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Demonstration of Enhancement-mode Operation in AlGaN/GaN MOS-HEMT on Si by utilizing ALD Al_2O_3 layer

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Abstract

In this work, we report on the Enhancement-mode operation of AlGaN/GaN MOS-HEMT by utilizing the presence of negative charges in atomic layer deposited (ALD) Al_2O_3 layer.

1. Introduction

AlGaN/GaN high-electron-mobility transistors (HEMTs) on Si have recently evolved as an excellent candidates for high-power applications due to the improvements in the epitaxial growth of GaN on Si [1], [2]. As an outcome, AlGaN/GaN depletion-mode (D-mode) HEMTs have been successfully demonstrated on large size Si wafer scaled upto 8-inches [3]. However, for high-speed power switching applications, enhancement-mode (E-mode) AlGaN/GaN based devices on Si are highly desired, as they are cost effective and can greatly improve circuit design, safety, as well as reliability issues. Realizing such positive threshold voltage (V_{th}) along with high drain current density (I_{dsmax}) and improved breakdown voltage are essential to promote AlGaN/GaN based E-mode devices.

2. Device design and fabrication

The schematic cross-sectional view of fabricated Al_2O_3/AlGaN/GaN MOS-HEMT is shown in Fig. 1. The AlGaN/GaN HEMT heterostructures used to fabricate MOS-HEMTs was grown on a 4-inch p-type Si (111) substrate by Taiyo Nippon Sanso (SR 4000) metal-organic chemical vapor deposition (MOCVD) system. The HEMT structure consists of 4 μm buffer, 1 μm GaN channel, 1 nm AlN spacer and 25 nm AlGaN barrier layer with an Al concentration of 26 %. The measured Hall mobility and sheet carrier density of the AlGaN/GaN heterostructures were 1250 $cm^2V^{-1}s^{-1}$ and of 1 x 10^{13} cm^{-2} respectively.

The device fabrication started with mesa isolation by using BCl_3 plasma based reactive ion etching (RIE). Source and drain ohmic electrodes were formed by annealing the alloy metals (Ti/Al/Ni/Au: 15/72/12/40 nm) at 850 °C for 30 sec at N_2 ambient. A 10 nm Al_2O_3 layer was deposited by using Cambridge Nanotech ALD system. Prior to the oxide layer deposition the AlGaN surface was cleaned by HCl solution. The Al_2O_3 layer was then deposited at 300 °C by using tri-methyl aluminum (TMA), H_2O vapor and O_3 in as precursor sources in alternate pulses. The main effect of the O_3 and H_2O vapor pulsing sequence is to reduce the hydroxyl and carbon content and to minimize the leakage current. The gate and contact metals (Pd/Ti/Au: 40/20/80 nm) was deposited on the Al_2O_3 layer. Finally, the oxide layer in the source/drain electrodes were etched by a buffer based oxide etchant. A standard Schottky gate AlGaN/GaN HEMT was processed simultaneously for comparison. The I_{ds}-V_{ds} and transfer characterisistics of the devices were measured using 4156 C semiconductor parameter analyzer and the three terminal *off-state* breakdown voltage (3*TBV*) were measured using Kiethley pico-ammeters interfaced to a probe station and a computer.

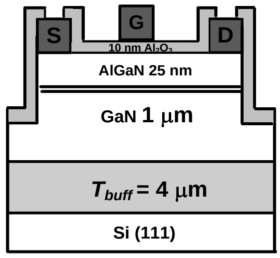

Fig.1. Schematic cross section of fabricated E-mode Al_2O_3/AlGaN/GaN MOS-HEMT on Si.

3. Results and Discussion

Typical *C-V* and I_g-V_g characteristics of the Al_2O_3/AlGaN/GaN MOS-diode is shown in Fig. 2 (a) and (b) respectively. Initially, the MOS-diode exhibited D-mode operation with V_{th} of -3.7 V and a steep transition from depletion to accumulation region. This V_{th} value is consistent with the estimated theoretical value of $V_{th\text{-}MOS}=V_{HEMT}$ $(1+C_{HEMT}/C_{oxide})$ relative to the HEMT. The values of V_{HEMT} C_{HEMT} and C_{oxide} are -2.3 V, 241and 383 nF/cm^2 respectively. On applying a positive gate bias of + 6 V the MOS-diode showed E-mode behavior with V_{th} of + 1.2 V. This positive flat band voltage shift above the ideal V_{th} value indicates the negative charge densities approaching ~10^{13} cm^{-2} are present in the oxide layer or the oxide/AlGaN interface [4].

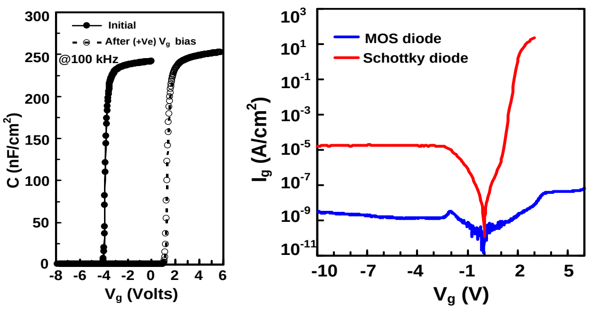

Fig. 2. (a) Typical *C-V* charactersistics of Al_2O_3/AlGaN/GaN MOS-diode before and after positive V_g biasing. (b) Gate leakage charactersistics of Schottky and Al_2O_3/AlGaN/GaN MOS-diodes.

The ALD Al_2O_3 layer effectively reduces the I_g by four orders of magnitude at reverse bias and I_g remains as low as pA at forward bias of + 6 V.

The transfer characteristics of Al_2O_3/AlGaN/GaN MOS-HEMT before and after applying positive bias at the gate terminal are shown in Fig. 3. Before applying a positive bias, MOS-HEMTs exhibited a V_{th} of -3.7 V with an I_{dsmax} and g_{mmax} values of 650 mA/mm and 140 mS/mm respectively. On applying a V_g of + 6 V for a period of 1 sec, the MOS-HEMTs exhibited E-mode characteristics with a V_{th} of + 1.2 V. Thus, a threshold voltage shift (ΔV_{th}) of nearly 4.9 V between the (E and D)-mode operation validates the presence of negative charges in the ALD Al_2O_3 layer or at the Al_2O_3/AlGaN interface. Recently, the existence of such negative charges and corresponding threshold voltage shift was also observed in the case of ALD SiO_2 based MOS-HEMT [5]. An I_{dsmax} of 563 mA/mm and negligible change in g_{mmax} was observed for E-mode MOS-HEMT.

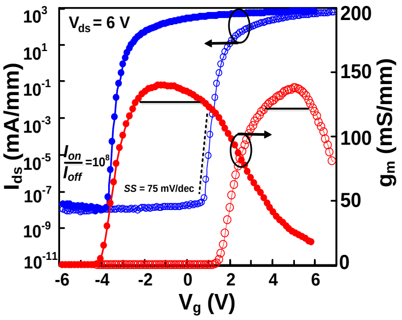

Fig. 3. Transfer charactersistics of Al_2O_3/AlGaN/GaN MOS-HEMT before and after V_g biasing of + 6 V.

Retention measurements of V_{th} for these Al_2O_3/AlGaN/GaN based E-mode MOS-HEMTs were performed at various programmed time intervals at room temperature as shown in Fig. 4. The positive V_{th} was stable over a retention period ≥ 10^5 sec indicating no charge loss occurs once the device has been charged due to negative charges in the oxide and exhibit E-mode operation. The trapped charges were neither emitted by applying a negative stress of -8 V at the gate. In addition, the retention characteristics of V_{th} performed as a function of temperature is also shown in Fig. 4. On increasing the temperature gradually from room temperature to higher temperatures the device continued to exhibit E-mode operation, although a slight V_{th} shift of 0.2 V was observed. However, this value corresponds to 4 % when compared to the initial ΔV_{th} shift of 4.9 V from D-mode to E-mode due to charging effects. This indicates that the negative charges acts like fixed charges. Apparently, the presence of such fixed negative charges are known to exist in ALD grown Al_2O_3 layer that can enhance the shift of threshold voltage in GaN based MOS-HFETs towards the positive voltages for realization of normally-off transistors [7]. The thermal stability of V_{th} in these devices can be further improved by optimizing the ALD oxide deposition and/or post deposition conditions. Furthermore, a high *off-state* breakdown voltage of 532 V at a V_g of 0 V, exhibited the highest power device *figure-of-merit* of 4.0 x 10^8 $V^2\Omega\cdot cm^{-2}$ for this device ($W_g/L_g/L_{gd}$ =15/1.5/4 μm).

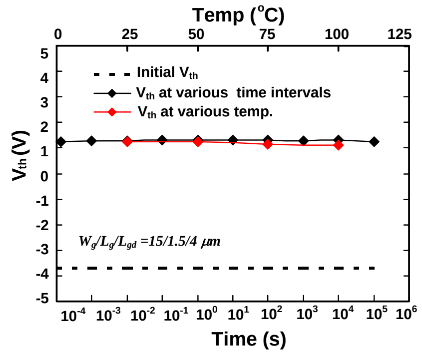

Fig. 4. V_{th} retention characteristics of Al_2O_3/AlGaN/GaN E-mode MOS-HEMT as a function of elapsed time and temperature respectively.

4. Conclusions

We have demonstrated E-mode Al_2O_3/AlGaN/GaN MOS-HEMTs on Si substrates by ALD deposited Al_2O_3 layer. E-mode operation is due to the presence of negative charges in ALD Al_2O_3 layer . The MOS-HEMTs exhibited a threshold voltage of + 1.2 V and drain current density 563 mA/mm that accompanied a low specific on-state resistane of 0.7 $m\Omega\cdot cm^{-2}$. The MOS-HEMTs effectively reduced the gate leakage current, thereby improving *off-state* breakdown voltage. Furthermore, a high breakdown voltage of 532 V for AlGaN/GaN E-mode MOS-HEMT ($W_g/L_g/L_{gd}$ =15/1.5/4 μm) exhbited the highest power device *figure-of-merit* of 4.0 x 10^8 $V^2\Omega\cdot cm^{-2}$. The retention characteristics and thermal stability of V_{th} in these devices suggets potential future application. The ALD Al_2O_3/AlGaN/GaN based E-mode MOS-HEMTs should be further explored and are attractive for high-power applications.

Acknowledgements

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