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(111) Vertical-type 2DHG Diamond MOSFETs with Hexagonal Trench Structures

Jun Nishimura[1], Masayuki Iwataki[1], Nobutaka Oi[1], Aoi Morishita[1], Atsushi Hiraiwa[1], Hiroshi Kawarada[1, 2]

[1] School of Fundamental Science & Engineering Waseda Univ.
3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan
Phone:+81-3-5286-3391 E-mail: junjun0806sky@toki.waseda.jp
[2] The Kagami Memorial Laboratory for Materials Science and Technology, Waseda University
2-8-26 Nishiwaseda, Shinjuku-ku, Tokyo 169-0051, Japan

Abstract

We fabricated the vertical-type two-dimensional hole gas (2DHG) diamond metal-oxide-semiconductor field-effect transistors (MOSFETs) with hexagonal trench structures using (111) diamond for the first time. The maximum drain current density per gate width increased about three times compared to that of (001) diamond. Lowest specific on-resistance and highest current density were confirmed by the device with hexagonal trench 12 µm on a side and gate width (W_G) of 72 µm, which are 9.2 mΩcm^2 and -5400 A/cm^2 at V_{DS} : -50 V. These results indicate using (111) diamond is profitable for vertical-type 2DHG diamond MOSFETs.

1. Introduction

In power devices, vertical structure is suitable for low on-resistance and large current operation which are required for power MOSFETs. Therefore, the development of vertical-type device is essential for power electronics. We have fabricated vertical-type diamond MOSFETs [1] using 2DHG which is induced independently of crystal orientation by C-H termination structure and high temperature ALD-Al_2O_3 [2]. In this work, we fabricated vertical-type 2DHG diamond MOSFETs with hexagonal trench structures using the (111) diamond for the first time. The maximum current density obtained from these devices at the same drain voltage V_{DS} (-50 V) is three times higher than in the previous work [1]. Lowest specific on-resistance and highest current density were confirmed by the device with inner trench length of 12 µm on each side.

2. Device Fabrication

The cross-sectional view of the vertical-type 2DHG diamond MOSFETs with hexagonal trench structure is shown in Fig.1. Fig.2 shows an optical micrograph of the hexagonal trench device with 20 µm side (W_T), the active area and scanning electron microscope (SEM) image of the hexagonal trench. The active area is defined by the part painted in blue. The undoped layer and nitrogen-doped layer was epitaxially grown on the (111) p+ diamond substrate by microwave plasma chemical vapor deposition (MPCVD). The thickness of undoped and nitrogen-doped layer were 500 nm and 1.5 µm, respectively. The nitrogen-doped layer (8×10^{18}-1×10^{19} cm^{-3}) worked as a current blocking layer. Hexagonal trench structure was formed by O_2 gas inductive coupled plasma reactive ion-etching. Length on each side of the trenches was 10-20µm, and depth (D_T) was fixed at 3.0 µm. 200 nm re-growth undoped layer was deposited by MPCVD after trench fabrication to induce the 2DHG and to recover the etching damages. Ti/Au (10/250 nm) were deposited to form drain electrode on the back side of the substrate and Al (100 nm) was deposited to form gate electrodes. The gate length was fixed to 6µm, while 3 µm (half) of the gate overlapped with the source electrodes. This overlapping structure is advantageous for eliminating the resistance between the source and gate (R_{SG}) and reducing the device area. Gate-trench distance (L_{GT}) was 3~5 µm. Thus, the total length between gate and drain (L_{GD}), which was defined as distance from gate edge to p$^+$ substrate, was 5~7 µm and gate width (W_G) was defined as the outer periphery of the trench (60 - 120 µm) for standardization.

3. Results and Discussion

The drain current density (I_{DS}) normalized by gate width exceeds 400 mA/mm in each of the four types of devices at drain voltage (V_{DS}) of -50 V. Fig.3 (a) and (b) show I_{DS}-V_{DS} characteristics with 12 µm trench length on each side (W_G : 72 µm). Maximum drain current density at V_{DS} of -20 V and -50 V are -250 mA/mm and -680 mA/mm, respectively. These values are three times higher than the maximum drain current density of vertical-type (001) diamond FETs at the same V_{DS} (-50 V) [1]. It is derived from the fact that the sheet resistance of the (111) diamond is lower than that of the (001) diamond [3]. Therefore, fabricating vertical-type 2DHG diamond MOSFETs having hexagonal trenches structure on the (111) diamond greatly improves the current density and on-resistance. Fig.4 shows I_{DS}-V_{GS} characteristics at room temperature. On/off ratio is about 8.5 orders of magnitude. As a result, the film thickness and concentration of the nitrogen-doped layer as the current blocking-layer are sufficient. Threshold voltage determined by $\sqrt{I_{DS}}$-V_{GS} characteristics at V_{DS} of -10 V is 33.2 V. The relationship between drain current density and specific on-resistance normalized by device active area (Fig.2 (b)) is shown in Fig.5. Also shown in Fig.5 is the line approximated by measured values. Maximum drain current density and minimum specific on-resistance are obtained by the device with a hexagonal trench side W_T of 12 µm and a gate width W_G of 72 µm ($6W_T$).

Maximum drain current density and lowest specific on-resistance are -5400 A/cm^2 and 9.2 mΩcm^2, respectively. In addition, on-resistance decreases with the decrease of hexagonal trench side (W_T). Variations in specific on-resistance due to reduced hexagonal trench side (W_T) will be improved by the reconsideration of etching methods and regrowth layer. Further performance enhancement in the smallest hexagonal structure devices is of great importance and benefit to close-packed structures with smaller W_T.

4. Conclusion

We have fabricated (111) vertical-type 2DHG diamond MOSFETs with hexagonal trench structures for the first time. Maximum drain current is -680 mA/mm at V_{DS} of -50 V and on/off ratio is about 8.5 digits. Lowest specific resistance is obtained by a device which has with gate width of 72 µm, which is 9.2 mΩcm^2. Drain current and on-resistance can be improved by adjusting the roughness of trench sidewalls and reducting the device area.

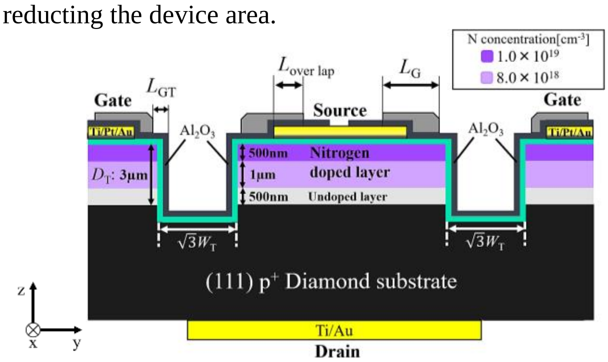
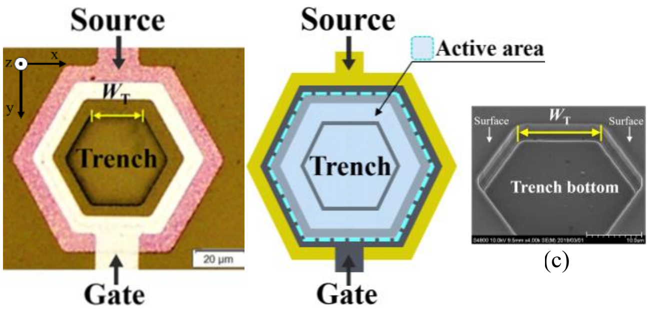


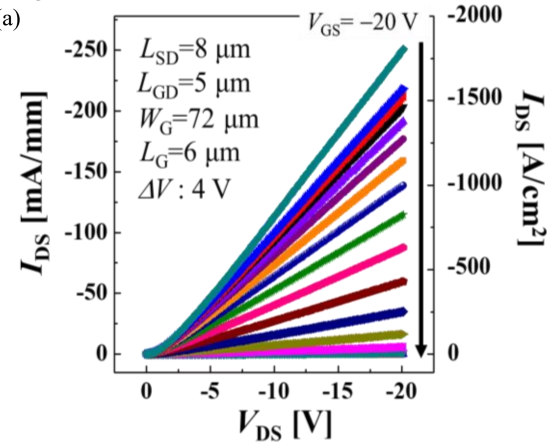
Fig.1 Cross sectional image of vertical-type diamond MOSFETs.



(a) (b) (c)

Fig.2 (a) An optical micrograph of the device. (b) Device active area image. (c) The scanning electron microscope (SEM) image of the hexagonal trench.

(a)



(b)

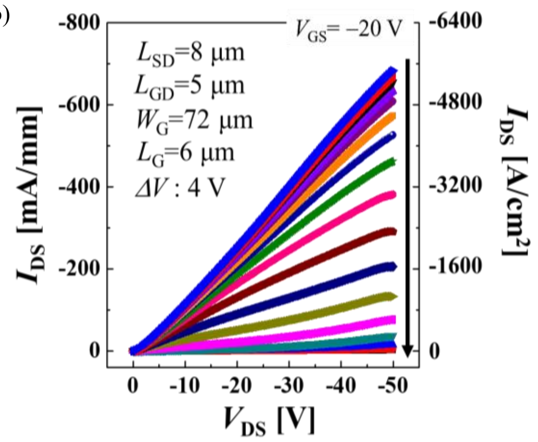


Fig.3 I_{DS}-V_{DS} characteristics. (a) The maximum drain current density was -250 mA/mm at V_{DS} and V_{GS} of –20 V and −20 V. (b) The maximum drain current density was -680 mA/mm at V_{DS} and V_{GS} of –50 V and −20 V. (W_G = 72 µm, L_{SD} = 8 µm, L_{GD} = 5 µm)

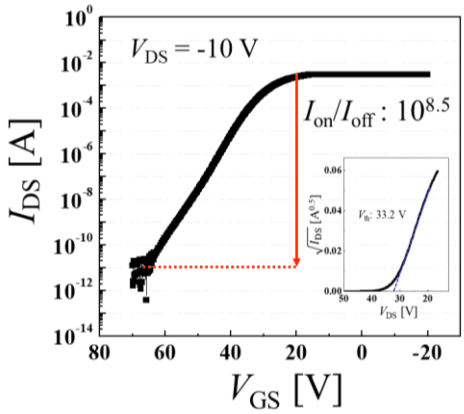


Fig.4 I_{DS}-V_{GS} characteristics at room temperature. On/off ratio was 8.5 orders of magnitude. Threshold voltage is 33.2 V.

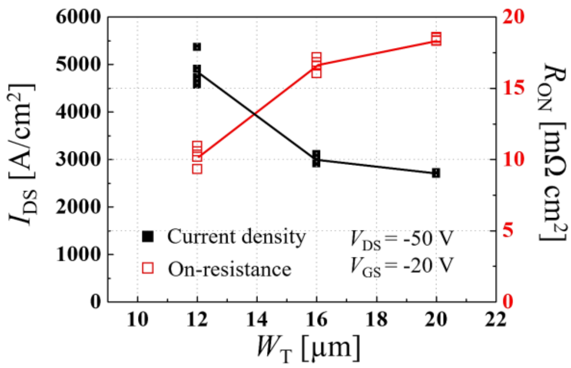


Fig.5 The hexagonal trench side (W_T) dependence of drain current density at V_{GS} of -50 V and V_{GS} of -20 V, and specific on-resistance. Drain current density are indicated by closed symbol and specific on-resistance are indicated by opened symbol.

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