D-1-01 Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp179-180

1.2 A/mm Drain Current Density and 1.1 Ω mm Lowest Contact Resistance for 2DHG Diamond MOSFETs Using High Concentration Selective Regrowth B-doped Diamond

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Abstract

High drain current density of diamond MOSFETs with two-dimensional hole gas (2DHG) has been achieved by selectively grown p^{++}-diamond layers using microwave plasma chemical vapor deposition (MPCVD) The contact resistance (R_c) has been reduced to 1.1 Ω mm in diamond by the heavily doped p^{++}-diamond And maximum drain current density and on-resistance of a device with L_G = L_{SD} = 1 µm have 1.2 A/mm and 8.9 Ωmm, respectively.

1. Introduction

Two-dimensional hole gas (2DHG) diamond is a promising material as high power and radio-frequency (RF) transistors due to its remarkable properties such as high breakdown field and the highest thermal conductivity.

The output power density (P_{out}) of RF transistors are described as $P_{out} = \{ I_{DSmax} \times (V_{max} - V_{knee}) \} / 8$, where I_{DSmax} is the maximum drain current density, V_{max} is the maximum drain voltage, and V_{knee} is the knee voltage. Thick ALD-Al_2O_3 (100 nm) diamond MOSFETs were fabricated to improve the V_{max} and P_{out} = 3.8 W/mm, which is the highest in p-channel FETs, was achieved at operating voltage $V_{DS,Q} = -50$ V [1]. However, I_{DSmax} and V_{knee} were restricted by high on-resistance R_{on} = 30 Ω mm [1]. TiC layer was formed on diamond as source and drain contact. However, the contact resistance R_c was 9 Ω mm, which means that 60 % of R_{on} was R_c [1]. In this study, p^{++} intermediate layer was introduced between TiC and 2DHG to reduce the R_c. As a result, R_C = 1.1 Ω mm and I_{DSmax} = 1170 mA/mm were obtained [2]. To the best author's knowledge, R_C = 1.1 Ω mm is the lowest ohmic contact of diamond. The I_{DSmax} = 1170 mA/mm is equivalent to the highest I_{DSmax} reported in diamond FETs [3,5] and has been obtained without additional adsorbates such as PTFE [3,4] or NO_2 [5].

2. Device Fabrication

The fabrication process of the devices is shown in Fig. 1 (a) ~ (d). The MOSFETs were fabricated on a Ib(111) single diamond. At first, undoped layer (500 nm) was epitaxially grown on the diamond substrate to induce 2DHG by MPCVD and the source and drain (S/D) regions on the undoped diamond layer was etched (30 nm depth) selectively by oxygen plasma RIE (Fig.1 (a)). After the etching, 210 nm boron-doped (p^{++}) diamond layer was additionally grown by MPCVD on the etched areas to form S/D regions (Fig.1 (b)). The p^{++} layer and 2DHG can be contacted in many areas by these processes. Second, a Ti/Pt/Au (20/30/90 nm) were deposited taking a margin of approximately 5 µm on p^{++} layer as the S/D electrodes and TiC layers are formed by annealing to improve the adhesion of the electrodes to the p^{++} layers. Third, the whole surface was H-terminated using a remote hydrogen plasma to form the 2DHG layer (Fig.1 (c)). The active areas were isolated by O_2 plasma treatment. Subsequently, 100nm Al_2O_3 film was deposited as gate insulator by high temperature ALD method (Oxidant: H_2O, Temperature: 300 °C). Finally, 100nm Al layer was deposited as gate electrodes (Fig.1 (d)). Fig.2 (a) shows an optical micrograph of the device and Fig. 2 (b) shows a scanning electron microscope (SEM) image of the fabricated device.

3. Results and Discussion

The R_c between p^{++}-diamond layer and 2DHG was evaluated using a transmission-line model (TLM) structure before Al_2O_3 deposition. Fig. 3 shows the normalized resistance of these two electrodes as a function of distance from the results of I-V measurement of the two electrodes separated by varying gaps between p++ -diamond wells. The concentration of boron in this p^{++} diamond layer was approximately 1×10^{22} /cm^3 [6], where the resistivity is less than 1×10^{-3} Ω cm. Therefore, L_{SD} was defined as the length of the p^{++}-diamond sidewall. The S/D length (L_{SD}) was 1 µm and the gate overlapped the S/D region resulting the effective gate length (L_G) 1 µm, R_C = 1.1 Ω mm was obtained from TLM methods. R_C = 1.1 Ω mm is the lowest contact resistance of diamond.

Fig. 4 (a)(b) shows the pulsed I_{DS}-V_{DS} were measured by using a 2 ms pulse width and 5% duty cycle at $V_{GS,Q} = V_{DS,Q}$ = 0 V. When the V_{GS} was ranged from -48 V to 8 V (Fig.4 (a)), the I_{DSmax} was 1120 mA/mm at V_{GS} = -48 V and V_{DS} = -20 V, and the R_{on} was 9.3 Ω mm at V_{GS} = -48 V and V_{DS} = -1 V, respectively. However, according to the pulsed I-V measurement results obtained with V_{GS} ranging from 8 V to -48 V

(Fig.4 (b)), the I_{DSmax} was 1170 mA/mm at V_{GS} = -48 V and V_{DS} = -20 V, and the R_{on} was 8.9 Ω mm at V_{GS} = -48 V and V_{DS} = -1 V, respectively.

4. Conclusion

To improve the P_{out} of the RF MOSFETs, it's important to reduce its on-resistance. We fabricated 2DHG diamond FETs with selectively regrown p^{++}-diamond S/D contacts and R_c of 1.1 Ω mm and I_{DSmax} of 1170 mA/mm were obtained without using additional adsorbates such as NO_2. The R_c was the lowest in diamond.

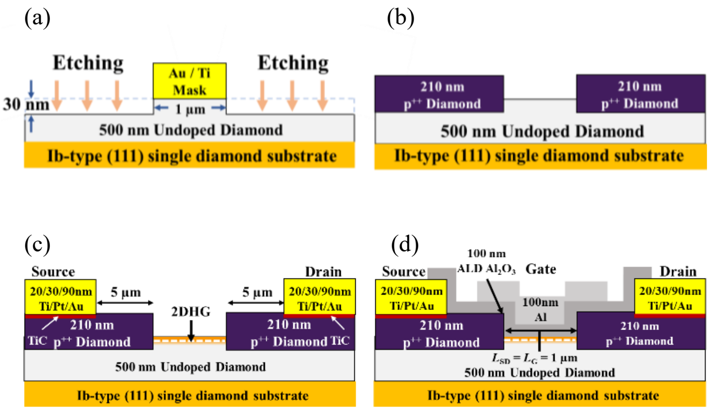

Fig. 1 A cross-sectional view of the 2DHG diamond MOSFETs' fabrication processes. (a) Etching undoped diamond layer selectively by oxygen plasma. (b) Growing p^{++} diamond selectively. (c) Deposition of S/D electrodes and H-termination of the diamond surface. (d) Deposition of the gate insulator and gate electrodes.

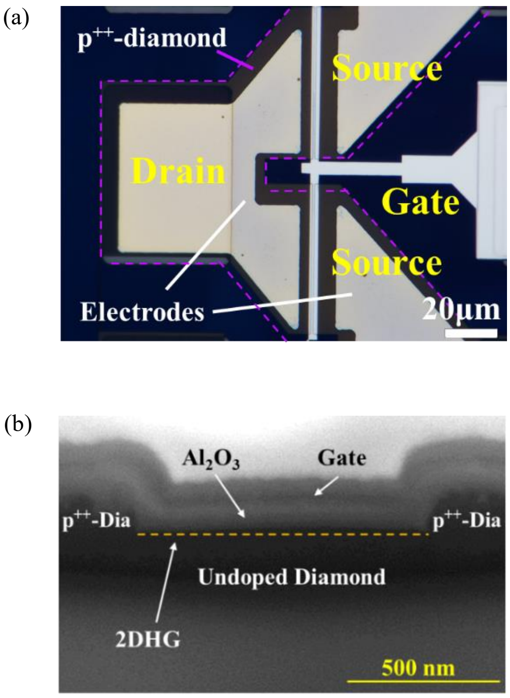

Fig. 2 (a) An optical micrograph of the device (b)Scanning electron microscope (SEM) image of the diamond MOSFET (L_G = 1 µm).

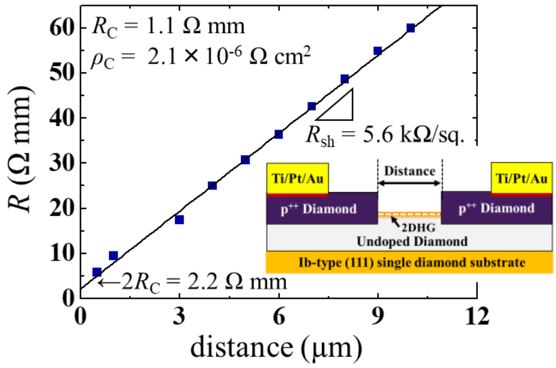

Fig. 3 The on-resistance of two boron-doped electrodes as a function of their distance.

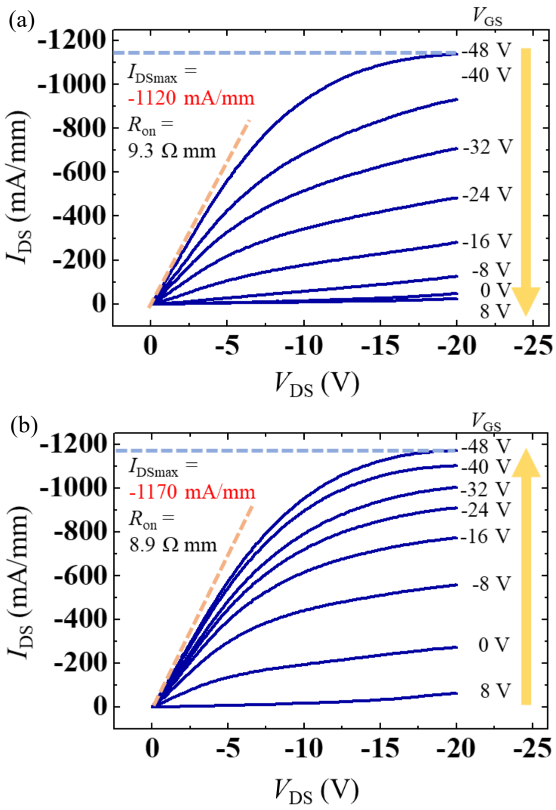

Fig. 4 Pulsed I_{DS}-V_{DS} characteristics of device A with L_{SD} = L_G = 1 µm and W_G = 100 µm with V_{GS} ranging from (a) -48 V to 8 V and (b) 8 V to -48 V. (2 ms pulse width and 5% duty cycle at $V_{GS,Q}$ = $V_{DS,Q}$ = 0 V.).

Acknowledgements

This study was partially supported by Creation of Life Innovation Materials for Interdisciplinary and International Researcher Development.

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