Normally Off AlGaN/GaN MIS-High Electron Mobility Transistors Fabricated by Using Low Pressure Chemical Vapor Deposition Si$_3$N$_4$ Gate Dielectric and Standard Ion Implantation

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Abstract—This paper presents a fabrication technology of enhancement-mode (E-mode) AlGaN/GaN metal insulator semiconductor high electron mobility transistors (MIS-HEMTs) using 10 keV fluorine ion implantation. An 8 nm low pressure chemical vapor deposition (LPCVD) silicon nitride layer was deposited on the AlGaN as gate dielectric and energy-absorbing layer that slows down the high energy (10 keV) fluorine ions to reduce the implantation damage. The E-mode MIS-HEMTs exhibit a threshold voltage as high as 3.3 V with a maximum drain current of 200 mA/mm (250 mA/mm for depletion-mode (D-mode) MIS-HEMTs) and a high on/off current ratio of $10^5$. Meanwhile, the E-mode MIS-HEMTs dynamic $R_{ON}$ is only 1.53 times than the static $R_{ON}$ after off-state $V_{DS}$ stress of 500 V.

Index Terms—AlGaN/GaN high electron mobility transistor (HEMT), standard fluorine ion implantation, normally off.

I. INTRODUCTION

AlGaN/GaN HEMTs have successfully demonstrated promising potential in high frequency and power electronics applications [1]. Due to the strong spontaneous and piezoelectric polarization effect, conventional AlGaN/GaN HEMTs are intrinsically normally-on devices. However, normally-off operation is necessary when gallium nitride-based power transistors are targeting at high-voltage power switching applications because of the fail-safe requirement in a power conversion system [2]. Various techniques have been proposed to realize the normally-off operation of GaN-based HEMTs, such as gate recess [3, 4], fluorine plasma treatment [5], p-type III–nitride gate engineering [6, 7]. Among all methods to achieve E-mode HEMTs, traditional fluorine plasma treatment is a robust process that enables the channel threshold voltage modulation. However, it is very difficult to control the threshold voltage exactly because of no standard equipment for this process and the etching effect of fluorine plasma on barrier AlGaN layer [8]. Ion implantation technology is very mature in semiconductor device fabrication with well-controlled dose and precise doping profile. Hongwei Chen et al [9], demonstrated an E-mode HEMT using standard ion implantation equipment with a thicker Si$_3$N$_4$ (80 nm) energy absorbing layer. However, the Si$_3$N$_4$ must be removed after ion implantation and thus complicates the device fabrication process. In addition, the E-mode HEMT has small threshold voltages and small gate swings that are limited by the Schottky-gate forward turn-on voltages. MIS-HEMTs [10-12] are highly preferred over the Schottky-gate’s HEMTs for high-voltage power switches, owing to the suppressed gate leakage and the enlarged gate swing. Compared with other SiN$_x$ deposition methods (i.e. plasma enhanced chemical vapor deposition, inductively coupled plasma chemical vapor deposition), LPCVD deposited Si$_3$N$_4$ is free of plasma-induced damage, has higher film quality and higher thermal stability due to higher deposition temperature [13]. These characteristics offer a great potential of LPCVD Si$_3$N$_4$ as gate insulator for GaN MIS-HEMTs.

In this work, we demonstrate a fabrication process of E-mode AlGaN/GaN MIS-HEMTs using standard ion implantation equipment and present detailed device characteristics. An 8 nm silicon nitride layer was deposited on the AlGaN barrier layer as the gate dielectric and energy-absorbing layer, thus simplifies the device fabrication process and reduces fabrication cost. The fabricated normally-off MIS-HEMTs exhibit a threshold voltage as high as 3.3 V, a high on/off current ratio ($\sim 10^5$) and are well pinched off at zero gate bias. Besides, the dynamic on-resistance $R_{ON}$ is only 1.53 times than the static $R_{ON}$ after OFF-state $V_{DS}$ stress of 500 V.

II. DEVICE FABRICATION

AlGaN/GaN heterostructure epitaxy materials were grown by metal organic chemical vapor deposition (MOCVD) on a 2-inch Si (111) substrate. They included from bottom to top a
Device characterization was carried out on devices with \( L_{GS} = 4 \, \mu m, W/G/L_G = 100 \, \mu m/4 \, \mu m, L_{GD} = 15 \, \mu m \) and the fluorine ion implantation window \( (W/L) \) \( f \) window = 100 \( \mu m/2 \) \( \mu m \). Fig. 2 shows typical DC transfer curves. The threshold voltages \( V_{th} \), determined by the linear extrapolation method are \(-4.4 \) \( V \) and \(+3.3 \) \( V \) for the D-mode MIS-HEMTs and E-mode MIS-HEMTs, respectively. The maximum drain current \( I_{DS} \) (max) of the E-mode MIS-HEMTs are about 211 mA/mm at \( V_{GS} = 9 \) \( V \) and D-mode MIS-HEMTs are about 254 mA/mm at \( V_{GS} = 9 \) \( V \). Hysteresis of \( V_{th} \) of the devices between the forward and reverse \( V_{GS} \) sweep from \(-8 \) to \( 9 \) \( V \) and then back to \(-8 \) \( V \) is also evaluated. The hysteresis of \( V_{th} \) is 0.3 \( V \) between the forward and reverse gate bias sweep extracted by CV measurement for D-mode and E-mode MIS-HEMTs (not shown), which is most likely caused by acceptor-like states in the Si\_3N\_4/GaN interface.

The density of traps \( (D_{tr}) \) could be estimated by using equation of \( D_{tr} = C_{MIS} \cdot \Delta V_{GS} / e \) to be \( 4.1 \times 10^{11} \, \text{cm}^{-2} \) (where \( C_{MIS} = (C_{SN} \cdot C_{AlGaN}) / C_{SN} + C_{AlGaN} = 0.22 \, \mu F/cm^2 \)).

Fig. 2(b) presents the transfer curves of the devices in semi-log scale together with the gate leakage current \( (I_G) \). It can be observed that the off-state drain current \( (I_{off}) \) is \(~10^{-7} \) mA/mm, leading to an excellent on/off current ratio of \(~10^9\). Besides, the E-mode MIS-HEMTs are well pinched off at zero gate bias. The forward \( I_{th} \) are \( 10^{-3} \) mA/mm for E-mode MIS-HEMTs and \( 10^{-7} \) mA/mm for D-mode MIS-HEMTs at \( V_{GS} \) of 9\( V \), respectively. The higher \( I_{th} \) of E-mode MIS-HEMTs could be attributed to the implantation induced damages, which could be improved by some techniques, such as post gate annealing optimization or lower energy implantation.

The output characteristics of the Si\_3N\_4/AlGaN/GaN/Si MIS-HEMTs are shown in Fig. 3. For the E-mode MIS-HEMTs, \( V_{GS} \) vary from 0 to 9 \( V \) with step of 1 \( V \). The static \( R_{ON} \) is \( 17.2 \, \Omega \) mm at \( V_{GS} = 9 \, V \). For comparison, the D-mode MIS-HEMTs \( V_{GS} \) vary from -5 to 1 \( V \) with steps of 1 \( V \). The static on-resistance is 14.9 \( \Omega \) mm at \( V_{GS} = 1 \, V \). A moderate increase of \(~15 \%\) for E-mode MIS-HEMTs’ static \( R_{ON} \) than that of D-mode MIS-HEMTs is mainly due to mobility decrease after fluorine ion implantation. The off state breakdown voltage at room temperature is about 573 \( V \) at \( V_{GS} = 0 \, V \) for the E-mode MIS-HEMTs with substrate floating, showing almost no degradation compared with that observed in the D-mode MIS-HEMTs (for D-mode MIS-HEMTs, the off-state drain breakdown voltage at \( V_{GS} = -5 \, V \) is 575 \( V \) at \( I_{DS} = 1 \, mA/mm \) with substrate floating).
Fig. 3. (a) E-mode MIS-HEMTs output curves with $V_{GS}$ varying between 0 V and 9 V with step of 1 V and (b) D-mode MIS-HEMTs output curves with $V_{GS}$ varying from -5 V to 1 V with step of 1 V.

Fig. 4 (a) shows the linear and logarithmic (inset) $I_{DS}$-$V_{GS}$ of MIS-HEMTs with fluorine ion implantation dose from $1.3 \times 10^{13}$ cm$^{-2}$ to $2.7 \times 10^{13}$ cm$^{-2}$ and the implantation energy is 10 keV for all devices. It should be noted that the $I_{DS}$ degradation in fluorine ion implantation MIS-HEMTs results from mobility drop. The effective mobility ($V_{GS}=8$ V) for implantation dose $1.3 \times 10^{13}$ cm$^{-2}$, $2 \times 10^{13}$ cm$^{-2}$ and $2.7 \times 10^{13}$ cm$^{-2}$ are 239 cm$^2$/V·s, 136 cm$^2$/V·s and 74 cm$^2$/V·s, respectively (526 cm$^2$/V·s) for D-mode MIS-HEMTs. Meanwhile, the $V_{GS}$ at minimum drain current point of $I_{D}(\text{min})$=0.1 nA/mm and $V_{th}$ move toward positive values with the increase of ion implantation dose, showing a linear relationship with fluorine ion implantation dose (Fig. 4 (b)). Therefore, we are able to control the threshold voltage exactly by implantation dose.

For low-speed high-voltage switching measurement, the ON-state $R_{ON}$ is determined to be the reciprocal of the slope of the fitted line. First, it is necessary to set two programs to measure the dynamic $R_{ON}$ after different stress, “dynamic $R_{ON}$ measured” and “high off state stress”. In “dynamic $R_{ON}$ measured”, the $V_{DS}$ varies from 0 to 0.8 V with step of 160 mV at $V_{GS}$=8 V and various $V_{DS}$ is applied at $V_{GS}$=0 V in “high off state stress”, respectively. Second, when the program “high off state stress” is complete, the program “dynamic $R_{ON}$ measured” execute automatically, the time interval of two programs is 1.5 s. So the off-to-on switching time interval is determined to be ~1.5 s. As shown in Fig. 5(b), the dynamic $R_{ON}$ increases with higher $V_{GS}$ stress due to enhanced electron trapping at LPCVD Si$_3$N$_4$/barrier interface states and/or bulk traps in the barrier and buffer layers[14]. However, dynamic $R_{ON}$ is only 1.53 times than the static $R_{ON}$ at OFF-state $V_{DS}$ stress of 500 V, suggesting that the effective current collapse suppression is achieved by LPCVD Si$_3$N$_4$ passivation layer and gate insulator.

IV. CONCLUSION

We demonstrated a fabrication technology for E-mode AlGaN/GaN MIS-HEMTs using standard fluorine ion implantation. An 8 nm silicon nitride layer was deposited on the AlGaN as a gate dielectric and energy-absorbing layer that slows down the high energy (10 keV) fluorine ions to reduce the implantation damage. The threshold voltage of MIS-HEMTs shifted from -4.4 to 3.3 V, converting D-mode MIS-HEMTs to E-mode ones. The fabrication process also allows the monolithic integration of E/D-mode HEMTs for high performance digital/analog integrated circuits and potential of industrial production.

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REFERENCES


