Investigation of passivation effects in AlGaN/GaN metal–insulator–semiconductor high electron-mobility transistor by gate–drain conductance dispersion study*

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(Received 4 January 2011; revised manuscript received 9 March 2011)

This paper studies the drain current collapse of AlGaN/GaN metal–insulator–semiconductor high electron-mobility transistors (MIS-HEMTs) with NbAlO dielectric by applying dual-pulsed stress to the gate and drain of the device. For NbAlO MIS-HEMT, smaller current collapse is found, especially when the gate static voltage is −8 V. Through a thorough study of the gate–drain conductance dispersion, it is found that the growth of NbAlO can reduce the trap density of the AlGaN surface. Therefore, fewer traps can be filled by gate electrons, and hence the depletion effect in the channel is suppressed effectively. It is proved that the NbAlO gate dielectric can not only decrease gate leakage current but also passivate the AlGaN surface effectively, and weaken the current collapse effect accordingly.

Keywords: metal–insulator–semiconductor high electron-mobility transistor, GaN, current collapse, passivation

PACS: 73.40.Qv, 85.30.Tv, 81.15.Gh **DOI:** 10.1088/1674-1056/20/8/087307

1. Introduction

The AlGaN/GaN metal–insulator–semiconductor high electron-mobility transistor (MIS-HEMT) has been widely used in high-power microwave devices because of the wide bandgap property of GaN.[1] However, GaN-based HEMTs still have some problems to be solved. One of the key issues is the large reverse gate leakage current under the high drain voltage, which will lead to poor reliability of the Schottky contact and limit the device performance. The majority of the gate leakage current originates from crystal dislocations in the lattice-mismatched AlGaN/GaN structure. To solve this problem, significant progress has been made on MIS-HEMTs by using various dielectrics, such as SiO_2,[2] Al_2O_3,[3,4] Si_3N_4,[5] HfO_2,[6] etc. In addition, another key issue that reduces the high frequency performance of the HEMT is current collapse, which is caused by traps in the AlGaN surface and can be passivated by some thin film. It is well known that a silicon nitride film covering the AlGaN surface could reduce the current collapse phenomenon.[7] For this reason, Si_3N_4 film has been used widely as the insulator film in the MIS structure in comparison with the SiO_2 and Al_2O_3 thin films.[5] However, the dielectric constant (ε_r) of Si_3N_4 is only 7. Thus, as the thickness of Si_3N_4 is increased to reduce the gate leakage current, the gate capacitance is lowered. Accordingly, the ability of gate-control is also reduced. Yue *et al.*[8] utilized HfO_2 ($\varepsilon_r \sim 25$) as the gate dielectric to solve this problem. However, a new problem is presented because of the low crystal temperature of HfO_2 (375 °C). This characteristic of HfO_2 not only affects the device fabrication proce-

*Project supported by the State Key Program and Major Program of the National Natural Science Foundation of China (Grant Nos. 60736033 and 60890191) and the Fundamental Research Funds for the Central Universities (Grant Nos. JY10000925002 and JY10000904009).

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dure, especially the Ohmic contact, but also decreases the temperature reliability of the device. In order to reduce the gate leakage current and prevent current collapse, an appropriate dielectric must be employed as an insulator layer and passivation layer.

In the previous work, we fabricated NbAlO/Al_2O_3 MIS-HEMTs with a gate leakage current of about three orders magnitude lower than that of HEMTs.[9] In this paper, the drain current (I_D) collapses of NbAlO MIS-HEMTs and HEMTs are studied. We reveal that the NbAlO dielectric can play a vital role in surface passivation by the characteristics of I_D collapse behaviours and gate–drain conductance curves.

2. Experimental

The AlGaN/GaN heterostructure used in this work was grown on (0001) sapphire substrate by metal–organic chemical vapour deposition (MOCVD). The intentionally undoped structure consists of a 40-nm undoped nuclear layer, a 2.38-μm undoped GaN layer, a 1.5-nm AlN insert layer, and a 22-nm $Al_{0.3}Ga_{0.7}N$ barrier layer. The room-temperature Hall mobility and sheet carrier concentration are 1544 cm^2/Vs and 1.2×10^{13} cm^{-2}, respectively. An insulator layer with 15-nm $Nb_{0.1}Al_{0.9}O$ was deposited on an AlGaN barrier layer by a F-120 atomic-layer deposited (ALD) system at 300 °C using alternating pulses of $Nb(OEt)_5$, $Al(CH_3)_3$, and H_2O as the precursors. In order to form Ohmic contact, extra etching processes to remove the NbAlO layer above the Ohmic contact areas were completed by reactive ion etch (RIE) etching. The Ohmic contacts were obtained by deposition of a Ti/Al/Ni/Au multilayer, followed by rapid thermal annealing at 870 °C for 60 s in a N_2 ambience. The gate metallization consists of the Ni/Au layer patterned by e-beam lithography. Devices with a gate length (L_g) of 0.5 μm and width (W_g) of 100 μm were fabricated. The experiments of capacitance–voltage (C–V) and pulsed I_D–V_{DS} (drain voltage relative to source) of MIS-HEMT and HEMT were performed by using an Agilent 4200 semiconductor analyser.

3. Results and discussion

The pulsed I_D–V_{DS} characteristics of NbAlO MIS-HEMT and HEMT for different gate and drain quiescent biases (V_{GS0}, V_{DS0}) of (0 V, 0 V) , (−8 V, 1 V) were measured. The pulse width is 500 ns and the pulse frequency is 1 kHz. Figure 1 shows the pulsed I_D–V_{DS} characteristics at the quiescent biases (V_{GS0}, V_{DS0}) of (0 V, 0 V) for HEMT and MIS-HEMT. In the DC performance of HEMT, due to the self-heating effect, the saturation current decreases with an increase in V_{DS}.[10] For NbAlO MIS-HEMT, there is no obvious decrease in the saturation current at V_{DS} = 10 V, indicating that the passivation of the NbAlO layer can restrain this effect. However, at the quiescent point (Q point) of (0 V, 0 V), both MIS-HEMT and HEMT represent an obvious increase in pulsed I_D. Therefore, the existence of the NbAlO layer cannot improve the I_D collapse of HEMT at the Q point. This phenomenon will be discussed and explained in detail at the end of the paper.

The pulsed I_D–V_{DS} characteristics at the Q point of (−8 V, 1 V) for HEMT and MIS-HEMT are shown in Figs. 2(a) and 2(b), respectively. From this graph, it is clear that HEMT suffers severely from collapse due to the surface related traps,[11] which is different from the I_d collapse behaviour at the Q point of (0 V, 0 V). About 58% and 15% I_D collapse suppressions in

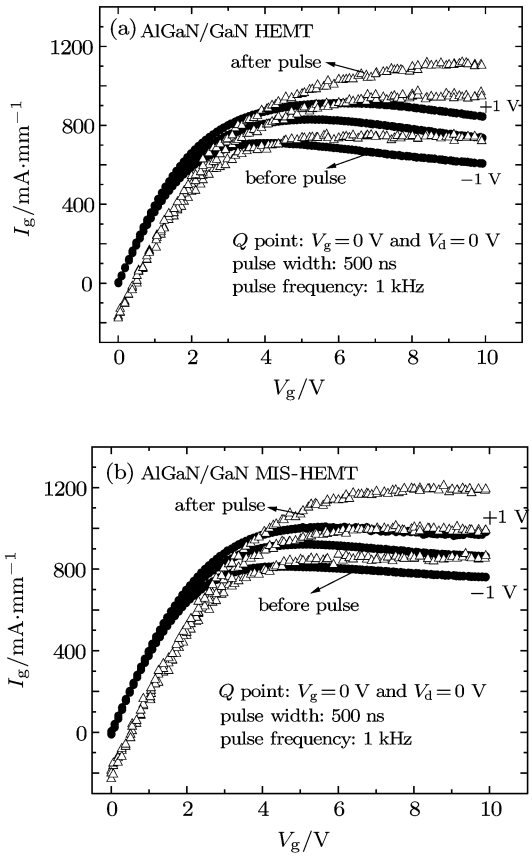


Fig. 1. DC and pulsed I_D–V_{DS} characteristics at the quiescent biases of (0 V, 0 V) for (a) HEMT and (b) MIS-HEMT. The pulse width is 500 ns with 1-kHz frequency.

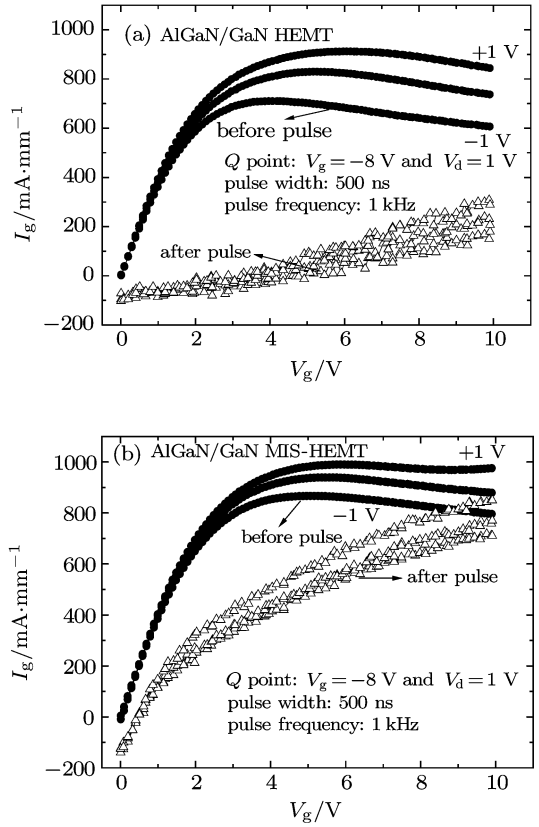


Fig. 2. DC and pulsed I_D–V_{DS} characteristics at the quiescent biases of (−6 V, 1 V) for (a) HEMT and (b) NbAlO MIS-HEMT. The pulse width is 500 ns with a 1-kHz frequency.

HEMT and MIS-HEMT were observed when the pulse with the pulse width of 500 ns was applied. In order to explain the effects of traps on current collapse, we measured the frequency-dependent capacitance and conductance of the gate–drain diode of MIS-HEMT and HEMT. A conductance model of HEMT was used, which is presented by Miller *et al.* in detail.[12] In order to eliminate the effect of traps in the channel layer, a voltage range that does not significantly deplete the GaN layer is selected (from −9.1 V to −9.3 V for MIS-HEMT and −3.8 V to −4.0 V for HEMT). The G_p/ω can be obtained from the experimental data of capacitance and conductance, with a detailed calculation in Ref. [12]. The G_p/ω of MIS-HEMT and HEMT are shown in Figs. 3 and 4, respectively. The solid lines are fitting curves. The correlation of equivalent parallel conductance G_p to frequency can be expressed as follows,[13]

$$\frac{G_p}{\omega} = \frac{qD_T}{2\omega\tau_T} \ln[1 + (\omega\tau_T)^2], \quad (1)$$

where D_T is the trap density, τ_T is the trap state time constant, and ω is the radial frequency. The D_T and τ_T can be extracted by fitting the calculation data of G_p/ω. From the fitting results of Figs. 3 and 4, D_T of $(2.2 \sim 6.2) \times 10^{12}$ cm^{-2}·eV^{-1} and τ_T of $(1.4 \sim 3.0) \times 10^{-7}$ s can be obtained for HEMT. For NbAlO MIS-HEMT, D_T is only $(1.1 \sim 2.3) \times 10^{12}$ cm^{-2}·eV^{-1} and τ_T is $(1.5 \sim 3.1) \times 10^{-7}$ s. The identical time constant τ_T for MIS-HEMT and HEMT indicates that the NbAlO dielectric layer could not change the properties of the traps but only reduce the quantity of them. In addition, the trap densities were fitted by selecting the gate voltage in the depletion region. The larger gate voltage (−3.8 V) in the depletion region can report the actual value accurately in comparison with −4.0 V. Because the trap density of the HEMT device is much greater than MIS-HEMT, the gap of the trap density between −3.8 V and −4 V is wider than that of MIS-HEMT spontaneously.

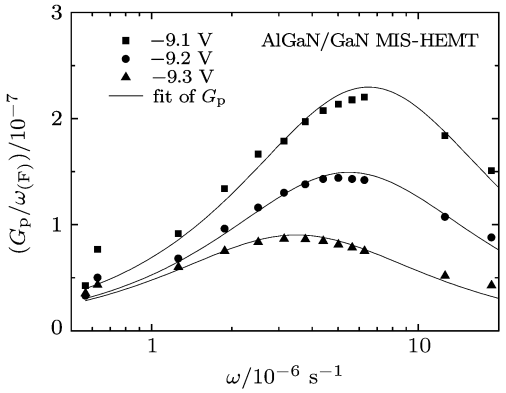


Fig. 3. Conductance versus radial frequency curves of the NbAlO MIS-HEMT for selected voltages. The solid lines are fitting curves.

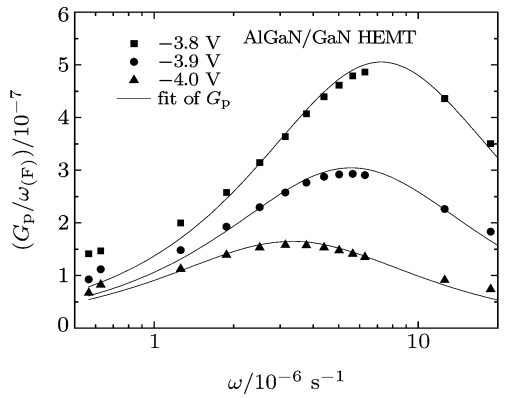


Fig. 4. Conductance versus radial frequency curves of the HEMT for selected voltages. The solid lines are fitting curves.

In the pulse model, the traps can capture electrons. The trapped electrons could deplete the channel under the gate–drain area, and thereby limit the output current.[14] From the calculation of traps, we

can conclude that at the Q point of (0 V, 0 V), the gate electrons were concentrated in the gate pole and could not fill the traps locating in the gate–drain area. Therefore, the output current of MIS-HEMT is the same as that of HEMT at the pulse model. At the Q point of (−8 V, 1 V), the gate electrons were excluded to fill the surface states distributing in the gate–drain area. Because the quantity of traps in MIS-HEMT is far less than that of HEMT, the depletion effect of NbAlO MIS-HEMT is weaker than that of HEMT. From the graph in Fig. 2, it is clear that NbAlO MIS-HEMT shows a smaller $I_{\rm D}$ collapse than HEMT. Therefore, the NbAlO dielectric can passivate the AlGaN surface effectively besides reducing the gate-leakage current effect.

4. Conclusions

The $I_{\rm D}$ collapses of NbAlO MIS-HEMT and HEMT with the AlGaN/GaN heterojunction structure are studied in this paper. At the Q point of (0 V, 0 V), both MIS-HEMT and HEMT show an identical $I_{\rm D}$ collapse. However, the MIS-HEMT shows a smaller $I_{\rm D}$ collapse (15%) than HEMT (58%) while applying the Q point of (−8 V, 1 V). The capacitance and conductance measurements show that the trap density $D_{\rm T}$ of MIS-HEMT is smaller than that of HEMT. However, the trap state time constants $\tau_{\rm T}$ for both of them are the same. It is the passivation effect of the NbAlO dielectric that reduces the current collapse for HEMT. It can be concluded that the NbAlO is a very promising candidate as a gate dielectric because of its dual advantages, i.e. surface passivant and insulator layer.

Acknowledgement

The authors would like to acknowledge Sun Qing-Qing (Fudan University) for kind assistance with the ALD NbAlO dielectric.

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