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Demonstration of β-$(AlGa)_2O_3$ (010) metal-semiconductor field-effect transistors with high breakdown voltage over 900 V

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Abstract

We report on the first demonstration of lateral metal-semiconductor field-effect transistors (MESFETs) with a β-$(Al_{0.16}Ga_{0.84})_2O_3$ (010) channel. The Sn-doped $(Al_{0.16}Ga_{0.84})_2O_3$ layers exhibit *n*-type characteristics and a fairly ohmic behavior. The specific contact resistivity and sheet resistance are 9×10^{-5} Ωcm^2 and 75 kΩ, respectively. The MESFETs provide good drain current saturation and stable pinch-off operation. The MESFETs have the transistor on/off ratio of ~10^4 and the off-state breakdown voltage of 940 V for drain-to-gate spacing of 20 μm. These results show the great potential of $(AlGa)_2O_3$-channel transistors for high-power applications.

1. Introduction

Ga_2O_3 is an attractive material for high-power applications due to its high critical electric field (E_c) and a large band-gap energy of 4.5 eV. $(AlGa)_2O_3$ alloys are expected for further high-power applications. However, β-$(AlGa)_2O_3$ (010) growth is quite difficult because of the phase stability limits of Al incorporation into β-Ga_2O_3 (010).[1)] Recently, we achieved the high-quality growth of *n*-type β-$(Al_{0.16}Ga_{0.84})_2O_3$ (010) layers via plasma-assisted molecular-beam epitaxy (PAMBE).[2)] In this study, we report on the electrical characterization of Sn-doped β-$(Al_{0.16}Ga_{0.84})_2O_3$ layers and the demonstration of $(Al_{0.16}Ga_{0.84})_2O_3$-channel metal-semiconductor field-effect transistors (MESFETs).

2. Experimental procedures

N-type $(AlGa)_2O_3$ growth

We used Fe-doped semi-insulating β-Ga_2O_3 (010) substrates. Using PAMBE, Sn-doped β-$(AlGa)_2O_3$/unintentional-doped (UID) β-$(AlGa)_2O_3$ (010) layers were grown at 700±50°C. The thickness and Al content of the $(AlGa)_2O_3$ layers were determined using Laue fringes and peak diffraction angle, respectively, from X-ray diffraction θ-2θ scans of the (020) plane, as shown in Fig. 1 (a).

In reciprocal space mapping, the in-plane lattice constant for the (421)-diffraction peak of 240-nm-thick β-$(Al_{0.16}Ga_{0.84})_2O_3$ (010) layer stacks corresponded to that of β-Ga_2O_3 (010) substrates, as shown in Fig. 1 (b), indicating that the $(Al_{0.16}Ga_{0.84})_2O_3$ layers are coherently grown on Ga_2O_3.

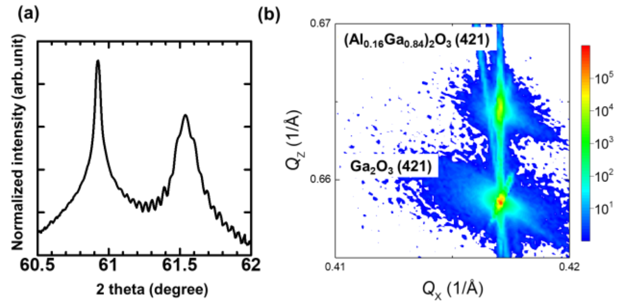

Fig. 1: (a) Symmetric HRXRD θ–2θ scans for (020) diffraction of 240 nm β-$(Al_{0.16}Ga_{0.84})_2O_3/Ga_2O_3$ (010) layers. (b) Symmetric on-axis (421) reciprocal space maps for the $(AlGa)_2O_3$ layer on Ga_2O_3 substrate.

Device fabrications

A 150-nm-deep mesa isolation was obtained by Cl_2-based reactive-ion etching. A Ti/Au metal stacks were deposited using an electron-beam evaporation for source/drain contacts, followed by annealing at 500°C for 30 s in a nitrogen ambient to form metal alloy. The gate-recess structure is used for the MESFET. The 40-nm deep recess is etched, followed by the deposition of Ni/Au metal stacks for a gate contact. Breakdown-voltage measurements were performed using an Agilent B1505A power-device analyzer and a high-voltage Tesla probe station. During breakdown measurements, the devices were immersed in a Fluorinert FC-770 solution to avoid surface flashover.

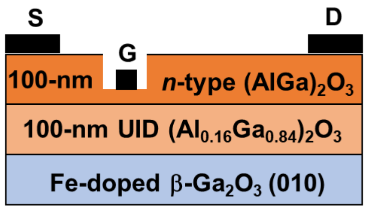

Fig. 2: Schematic cross section of Sn-doped β-$(Al_{0.16}Ga_{0.84})_2O_3$ (010) channel MESFET.

3. Results and discussion

Electrical property of n-type $(AlGa)_2O_3$ layer

Two Ti/Au contacts separated by various source-drain spacing (L_{sd}) were used for a transmission line measurement (TLM). We prepared the 100-nm-thick heavily Sn-doped $(Al_{0.16}Ga_{0.84})_2O_3$ /100-nm-thick UID $(Al_{0.16}Ga_{0.84})_2O_3$ layers. The net donor concentration of the Sn-doped $(AlGa)_2O_3$ layer is estimated to be 2×10^{18} cm^{-3} at room temperature from capacitance-voltage measurements. The current-voltage characteristics of the Sn-doped $(AlGa)_2O_3$ layer for various L_{sd} at room temperature are shown in Fig. 3 (a). The Sn-doped $(AlGa)_2O_3$ layers were conductive at room temperature and were electrically isolated by the bottom UID $(AlGa)_2O_3$ layers. Using TLM, the specific contact resistance R_c and sheet resistance R_{sh} of the $(AlGa)_2O_3$ layer is estimated to be 9×10^{-5} Ωcm^2 and 75 kΩ/□, respectively.

In the 150-nm-deep mesa structure, lateral breakdown voltage (V_{br}) of the UID $(Al_{0.16}Ga_{0.84})_2O_3$ and Ga_2O_3 layers were measured between the isolated source and drain contacts. The two-terminal V_{br} for various L_{sd} at room temperature are shown in Fig. 3 (b). V_{br} linearly increased with increasing L_{sd}. The effective E_c of the UID $(Al_{0.16}Ga_{0.84})_2O_3$ and Ga_2O_3 layers are 1.8 and 0.5 MV/cm, respectively. These values are higher than the one typically seen in III-nitride semiconductors, showing that $(AlGa)_2O_3$ materials have high potential for high-power applications.

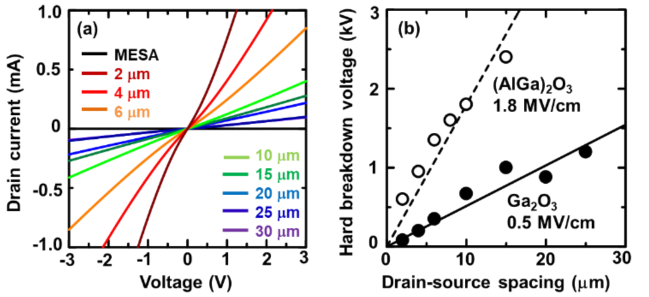

Fig. 3: Current-voltage characteristics of Sn-doped $(Al_{0.16}Ga_{0.84})_2O_3$ with a donor concentration of 2×10^{18} cm^{-3} for various contact resistances. (b) Two-terminal buffer-leakage breakdown voltage of unintentionally doped $(Al_{0.16}Ga_{0.84})_2O_3$ (dash) and Ga_2O_3 (solid) as a function of source-to-drain spacing.

Characteristics of $(AlGa)_2O_3$ MESFET

Output characteristics at room temperature for the MESFET with a lightly Sn-doped $(Al_{0.16}Ga_{0.84})_2O_3$ channel is shown in Fig. 4 (a). The MESFETs have a nearly normally-off operation with pinch-off characteristics for $V_{gs} < -0.4$ V due to the light Sn-doping and gate-recess structure. The subthreshold swing was 0.3 V/decade. I_d is effectively modulated by V_{gs} and shows good saturation. The maximum I_d was 3.3 µA/mm for $V_{gs} = +1.0$ V.

The MESFET with L_{gd} of 4 µm at a drain-voltage (V_{ds}) = +4 V at room temperature is shown in Fig. 4 (b). At room temperature, the off-state I_d was 0.6 nA/mm, which is comparable with the gate current, indicating a negligibly-small leakage current through the UID $(AlGa)_2O_3$ layers. The maximum transconductance was 1.6 µS/mm. The I_d on/off ratio was above 10^3.

The three-terminal V_{br} characteristics for the $(AlGa)_2O_3$ MESFET with L_{gd} of 20 µm at room temperature is shown in Fig. 4 (c). The leakage current of off-state I_d was below 1 nA/mm at -600 V. V_{br} for V_{gs} = -10 V at room temperature was 940 V. The three-terminal V_{br} for various L_{gd} at room temperature are shown in Fig. 4 (d). V_{br} increases linearly with increasing L_{gd}. The effective E_c of the three terminal V_{br} for $(AlGa)_2O_3$ is 0.6 MV/cm. Further high breakdown voltages of the MESFETs are expected in devices with a field-plate structure.

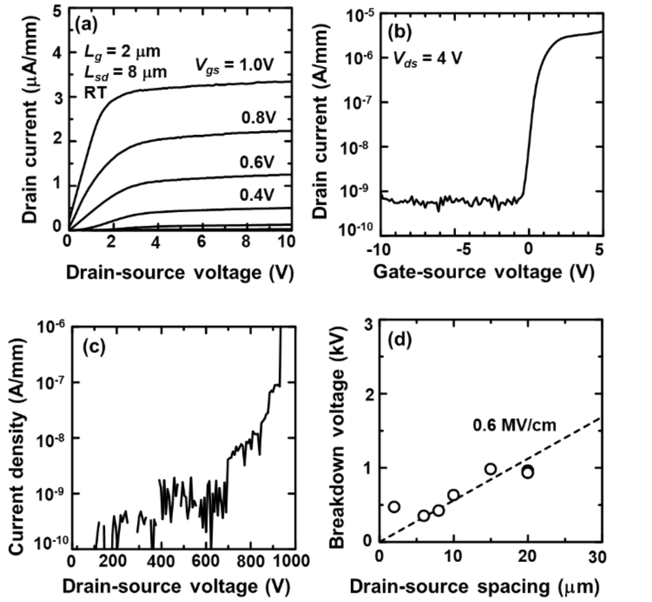

Fig. 4: (a) DC output characteristics of lightly Sn-doped $(Al_{0.16}Ga_{0.84})_2O_3$ MESFET with gate length of 2 µm at room temperature for V_{gs} from 0 to +1 V. (b) Transfer characteristics at a drain voltage of +4 V at room temperature. (c) Off-state breakdown characteristics of $(AlGa)_2O_3$ MESFET with drain-to-gate spacing of 20 µm at a gate voltage of -10 V at room temperature. (d) Three-terminal off-stat breakdown voltage as a function of gate-to-drain spacing.

3. Conclusions

We report on the electrical characteristics of $(AlGa)_2O_3$ layers. The Sn-doped $(Al_{0.16}Ga_{0.84})_2O_3$ layer exhibits a fairly ohmic behavior, showing the contact resistance of 9×10^{-5} Ωcm^{-2} and the sheet resistance of 75 kΩ/□. The effective critical electrical field of the $(Al_{0.16}Ga_{0.84})_2O_3$ layer is 1.8 MV/cm. Additionally, we achieved the demonstration of the $(AlGa)_2O_3$-used MESFETs. The three-terminal off-state breakdown voltage of the $(AlGa)_2O_3$-channel MESFETs is 940 V for drain-to-gate spacing of 20 µm. The $(AlGa)_2O_3$-used transistors show the great potential for high-power applications.

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