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Gallium oxide (Ga_2O_3) metal-semiconductor field-effect transistors on single-crystal β-Ga_2O_3 (010) substrates

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We report a demonstration of single-crystal gallium oxide (Ga_2O_3) metal-semiconductor field-effect transistors (MESFETs). A Sn-doped Ga_2O_3 layer was grown on a semi-insulating β-Ga_2O_3 (010) substrate by molecular-beam epitaxy. We fabricated a circular MESFET with a gate length of 4 μm and a source–drain spacing of 20 μm. The device showed an ideal transistor action represented by the drain current modulation due to the gate voltage (V_{GS}) swing. A complete drain current pinch-off characteristic was also obtained for $V_{GS} < -20$ V, and the three-terminal off-state breakdown voltage was over 250 V. A low drain leakage current of 3 μA at the off-state led to a high on/off drain current ratio of about 10 000. These device characteristics obtained at the early stage indicate the great potential of Ga_2O_3-based electrical devices for future power device applications. © *2012 American Institute of Physics*. [doi:10.1063/1.3674287]

A compound semiconductor system based on the group III-oxides gallium oxide (Ga_2O_3), aluminum oxide (Al_2O_3), and indium oxide (In_2O_3) has great potential to pioneer new semiconductor device technologies. The bandgap of β-Ga_2O_3 is 4.8–4.9 eV, which corresponds to the second largest bandgap after that of diamond among semiconductors. Recently, there have been some attempts to develop optical devices, Ga_2O_3 deep ultraviolet photo detectors[1,2] and GaN-based blue light emitting diodes,[3] using Ga_2O_3 epitaxial layers and substrates mainly by making the best use of its transparency. A few studies on transistors have also been reported such as Ga_2O_3 *p*-channel nanowire field-effect transistors (FETs)[4] and metal-insulator-semiconductor FETs having an unknown crystal structure on α-Al_2O_3 (0001) substrates.[5] These studies succeeded in modulating the channel conductance by the gate voltage (V_{GS}); however, the device characteristics were far from the required level to discuss the potential use of Ga_2O_3 for practical applications.

Table I compares the important material properties of major semiconductors with those of β-Ga_2O_3. From the interpolation of the relationships among the bandgaps and breakdown fields of the other semiconductors shown in Fig. 1(a), the breakdown field of β-Ga_2O_3 is expected to have a very large value of about 8 MV/cm. The electron mobility (μ) of β-Ga_2O_3 in Table I is estimated on the basis of the experimental data obtained for the Sn-doped epitaxial layers and *n*-type single-crystal substrates with electron densities (n) of 10^{17}–10^{19} cm^{-3} that were grown by our group. From these material properties, Baliga's figure of merit (FOM),[6] which is the basic power semiconductor device FOM and defines the material parameters to minimize conduction losses, of β-Ga_2O_3 is calculated to be at least four times larger than those of 4H-SiC and GaN. Figure 1(b) shows the theoretical limits of on-resistances as a function of the breakdown voltage for the semiconductors, as calculated from the parameters in Table I. These estimates indicate the great potential of Ga_2O_3 for high-power and high-voltage device applications.

Another important property of β-Ga_2O_3 is that single-crystal substrates can be fabricated from melt by the floating zone (FZ) and edge-defined film-fed growth (EFG) methods.[7,8] In general, large-diameter single-crystal wafers are required to mass produce vertical devices that are favorable for high-voltage and high-current power devices. To this end, the EFG method would be especially useful. In fact, it has recently been used to fabricate large sapphire wafers over 8 in. in diameter. The same method can be used to produce large Ga_2O_3 wafers not only at a low cost but also at low energy consumption. This is a great advantage of Ga_2O_3 over other representative widegap semiconductors such as SiC, GaN, and diamond for power device applications.

In this study, we fabricated and characterized *n*-channel Ga_2O_3 metal-semiconductor FETs (MESFETs) on a single-crystal β-Ga_2O_3 (010) substrate. This is the first demonstration of single-crystal Ga_2O_3 transistors that could be used for practical applications.

By molecular-beam epitaxy (MBE), a Sn-doped *n*-type Ga_2O_3 layer with a thickness of 300 nm was grown on a Mg-doped semi-insulating β-Ga_2O_3 (010) substrate fabricated by the FZ method. Ga and Sn fluxes were supplied by evaporation of Ga metal and SnO_2 powder heated in normal Knudsen cells. A gas mixture of ozone and oxygen was used as the oxygen source. The substrate temperature was 700 °C, and the growth rate of Ga_2O_3 was 0.6 μm/h. The density of the doped Sn in the Ga_2O_3 layer was estimated to be 7×10^{17} cm^{-3} from secondary ion mass spectrometry

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TABLE I. Material properties of major semiconductors and β-Ga_2O_3.

	Si	GaAs	4 H-SiC	GaN	Diamond	β-Ga_2O_3
Bandgap E_g (eV)	1.1	1.4	3.3	3.4	5.5	4.8–4.9
Electron mobility μ (cm^2/Vs)	1400	8000	1000	1200	2000	300
Breakdown field E_b (MV/cm)	0.3	0.4	2.5	3.3	10	8
Relative dielectric constant ϵ	11.8	12.9	9.7	9.0	5.5	10
Baliga's FOM[a] $\epsilon \mu E_b^3$	1	15	340	870	24 664	3444

[a]For DC and low frequency.

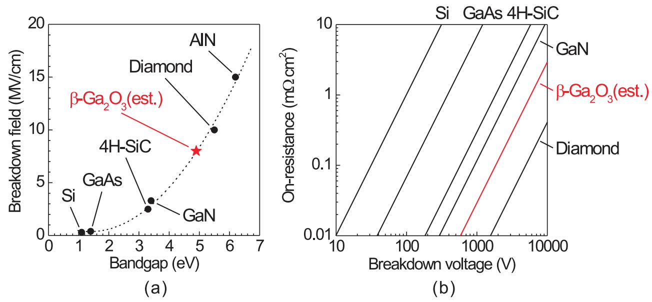

FIG. 1. (Color online) (a) Bandgap dependences of the breakdown field and (b) theoretical limits of on-resistances as a function of breakdown voltage for major semiconductors and β-Ga_2O_3. The broken line in (a) is fitted with the eyes.

profiles. Note that we have not confirmed μ and n of the n-Ga_2O_3 layer, because the substrate used in this study was a small-size chip. Typical μ and n of the epitaxial Ga_2O_3 films grown under the similar conditions were around 100 cm^2/Vs and 5×10^{17} cm^{-2}, respectively.

Figures 2(a) and 2(b) show a cross-sectional schematic illustration of the Ga_2O_3 MESFET structure and a micrograph of the fabricated device obtained using an optical microscope. We employed a circular FET pattern, because a device isolation technique has not yet been developed. In the first process of Ohmic contact formation, a reactive ion etching (RIE) treatment was performed using a gas mixture of BCl_3 and Ar for 1 min, followed by evaporation of Ti(20 nm)/Au(230 nm) and lift off. The chamber pressure and plasma power during the RIE process were 5.0 Pa and 150 W, respectively, leading to a 15-nm-deep etching of the Ga_2O_3 film. We found that the RIE treatment significantly reduces the contact resistance, as discussed below. Finally, Schottky gates were fabricated by Pt(15 nm)/Ti(5 nm)/Au(250 nm) deposition and lift off. Surface dielectric passivation was not performed for the devices. The gate length was 4 μm, and the spacing between the source and drain electrodes was 20 μm. The diameter of the inner circular electrodes for the drain was 200 μm.

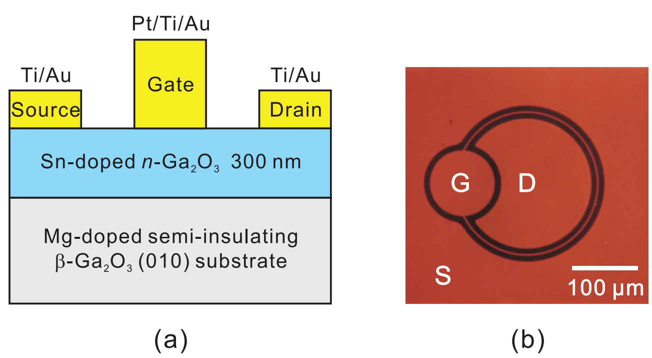

FIG. 2. (Color online) (a) Cross-sectional schematic illustration and (b) optical microscope micrograph of Ga_2O_3 MESFET.

Figure 3 shows two-terminal current–voltage (I–V) characteristics of the samples fabricated with and without the RIE process. The characteristics were measured between two as-deposited Ti/Au contacts formed on n-type Ga_2O_3 substrates with $n = 5 \times 10^{17}$ cm^{-3}. The two contacts were fabricated in a circular transmission line model pattern. One contact was a circle 200 μm in diameter, and the other was set to surround the circle and had an area hundreds times larger than that of the inner one. The spacing between the two electrodes was 20 μm. Note that the characteristics negligibly varied if the distance was changed from 4 to 20 μm because of the extremely low sheet resistance due to the substrate thickness of about 300 μm. The contacts fabricated with the RIE process showed an almost Ohmic behavior; on the other hand, the clear feature of the Schottky contact was observed for the sample fabricated without the RIE treatment. The detailed mechanism is unclear; however, we consider that the RIE treatment could generate large-density surface defects such as oxygen vacancies that act as donors. Similar phenomena have also been confirmed for $LaAlO_3$/$SrTiO_3$ metal-oxide-semiconductor FETs.[9]

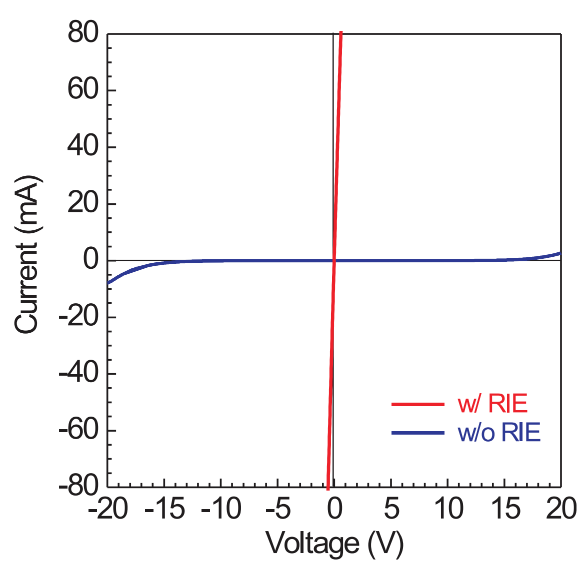

FIG. 3. (Color online) I–V curves measured between two contacts (as-deposited Ti/Au) fabricated with and without RIE treatment on n-Ga_2O_3 substrates.

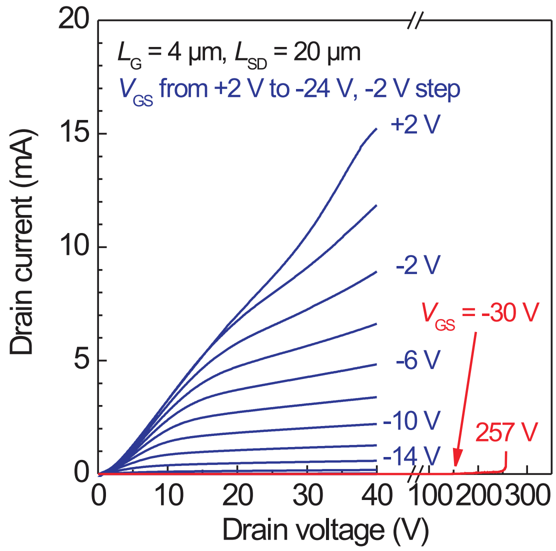

FIG. 4. (Color online) DC output characteristics of Ga_2O_3 MESFET.

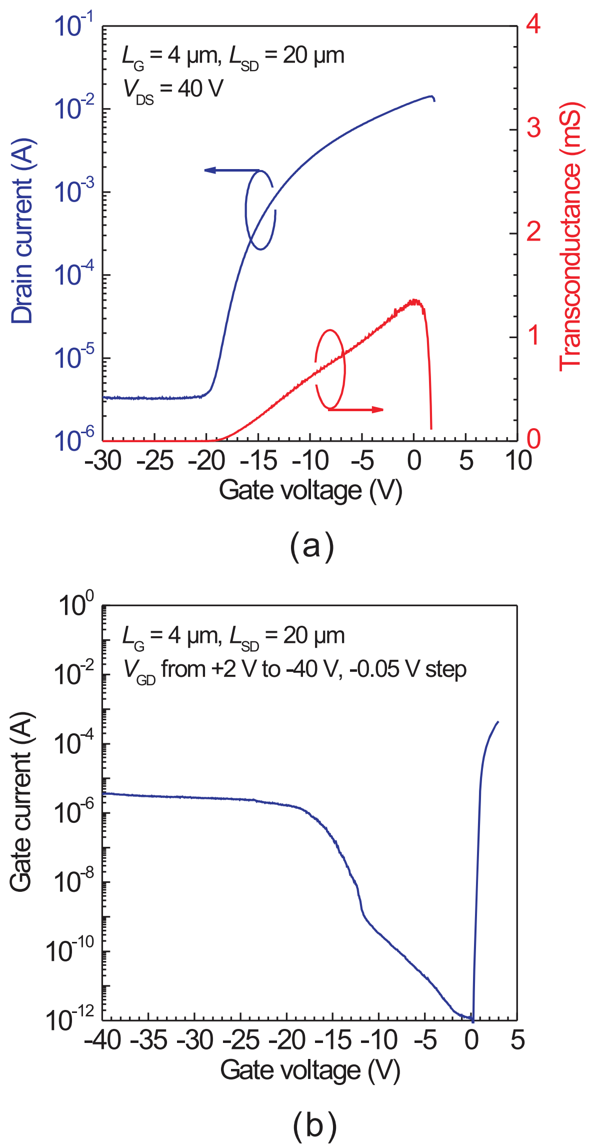

FIG. 5. (Color online) (a) Transfer characteristics at $V_{DS} = 40$ V and (b) two-terminal gate leakage current of Ga_2O_3 MESFET.

Figure 4 shows the DC output characteristics of the circular Ga_2O_3 MESFET. The maximum drain current (I_{DS}) was 15 mA for a V_{GS} of +2 V. The device exhibited a perfect pinch-off characteristic. The three-terminal breakdown voltage at the off-state was as large as 257 V at $V_{GS} = -30$ V. Note that the breakdown was catastrophic resulting in burned gate electrodes. Figures 5(a) and 5(b) show the transfer characteristics at a drain voltage (V_{DS}) of 40 V and the two-terminal gate-to-drain current, respectively. The maximum transconductance was 1.4 mS. The off-state I_{DS} was as small as 3 μA, and the on/off I_{DS} ratio reached a high value of around 10 000. The reverse gate leakage current was measured to be less than 4 μA down to −40 V. This value includes leakage from the large gate pad (100 $\mu m\phi$) of the device [Fig. 2(b)]; therefore, the actual leakage current from the gate finger should be at least one order of magnitude less than this value. Furthermore, the off-state current was comparable with the gate leakage current, indicating that the leakage current through the semi-insulating Ga_2O_3 substrate was negligibly small. The off-state current can be further decreased simply by changing the device configuration. All these device characteristics are comparable to or better than those of early GaN MESFETs.[10,11]

In summary, we have fabricated n-Ga_2O_3 MESFETs on a single-crystal Mg-doped β-Ga_2O_3 (010) substrate. The MESFETs exhibited excellent DC device characteristics including drain current modulation by the gate voltage, a perfect pinch-off of the drain current, an off-state breakdown voltage over 250 V, a high on/off drain current ratio of around 10^4, and a small gate leakage current. All these device characteristics demonstrated the great potential of Ga_2O_3 electron devices and will pave the way for future high-power and high-voltage device applications.

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