Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp597-598

N-6-02

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 intensivly 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 Al_2O_3 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 Al_2O_3 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-Al_2O_3 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 1×10^{19} 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. Al_2O_3 formed by ALD was deposited as a gate insulator. Finally, Al as gate electrode and Au as back-side drain electrode were deposited.

3. Device characteristics of vertical type C-H diamond MOSFETs

Figs. 2 and 3 show the I_{DS}-V_{DS} and I_{DS}-V_{GS} 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 $V_{DS} = 0$ V and $V_{GS} = 0$ V (condition ① in Fig. 2). When applying $-40 < V_{DS} < 0$ 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, I_{DS} does not increase in this range. When applying $V_{DS} < -40$ 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 I_{DS} 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 on-set 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.

Acknowledgements

This study was supported by a Grant-in-Aid for Fundamental Research S (26220903, JSPS).

References

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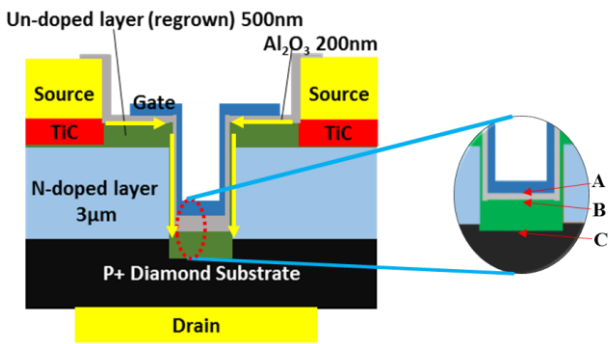

Fig. 1 Schematic image of vertical type C-H diamond MOSFET with trench channel. Position A, B and C in the enlarged image correspond to A, B, and C of Fig. 4, respectively.

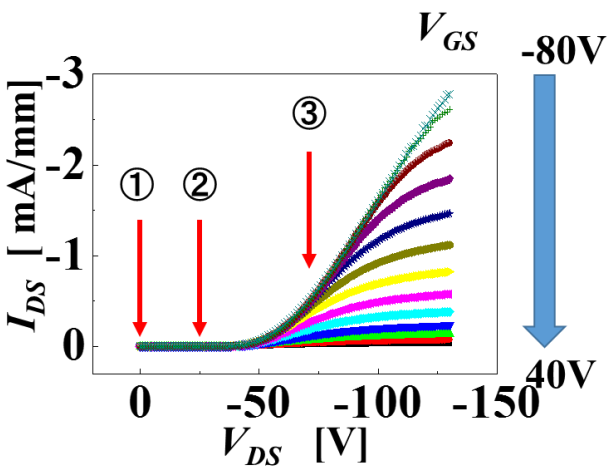

Fig. 2 I_{DS}- V_{DS} characteristics of a vertical type C-H diamond MOSFET. ①,② and ③ correspond to (a),(b) and (c) of Fig. 4, respectively.

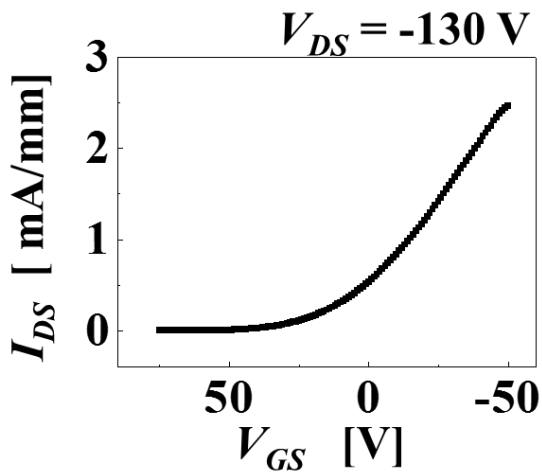

Fig. 3 I_{DS}- V_{GS} characteristics of a vertical type C-H diamond MOSFET.

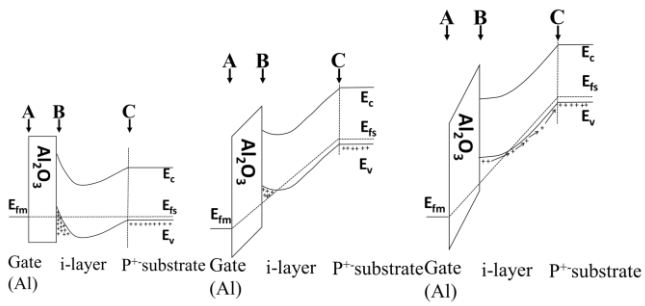

Fig. 4 Band diagrams across the trench bottom of the device (the enlarged image of Fig. 2), when applying V_{GS} = 0 V and (a) V_{DS} = 0 V, (b) -40 < V_{DS} < 0 V, and (c) V_{DS} < -40 V.