AlGaN/GaN High Electron Mobility Transistors Employing Multiple Al$_2$O$_3$/Ga$_2$O$_3$ stacks

Ogyun Seok$^{1)}$, Woojin Ahn$^{1)}$, Young-Shil Kim$^{1)}$, Min-Woo Ha$^{2)}$, and Min-Koo Han$^{1)}$

$^{1)}$Department of Electrical Engineering, Seoul National University, Seoul 151-744, Korea
$^{2)}$Korea Electronics Technology Institute, Seongnam, Gyeonggi-do 463-816, Korea

E mail: mkh@snu.ac.kr, Phone: +82-2-880-7254, Fax: +82-2-875-7254

Keywords: GaN, HEMT, Sputter, Al$_2$O$_3$, Ga$_2$O$_3$, stack

Abstract

We have proposed and fabricated AlGaN/GaN HEMTs employing a new structure of multiple Al$_2$O$_3$/Ga$_2$O$_3$ stacks under gate metal in order to increase of the breakdown voltage and shift $V_{TH}$ in positive direction. 10 nm thick rf-sputtered Al$_2$O$_3$/Ga$_2$O$_3$ stacks, which consist of 2 nm thick Al$_2$O$_3$ and Ga$_2$O$_3$, induce electrons and holes accumulation during the switching operation of AlGaN/GaN HEMTs. The proposed device shows a high breakdown voltage of 1100 V and drain leakage current of 33 nA/mm at $V_{GS}$ of -10 V and $V_{DS}$ of 100 V while those of the conventional device are 380 V and 654 $\mu$A/mm respectively. The $V_{TH}$ of the proposed device employing the multiple Al$_2$O$_3$/Ga$_2$O$_3$ stacks is -1.4 V while that of the conventional device is -2 V due to the electrons accumulation in the multiple Al$_2$O$_3$/Ga$_2$O$_3$ stacks.

INTRODUCTION

AlGaN/GaN HEMTs have a considerable attention for high power applications due to wide bandgap properties such as a high critical electric field and a low intrinsic carrier concentration [1]. Also they exhibit a very low on-resistance and a fast switching speed due to the 2DEG induced by discontinuity of conduction band in the AlGaN/GaN heterostructure and its piezoelectric polarization [2].

However, the soft breakdown characteristics of the AlGaN/GaN HEMTs should be investigated for reduction of off-state power loss and stable blocking operation besides. It has been reported that the leakage current of AlGaN/GaN HEMT is attributed to surface traps, defects, and dislocations which is formed by the lattice mismatch between GaN and substrate [3].

Various surface passivations such as SiO$_2$, SiNx, MgO, Al$_2$O$_3$ and AlN have been reported in order to suppress the surface related problems and improve reverse blocking characteristics of AlGaN/GaN HEMTs [4-8]. The edge termination structure such as filed plate, floating metal and formation of LDD region using fluorine treatment are also reported for suppression of electron trapping from gate into the surface states by reducing electric field at drain-side gate edge and increase of breakdown voltage [9-11].

It is important to study an electron trapping mechanism through surface traps for investigation of the reverse blocking operation of the AlGaN/GaN HEMTs. Electron trapping through shallow traps would induce surface leakage current. It is well known that shallow trap is originated from the unintentionally formed N vacancies due to dislocations, plasma and thermal damage during the process. An electron trapping through deep traps suppresses the leakage current due to a low probability of electron de-trapping from traps site into conduction band. However, an electron trapping through deep traps causes a transient delay which is called current collapse [12].

We reported a low drain leakage current of 20 nA/mm and a high breakdown voltage of 1140 V by employing O$_2$ annealing on AlGaN/GaN HEMTs on SiC substrate [13]. Electron trapping through the deep trap site such as Ga vacancies which are generated by O$_2$ annealing suppresses the surface leakage current.

The purpose of our paper is to propose the AlGaN/GaN HEMTs employing a new structure of the multiple Al$_2$O$_3$/Ga$_2$O$_3$ stacks under the gate in order to increase the breakdown voltage and shift $V_{TH}$ in positive direction. The devices were fabricated by using AlGaN/GaN heterostructure (1.7 $\mu$m thick GaN buffer) on Si substrate. Al$_2$O$_3$ and Ga$_2$O$_3$ layer were deposited by rf-sputtering at room temperature. Ga$_2$O$_3$ layer which is sandwiched by Al$_2$O$_3$ acts as charge accumulation center due to the unintentionally formed Ga vacancies. The accumulated electrons when $V_{GS} < V_{TH}$ deplete the electrons in bulk and 2DEG so that breakdown voltage and $V_{TH}$ are increased. The proposed device employing multiple Al$_2$O$_3$/Ga$_2$O$_3$ stacks shows a high breakdown voltage of 1100 V and a low drain leakage current of 33 nA/mm with a large hysteresis while AlGaN/GaN HEMT employing Al$_2$O$_3$ only shows 1050 V and 1.8 $\mu$A/mm with a small hysteresis. It means that a large hysteresis and suppression of leakage current are originated from charge accumulation in Ga$_2$O$_3$ layer.
DEVICE STRUCTURE AND FABRICATION

The systematic of cross-sectional view of the proposed device is shown in Fig. 1. Transition layer, 1.7 μm thick UID GaN buffer layer, 20 nm thick UID Al0.25Ga0.75N barrier layer, and 4 nm thick UID GaN capping layer are grown on Si substrate in sequence by MOCVD. The mesa isolation was performed by BCl3 and Cl2 based ICP-RIE in order to define active region. Ohmic metal, Ti/Al/Ni/Au (20/80/20/100 nm), was formed by lift-off and it was annealed at 880 °C for 40 sec under N2 ambient. Prior to sputtering of the multiple Al2O3/Ga2O3 stacks, 30:1 BOE cleaning was performed to remove native Ga2O3. 10 nm thick-multiple Al2O3/Ga2O3 stacks (consisting of 5 layers) was sputtered at room temperature at 50 W under Ar ambient. The stacks were sputtered at a low power of 50 W for a low sputtering damage on AlGaN/GaN HEMTs. Finally, Schottky contact, Ni/Au (30/150 nm), was formed by lift-off. We also fabricated the conventional HEMT and one employing 10 nm thick Al2O3 only for comparison. The device width, gate length, gate-drain distance were 50, 3, and 20 μm respectively.

EXPERIMENTAL RESULTS

Fig. 2 shows the drain leakage current of the fabricated devices. The drain leakage (VGS = -10 V, VDS = 100 V) of the AlGaN/GaN HEMT employing the multiple Al2O3/Ga2O3 stacks, the HEMT employing Al2O3 only, and the conventional one are 33 nA/mm, 1.8 μA/mm, and 654 μA/mm respectively. It is well known that electron trapping through shallow traps at the surface is dominant mechanism of leakage current in AlGaN/GaN HEMTs. The conventional device shows a relatively high leakage current due to the considerable amount of surface traps. Decrease of the leakage current for the device employing Al2O3 only indicates that sputtered Al2O3 passivates the surface of GaN cap layer so that electron trapping through surface states is suppressed. For the device employing the multiple Al2O3/Ga2O3 stacks, the injected electrons in Ga2O3 layer deplete the electrons in bulk and 2DEG so that electron trapping is rather suppressed.

Fig. 3 shows 2 terminal breakdown voltages of the fabricated devices. The conventional device shows a soft breakdown characteristics due to a relatively high drain-gate surface leakage current. The breakdown voltage of the proposed device employing the multiple Al2O3/Ga2O3 stacks is 1100 V while that of the conventional device and one employing Al2O3 only are 380 V and 1050 V respectively. The breakdown voltage is determined by the leakage current of 1 mA/mm. The accumulated electrons in Ga2O3 sandwiched by Al2O3 extend the depletion region so that the AlGaN/GaN HEMT employing the multiple Al2O3/Ga2O3 stacks shows a less leakage current than that of the device employing Al2O3 only. A small breakdown voltage increment of the device employing the multiple Al2O3/Ga2O3 stacks compare to the device employing Al2O3 only is attributed to the Si substrate breakdown.
Our experimental results show that breakdown voltage of the AlGaN/GaN HEMTs with longer gate-drain distance than 20 μm is limited to 1100 V.

Output characteristics (Figure 4) are measured with sweeping $V_{GS}$ from 2 V to -4 V at -2 V increment. The AlGaN/GaN HEMT employing the multiple Al$_2$O$_3$/Ga$_2$O$_3$ stacks shows the increased drain current. Drain current of the AlGaN/GaN HEMT employing the multiple stacks, Al$_2$O$_3$ only, and the conventional device when $V_{GS}$: 2V and $V_{DS}$: 20 V are 305 mA/mm, 221 mA/mm, and 224 mA/mm respectively. It is due to the injected holes in Ga$_2$O$_3$ layer of the device employing the multiple Al$_2$O$_3$/Ga$_2$O$_3$ stacks at forward bias accumulate more electrons in quantum well of 2DEG than conventional Ni/GaN Schottky contact. However, the charging and de-charging process of electron/hole from gate into Ga$_2$O$_3$ layer causes the increase of on-resistance.

Fig. 5 shows the transfer curve of the fabricated devices. The $V_{TH}$ of the AlGaN/GaN HEMT employing Al$_2$O$_3$ only is shifted from -2 V to -2.2 V (determined by the 1 mA/mm) by longer distance from gate to 2DEG than that of the conventional device while the $V_{TH}$ of the AlGaN/GaN HEMT employing Al$_2$O$_3$/Ga$_2$O$_3$ stacks is -1.4 V. It indicates that the electron accumulation at reverse bias under gate extends the depletion region in vertical direction.

Charge accumulation of the proposed devices is investigated by capacitance-voltage measurement in Fig. 6, 7. The capacitance between gate and drain is measured in double direction with frequency of 1 MHz. The large capacitance of the AlGaN/GaN HEMT employing Al$_2$O$_3$ only is attributed to the MIS structure. Charge accumulation in Ga$_2$O$_3$ of the device employing the multiple Al$_2$O$_3$/Ga$_2$O$_3$ stacks also induces increase of maximum capacitance. This maximum capacitance agrees well with the increase of drain current shown in Fig. 4. The AlGaN/GaN HEMT employing Al$_2$O$_3$/Ga$_2$O$_3$ stacks show a large hysteresis. The large hysteresis induces the positive shift of $V_{TH}$, suppression of leakage current, and increase of output current.

A small hysteresis of the device employing Al$_2$O$_3$ only indicates that the hysteresis of the device employing the multiple Al$_2$O$_3$/Ga$_2$O$_3$ stack is not attributed to Al$_2$O$_3$/GaN interface and that originated from charge accumulation in Ga$_2$O$_3$ sandwiched by Al$_2$O$_3$.

Fig. 8 shows the conductance modulation with gate-drain voltage sweep and frequency of 1 MHz. The AlGaN/GaN HEMT employing the multiple Al$_2$O$_3$/Ga$_2$O$_3$ stack has a
clearly separated two peak with high peak value. It indicates that the both of on-state and those of off-state electrical properties can be improved by hole/electron accumulation in the Al₂O₃/Ga₂O₃ stacks.

CONCLUSIONS

We proposed and successfully fabricated the AlGaN/GaN HEMTs employing the 10 nm thick Al₂O₃/Ga₂O₃ stacks, which consist of 2 nm thick Al₂O₃ and Ga₂O₃ for increase of breakdown voltage and positive shift of $V_{TH}$. We achieved a high breakdown voltage of 1100 V and $V_{TH}$ of -1.4 V while those of the conventional device had 380 V and -2 V. The unintentionally formed Ga vacancy site in multiple Al₂O₃/Ga₂O₃ stacks formed by rf-sputtering at room temperature acted as accumulation center under gate. The charge accumulation induced improvement of reverse blocking characteristics such as leakage current and breakdown voltage. The large hysteresis of the AlGaN/GaN HEMT employing the Al₂O₃/Ga₂O₃ stacks and small hysteresis of the device employing Al₂O₃ only revealed that the improved electrical properties were attributed to charge accumulation in Ga₂O₃ sandwiched Al₂O₃. The proposed multiple Al₂O₃/Ga₂O₃ stacks may be suitable structure for a high voltage AlGaN/GaN HEMTs.

ACKNOWLEDGEMENTS

This work was supported by the ‘Power Generation & Electricity Delivery’ of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea Government Ministry of Knowledge Economy.