bare AlGaN/GaN HEMT is 103.87 mS/mm, and the values of correspond-

ing $g_{\mathrm{m\ max}}$ of the dielectric/AlGaN/GaN HEMT are 114.7, 115.9, 166.2, and 180.47 mS/mm for acetone, ethanol and DMF, and DMSO, respectively. It is noted that the maximum transconductance $g_{\mathrm{m\ max}}$ can be significantly enhanced (by 73.7%) after introducing the DMSO dielectric. The dielectric-constant dependence of the $g_{\mathrm{m\ max}}$ is summarized in Fig. 5(b). One can find that $g_{\mathrm{m\ max}}$ slowly increases when $\varepsilon < 25$ and sharply when $\varepsilon > 25$ and finally tends to be saturate. Although the mechanisms of the significant enhancements in $I_{\mathrm{D\ max}}$ and $g_{\mathrm{m\ max}}$ are still unclear, some possible effects are simply described as follows. Firstly, like conventional inorganic dielectric such as SiO_2, Si_3N_4, and SiON, the organic dielectric can also have a passivation effect to improve the electric property of the AlGaN/GaN HEMT. Secondly, compared with the interface of conventional oxide dielectric AlGaN/GaN, which can be damaged during its fabrication at high temperature and/or high oxygen partial pressure, the interface in our case cannot be damaged because the organic dielectric is directly dipped onto the HEMT at room temperature without any high temperature and oxidizing process. In addition, the electrical characteristics of the 2DEG channel is ultimately limited by electron–phonon scattering, including the scattering between optical and acoustic phonons and that between background and remote impurities, and also limited by alloy disorder, interface roughness and dislocations.[8] Furthermore, Jena and Konar[9] reported that the scattering from Coulombic impurities could be strongly damped and the carrier mobility could be improved by an order of magnitude through coating two- and one-dimensional semiconductor nanostructures with high-κ dielectrics. Similar dielectric-enhanced mobility was also observed in a field-effect structure with a two-dimensional graphene channel, in which the effective charged impurities, long-range scattering and other scatterings can reduce as dielectric constant increases.[10] So, we think that in this study, high-κ organic dielectric might have a similar function to reduce Coulombic-impurities scattering, long-range scattering, and other scatterings, which results in the improvement on the performance of AlGaN/GaN HEMT.

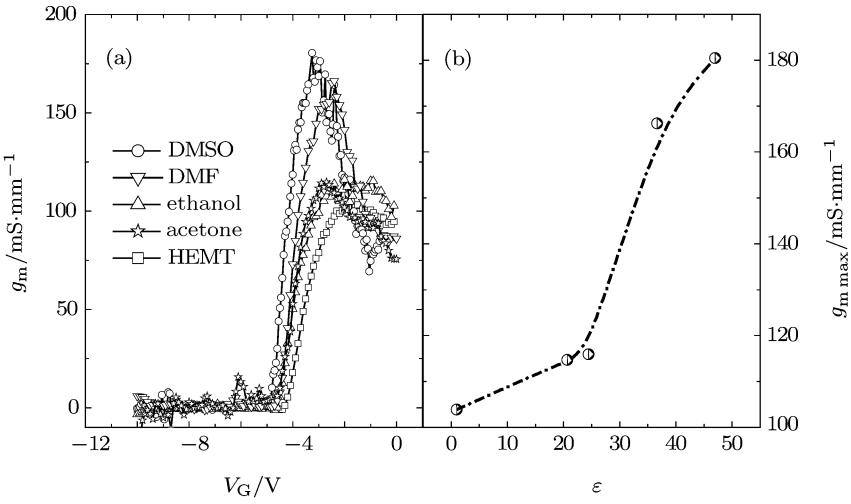


Fig. 5. Transconductance characteristics of AlGaN/GaN HEMT with and without dielectrics (a) and the dielectric constant dependence of transconductance (b).

4. Conclusion

We have characterized the electrical properties of AlGaN/GaN HEMT with and without high-κ organic dielectrics of DMSO, DMF, acetone and ethanol. $I_{\mathrm{D\ max}}$ and $g_{\mathrm{m\ max}}$ are enhanced by 74.5% and 73.7%, respectively, after introducing DMOS dielectric. Both V_{T} and $g_{\mathrm{m\ max}}$ of the HEMT are strongly dielectric-constant-dependent: V_{T} negatively shifts with dielectric constant increasing, while $g_{\mathrm{m\ max}}$ increases slowly when $\varepsilon < 25$ and sharply when $\varepsilon > 25$ and finally tends to be saturated. It suggests that it is promising to improve the performance of the AlGaN/GaN HEMT by simply introducing high-κ organic dielectric.

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