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Normally-off Diamond p-FET Application in Cascode with Breakdown Voltage over 1.7 kv

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Abstract

C-H Diamond have high current density of 10^{13}cm^{-2}[1] cause of the two-dimensional-hole-gas (2DHG) on the C-H diamond surface. C-H diamond MOSFETs have high breakdown voltage characteristics but it shows Normally-on operation. For security and energy-saving, we fabricated the diamond cascode by using the C-H diamond p-FET combination of the normally-off silicon p-FET, diamond cascode shows the normally-off characteristics and high Breakdown voltage over 1.7kV.

1. Introduction

Diamond devices have now been researched for many years for power conversion applications, C-H Diamond FET using the two-dimensional hole gas (2DHG) induced by atomic-layer-deposited (ALD) Al2O3 insulator on the hydrogen-terminated (C-H) diamond surface, and it can operate in wide temperature range (10~637k) [2], in polycrystalline diamond p-FET the breakdown voltage over 2kV [3] has been reported. On C-H diamond surface, the 2DHG produce normally-on operation without bias voltage. Partially oxidized diamond FET shows normally-off operations but the drain current density is smaller than C-H diamond FET about 1-2 orders. In the circuit, in consideration of security and energy-saving the normally-off operation is required.

The semiconductor power device application in cascode have been reported in recent years, new era semiconductor materials like GaN (gallium nitride) has been application in cascode structure [4], GaN cascode using as switch in currents but hard to reach high breakdown voltage over 1000V.

In this study, we fabricated the diamond cascode by the combination of the normally-off silicon p-MOSFET with low breakdown voltage (LV) and normally-on C-H high breakdown voltage (HV) diamond FET. This breakthrough shows the gate of diamond FET is controlled by the LV silicon p-FET effectively, the diamond cascode shows normally-off characteristics and maximum transconductance has been drastically enhanced. At last, great breakdown performance of diamond cascode was confirmed.

2. C-H diamond p-FET power devices

Fabrication Process of diamond MOSFETs.

We fabricated single crystal C-H diamond p-FETs (Fig.1) by follow process. Firstly, we deposited undoped CVD layer on Ib (100) diamond substrate and Ti/Au (30nm/100nm) were deposited as source and drain electrode by electron beam deposition system. Then the process of hydrogen-terminated by remote plasma and O-terminated for isolation on diamond surface. At last, the passivation Al_2O_3 film (200nm) were deposited by ALD at 450 °C and Al was deposited as gate electrode.

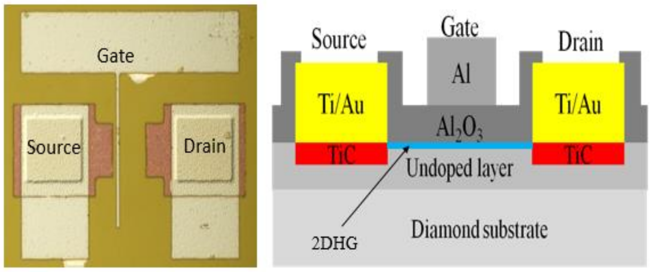

Fig.1 Diamond p-FET in microscope and sectional model of diamond MOSFET.

Characterizations of diamond MOSFETs

We tested diamond p-FET in vacuum chamber, the V_{GS}- I_{DS} shown in Fig.2(a), V_{DS}-I_{DS} shown in Fig.2(b). The size of diamond MOSFET were L_G= 2µm,L_{SG}= 2µm and L_{GD}= 5µm.

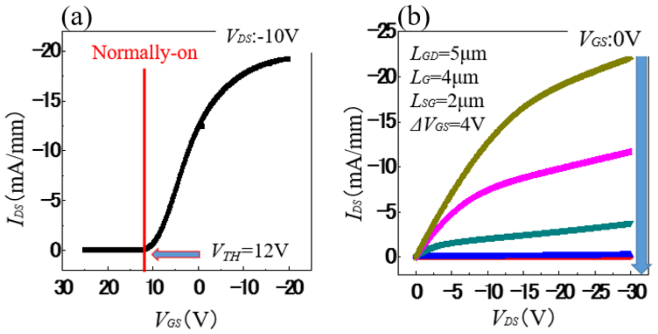

Fig.2 V_{GS}- I_{DS} and V_{DS}-I_{DS} characteristics of the diamond MOSFET

The maximum drain current density is -22mA/mm (at V_{DS}= -30V) was obtained at V_{GS}= 0V, also we figure out the maximum transconductance $g_{m,max}$ of this diamond p-FET is about of 2.6 mS/mm. The HV diamond FET had the threshold voltage V_{TH} of 12 V which operate as normally-on.

3. Diamond p-FET Cascode

Controllability and Fabrication of diamond p-FET cascode

The principle structure of the diamond p-FET cascode is shown in Fig.3 (a), the normally-on HV diamond p-FET and normally-off LV silicon p-FET (<100V) (2sj380, TOSHIBA) combined. Gate of the diamond p-FET and source of Si p-FET were commonly grounded, the drain of diamond p-FET was connected to the source or Si p-FET. The drain source voltage of the LV FET ($V_{DS,\,LV}$) is equivalent to the gate drain voltage of the HV FET ($V_{GS,\,HV}$). We made a pin box, and changed the wiring of high voltage measuring device system, in order to connect FET in the vacuum chamber into external circuit. When turn on the LV FET, the $V_{DS,\,LV}$ drop to 0V, the cascode turns to ON state (shown in Fig.3(b)). If turn off the LV FET, the $V_{DS,LV}$ will increase and once $V_{DS,LV}$ exceed the threshold voltage of HV FET the cascode turns to OFF state(shown in Fig.3(c)).

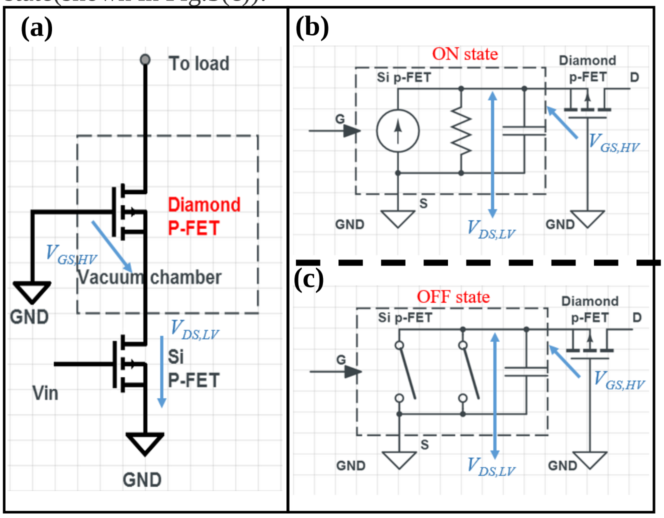

Fig.3 (a) Principle structure of the diamond p-FET cascode. (b)(c) Equivalent circuit of diamond p-FET in ON/OFF state.

Analysis and Characterization of Diamond p-FET Cascode

The V_{GS}- I_{DS} and V_{DS}-I_{DS} characteristics of diamond cascode shown in Fig. 4(a) (b). The characterizations shows cascode shifted V_{TH} of -0.8 V (normally-off) and drastically enhanced it to ~171 mS/mm, because V_{TH} and $g_{m,max}$ of cascode are determined by those of LV Si p-FET. The HV diamond FET extends the operating voltages of power systems. The maximum drain current density is -20.8mA/mm at V_{DS}= -30V.

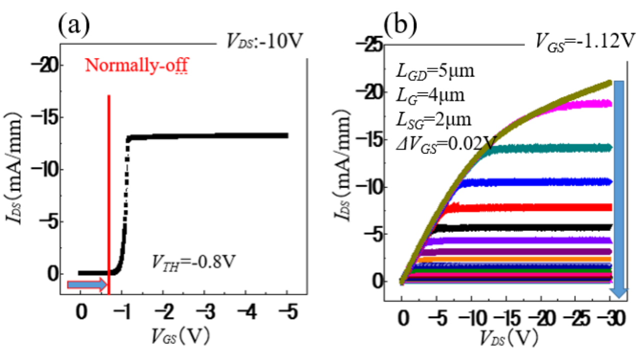

Fig.4 V_{DS}-I_{DS} and V_{GS}- I_{DS} characteristics of the diamond MOSFET after applied in cascode structure.

Breakdown voltage of diamond p-FET Cascode

We test the breakdown voltage characteristic of diamond p-FET cascode and shown in Fig.5. Characteristic shows the breakdown voltage properties of the single-crystalline diamond cascode (L_G=2µm,L_{SG}=2µm,L_{GD}=26µm)and the breakdown voltage reaches 1735V at V_{GS}=0V.

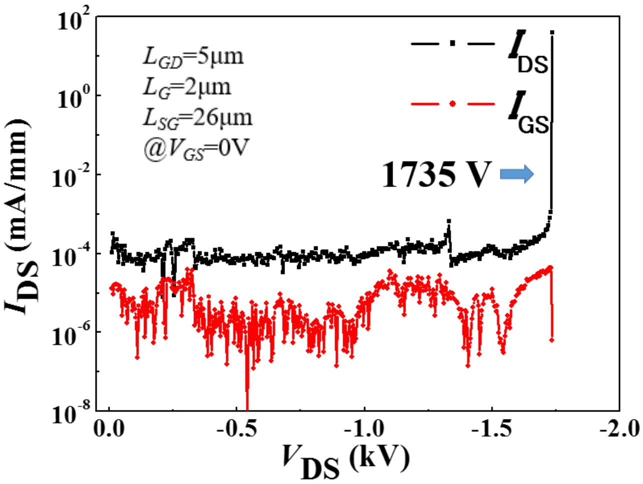

Fig.5 Breakdown voltage of diamond p-FET cascode reaches 1735V at V_{GS}= 0V.

3. Conclusions

The diamond p-FET cascode has been fabricated successfully. Threshold voltage of diamond MOSFET is totally controlled by the LV silicon P-FET in cascode structure, cascode enhanced transconductance of diamond FET and the breakdown takes place in the diamond MOSFET. Result shows the breakdown voltage of diamond p-FET cascode was obtained to 1735V, there is no doubt that this is the top class in semiconductor circuit. We also confirmed the normally-off diamond FET cascode is suitable for high voltage side in complementary inverter.

References

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