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Normally-off Recessed-gate ZrO_2/AlGaN/GaN MIS-HEMTs with Regrown AlGaN Barrier

Itsuki Nagase[1,*], Joel T. Asubar[1,*], Low Rui Shan[1], Shun Urano[1], Hirokuni Tokuda[1], Akio Yamamoto[1], and Masaaki Kuzuhara[2]

[1]University of Fukui, [2]Kwansei Gakuin University
*E-mail: ms200254@u-fukui.ac.jp, joel@u-fukui.ac.jp

Abstract

In order to achieve simultaneous normally-off and high drain current operation we have fabricated ZrO_2/AlGaN/GaN MIS-HEMTs with recessed-gate structure and regrown AlGaN layer. The fabricated devices achieved normally-off operation with threshold voltage of +2.0 V and maximum drain current of 550 mA/mm.

1. Introduction

GaN-based high-electron mobility transistors (HEMTs) are paving the way for unprecedented combination of high power, high frequency, and highly efficient operation due to desirable intrinsic properties of GaN resulting from its wide bandgap of 3.4 eV [1, 2]. However, in conventional AlGaN/GaN HEMTs, two-dimensional electron gas (2DEG) exist in the channel by default. Application of drain to source voltage with zero gate control voltage readily results into high drain current. This normally-on operation is undesirable because the devices conduct current when gate control power supply fails for some reason. Furthermore, the requirement for both negative and positive voltage supplies may lead to circuit complexity and added cost. From the above viewpoints, the development of E-mode (normally-off operation) devices is necessary for fail-safe and cost-effective solution.

Recessing the gate channel region of the MIS-HEMT to deplete the 2DEG is believed to be one of the most desirable ways to achieve normally-on operation in GaN-based materials [3]. In the recess gate structure, generally, as the depth of the recess is increased, the threshold voltage V_{TH} shifts in the positive direction. However, this usually accompanied by decrease in drain current [4]. That is, generally, the V_{TH} and drain current have a trade-off relationship. And in some cases, even degradation of maximum transconductance g_m with increasing recess depth [5]. One of the main factors for the decreased drain current and g_m seems to be related to the damage of the AlGaN/insulator interface due to dry etching. Regrowth of AlGaN layer after dry-etching is considered to be an effective method for mitigating etching damage [6]. In one of our previous reports, we reported Al_2O_3/AlGaN/GaN MIS-HEMTs with recessed-gate structure with regrown AlGaN layer and successfully achieved normally-off operation with drain current as high 425 mA/mm [7]. Meanwhile,

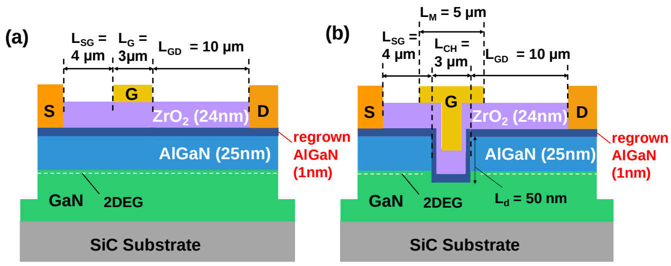

Fig. 1. Schematic illustration of ZrO2/AlGaN/GaN MIS-HEMTs w/o (a) and w/ (b) recess.

Hatano *et al.* reported highly improved stability in MIS-HEMTs employing high-K dielectric ZrO_2 in MIS-HEMTs with bilayer gate dielectric [8]. Aiming to achieve improved gate-to-channel modulation capability, in this work, we employ a high-K dielectric ZrO_2 as gate insulating film in our second generation MIS-HEMTs with recessed-gate structure and regrown AlGaN layer.

2. Experimental

Figures 1(a) and (b) show the schematic illustration of the devices fabricated in this work. As a starting wafer, we used an AlGaN/GaN heterostructure grown by metal-organic chemical vapor phase deposition (MOCVD) on a SiC substrate. The Al composition of AlGaN layer is 25%, and its thickness is 25 nm.

Device fabrication was initiated with the formation of isolation trenches by reactive ion etching (RIE) using a BCl_3/Cl_2 gas mixture and 20 W of inductively coupled plasma (ICP) and bias power. The recess structure region in the channel was then etched to a depth of 50 nm to completely remove the originally grown in-situ AlGaN in the channel region. This is then followed by ex-situ regrowth of 1-nm-thick AlGaN layer on the dry-etched GaN surface in the channel region by MOCVD. Ohmic contacts were then formed by electron beam evaporation of Ti/Al/Mo/Au metal stack, and then annealed under N_2 atmosphere at 880 ˚C for 30 s. ZrO_2 insulator layer was then deposited by atomic layer deposition using dimethylamino zirconium and ozone as precursors. Finally, the device fabrication was concluded by evaporating a bilayer metal stack of Ni/Au for the gate electrode.

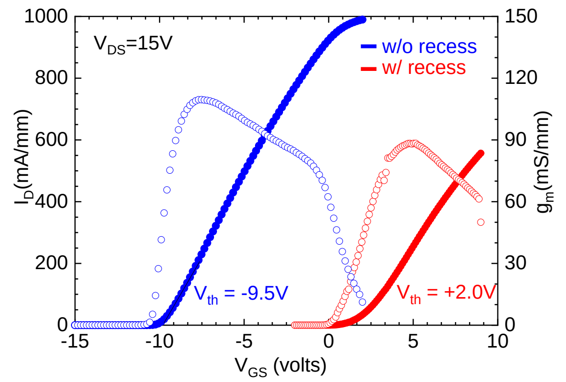

Fig. 2. Transfer curves measured at V_{DS}=15V of ZrO_2/AlGaN/GaN MIS-HEMTs w/o (blue) and w/ (red) recess.

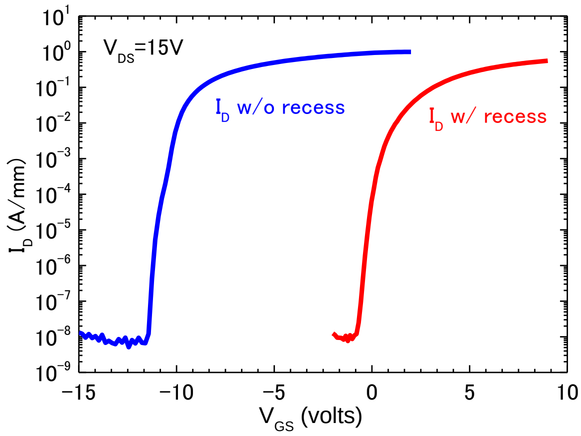

Fig. 3. Semi-log transfer curves measured at V_{DS}=15V of ZrO_2/AlGaN/GaN MIS-HEMTs w/o (blue) and w/ (red) recess.

The relevant dimensions of the devices used for characterizations are: channel length L_{CH} = 3.0 μm, gate width W_G = 100 μm, gate-to-source distance L_{SG} = 4.0 μm, and gate-to-drain distance L_{GD} = 10.0 μm. As reference sample, we also fabricated planar devices without the gate recess structure.

3. Results and Discussion

From the measured transfer (I_D-V_{GS}) curves (Fig. 2 and Fig. 3), we observed about +12 V shift towards the normally-off operation by recessing. Additionally, a very high maximum drain current, I_{Dmax} of 550 mA/mm was obtained. Interestingly, an almost parallel shift of transfer curves for the device with recess was observed, suggesting not so substantial g_m degradation in spite of the +12 V shift in V_{TH}. Moreover, the on-to-off ratio of drain current did not change significantly by recessing and remained to be in the orders of 10^8. Both devices showed good drain output characteristics (Fig. 4). As we have hypothesized in an earlier work, we believe that the buried dry etching damage as well as reduced surface donors due to regrowth are the main reasons for the simultaneous realization of high threshold voltage and high drain current [7]. In addition, for the present devices, the high current and high transconductance even after recessing, can also be attributed to the high permittivity of the ZrO_2 gate dielectric material.

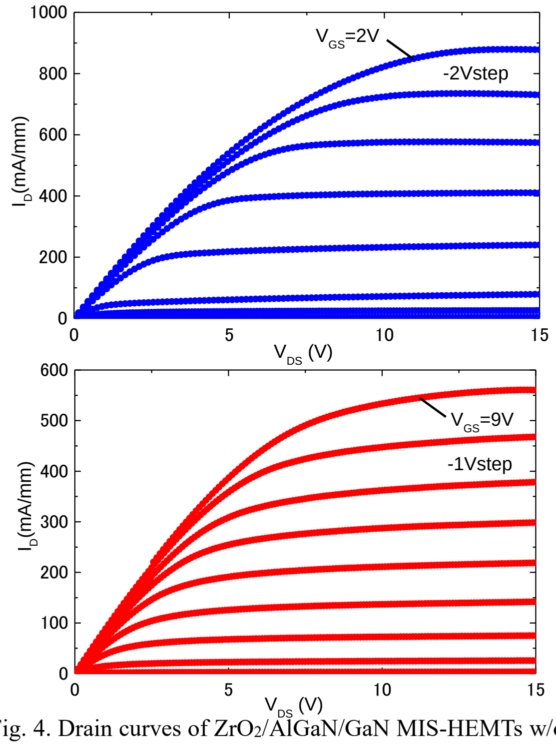

Fig. 4. Drain curves of ZrO_2/AlGaN/GaN MIS-HEMTs w/o (blue) and w/ (red) recess.

4. Conclusions

We have employed ZrO_2 as the gate dielectric material for our second generation AlGaN/GaN MIS-HEMTs with recessed-gate structure and regrown AlGaN layer. We realized normally-off operation with threshold voltage (V_{TH}) of +2 V simultaneous with maximum drain current (I_{Dmax}) of 550 mA/mm.

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