Vertical MOSFET using C-H Diamond with Trench-channel
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Abstract
We fabricated a hydrogen terminated diamond (C-H diamond) vertical type metal-oxide-semiconductor field-effect transistors (MOSFETs) with trench-channel structure. The trench structure was formed by inductive coupled plasma reactive ion etching. The side-wall of the trench can be used for p-channel. This result indicates that a vertical diamond MOSFET with trench gate and bottom drain can modulate an electric current for power device application.

1. Ubiquitous 2 dimensional hole gas (2DHG) layer is preferable for vertical type MOSFETs
Recently, large current controllable semiconductor devices made of silicon carbide, gallium nitride (GaN), or diamond have been intensively studied. Power devices made of diamond have remarkable potentials based on the highest breakdown field and the thermal conductivity. We have reported high blocking voltages in planar type C-H diamond MOSFETs [1-3]. Hydrogen terminated diamond surface induces 2 dimensional hole gas (2DHG) layer and become a p-type channel of FETs. A thick Al2O3 passivation film was used as gate insulator inducing the additional holes as carrier beneath the diamond surface. The planar C-H diamond MOSFETs have well controlled the source-drain current, but have the difficulty in improving the current density normalized by the device lateral area including large drift region. To achieve high current density, it is inevitable to form vertical-shaped devices to stow the large drift area.

AlGaN/GaN-HEMT is well-known as FET utilizing two-dimensional electron gas (2DEG) on its interface. The 2DEG layer is induced by spontaneous- and piezo- polarization at regularly arranged AlGaN/GaN interfaces. Therefore, the 2DEG layer cannot be formed on the sidewall of GaN due to the crystalline orientation. On the contrary, C-H diamond surface, and Al2O3 layer formed by atomic layer deposition (ALD) as a passivation layer and a gate insulator sheet, induce two-dimensional hole gas (2DHG). The 2DHG on C-H diamond covered by ALD-Al2O3 can be ubiquitously formed on any crystal surface, even on the sidewall. This is very advantageous to fabricate vertical type devices. In this study, we fabricated the vertical type C-H diamond power MOSFETs and confirmed the vertical current through trench.[4]

2. Fabrication of vertical MOSFET
Fig. 1 shows the schematic image of vertical type C-H diamond MOSFETs. The A nitrogen doped layer about 3μm was grown on p+ diamond substrate (boron concentration of 1×1019 cm-3) by plasma enhanced CVD (PECVD). Trench structure with the depth of about 3 μm was formed by inductively coupled plasma ion etching (ICP-RIE). To form 2DHG on to the diamond top surface and the sidewall of trench, 500 nm-thick undoped layer was regrown by PECVD. The N-doped layer blocks leakage current passing through directly below source electrodes. The undoped layer conceals the damages by plasma etching. Next, Ti/Au were deposited as a source electrode. Al2O3 formed by ALD was deposited as a gate insulator. Finally, Al as gate electrode and Au as backside drain electrode were deposited.

3. Device characteristics of vertical type C-H diamond MOSFETs
Figs. 2 and 3 show the Ids-Vds and Ids-Vgs characteristics of a fabricated vertical type C-H diamond MOSFET, respectively. Clear drain current modulation by gate voltage was observed, but large onset voltage existed. This onset is due to the existence of 500 nm-thick undoped layer at the bottom of the trench. This undoped layer behaves as intrinsic semiconductor. Fig. 4 shows the band diagram of the bottom of the trench. Each position (A-C) corresponds to the position in the enlarged image of Fig. 2. Fig. 4(a) shows the band diagram when VDS = 0 V and VGS = 0 V (condition ① in Fig. 2). When applying -40 < VDS < 0 V (condition ② in Fig. 2), the potential of p+ diamond goes up and simultaneously the Fermi level of the i-layer goes up like Fig. 4(b). However, in this condition, the valence band of the i-layer is still convex downward and B and C is electrically isolated. Therefore, Ids does not increase in this range. When applying VDS < -40 V (condition ③ in Fig. 2), the potential of p+ diamond further goes up, the valence band of the i-layer shows monotonic increase, and the hole carrier starts to drift from position B to C as Fig. 4(c), then Ids starts to increase (on-set). In order to avoid this phenomenon, it is important to pull up the valence band maximum of the homoepitaxial layer by slight boron doping at the trench bottom. If vertical MOSFETs using C-H diamond surface can be fabricated without convex downward band, there will be no offset of conduction.
4. Conclusion
We fabricated vertical MOSFET using C-H diamond with trench-channel and observed clear modulation, but large onset voltage existed. It is due to the existence of 500 nm-thick undoped layer at the bottom of the trench. It was confirmed that 2DHG on C-H diamond is suitable for forming vertical type MOSFET structure.

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References

Fig. 1 Schematic image of vertical type C-H diamond MOSFET with trench channel. Position A, B and C in the enlarged image correspond to A, B, and C of Fig. 4, respectively.

Fig. 2 $I_{DS}$ $V_{DS}$ characteristics of a vertical type C-H diamond MOSFET.①,② and ③ correspond to (a),(b) and (c) of Fig. 4, respectively.

Fig. 3 $I_{DS}$ $V_{GS}$ characteristics of a vertical type C-H diamond MOSFET.

Fig. 4 Band diagrams across the trench bottom of the device (the enlarged image of Fig. 2), when applying $V_{GS} = 0$ V and (a) $V_{DS} = 0$ V, (b) $-40 < V_{DS} < 0$ V, and (c) $V_{DS} < -40$ V.