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High hole current density in diamond MOSFETs fabricated on H-terminated IIa-type (111) diamond substrate

Kyosuke Tsuge[1], Yoshikatsu Jingu[1], Hitoshi Umezawa[2] and Hiroshi Kawarada[1]
[1]Univ. of Waseda, Faculty of Science and Engineering
3-4-1, Okubo, Shinjuku, Tokyo 169-8555, Japan
Phone: +81-3-5286-3391 E-mail: k1.t1.tsuge-0521@suou.waseda.co.jp
[2]National Institute of Advanced Industrial Science and Technology
Tsukuba, Ibaraki 305-8568, Japan

1. Introduction

High-performance RF diamond transistors have been reported using the hole accumulation layer on the surface of hydrogen-terminated diamond for the channel. Most are for (001) substrates, where homoepitaxial films are easily obtained compared with low indexed surfaces. However, the sheet carrier density of the hole accumulation layer in (111) substrates is higher than that in (001) substrates [1]. In this study, MOSFETs were fabricated on the (111) substrates by the self-aligned gate fabrication process [2]. The maximum value of drain current density normalized by gate width is –850mA/mm, which is the highest in diamond FETs.

2. High hole accumulation density on (111) surfaces

Due to the electronegativity difference between H (2.1) and C (2.4), the interface charge density by the H(+0.05e)-C(-0.05e) dipole is about 1×10^{14} e cm^{-2}. Negatively charged adsorbates are attracted to the H-side (surface side) and holes are induced to satisfy the charge neutral condition (Fig. 1).

The hole accumulation depends largely on the dipole density. Figure 2 shows a schematic representation of the top and side views of hydrogen-terminated (001) and (111) flat surfaces obtained by low-energy electron diffraction. After hydrogen plasma treatment, the stable surfaces are hydrogen-terminated (001) and (111), where the C-H bond densities are 1.6×10^{15} and 1.8×10^{15} cm^{-2}, respectively. Considering C-H bond angles to the surface, the dipole density of the hydrogen-terminated (111) surface is 1.23 times higher than the C-H bond density at the hydrogen-terminated (001) surface. The average hole accumulation density of (111) is $2.5\times10^{13}cm^{-2}$, which is 1.5 to 2 times higher than that of (001).

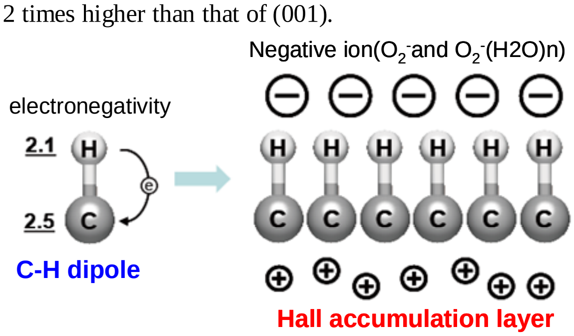

Fig. 1 Schematic model of hole accumulation layer formed by H-C surface dipoles due to the electronegativity difference between H (2.1) and C(2.5).

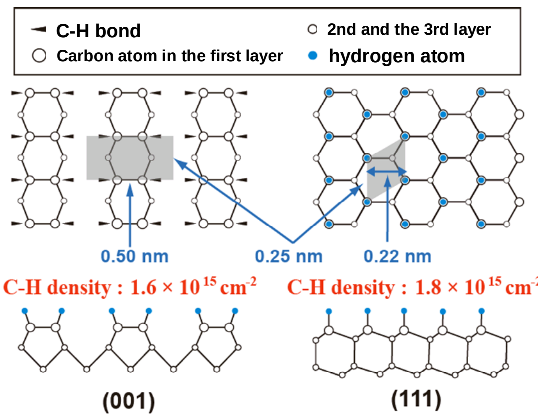

Fig.2 Top and cross-sectional views of hydrogen terminated (001) and (111) surfaces. The shaded area represents a unit cell.

3. Experiments

IIa-type single crystalline (111) substrates (3 mm × 3 mm × 0.5 mm) with hydrogen-terminated surfaces were used for fabricating diamond MOSFET. The microwave power, pressure, and temperature of the substrate during hydrogen plasma treatment were 750 W, 35 Torr, and 500°C, respectively. The surface after treatment was flat, and the roughness was less than 1 nm. The sheet carrier density, mobility, and sheet resistance of the hole accumulation layer evaluated with the Hall effect measurement were $2.0 – 3.0\times10^{13}/cm^2$, 50 cm^2/Vs, and 7 kohm/sq, respectively.

Figure 3 shows the schematic of diamond MOSFET fabricated on hydrogen-terminated (111) substrate.

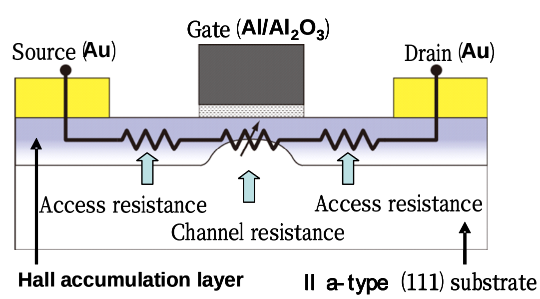

Fig. 3 Schematic of diamond MOSFET by the self-aligned gate fabrication process

4. Results and Discussion

Figure 4 shows the I_{DS}-V_{DS} characteristics of diamond MOSFET (gate length: 0.3 μm; gate width: 50 μm) fabricated on hydrogen-terminated (111) substrate. The maximum value of drain current density normalized by gate width was –850mA/mm, the highest value in diamond FET reported to date. The typical I_{DS}-V_{DS} characteristics of diamond MOSFET fabricated on undoped epitaxial thin film in (001) substrate are shown in Fig. 5. The maximum value of drain current density normalized by gate width on (001) substrate was –350 mA/mm.

The resistance between drain and source, which determines the drain current, consists of the channel resistance beneath the gate electrode and the parasitic resistance (access resistance) from source to channel and from channel to gate. As shown in Fig.3, the access resistance which limits the drain current is proportional to the sheet resistance in the hole accumulation layer. The excellent drain current density in the present study is due to the low access resistance originating from the low sheet resistance of the (111) surface. The drain leak current caused by residual acceptors of the substrate was not observed and excellent pinch-off characteristics were obtained (Fig. 4). This is a distinct advantage of IIa-type substrate with low residual impurities.

The difference in threshold voltage (Vth) between (001) substrate and (111) substrate is very large. In general, the characteristics of diamond FET with submicron gate length is normally on (Vth > 0), and there are many holes beneath the gate oxide without the bias voltage (floating state). The V_{th} of the MOSFET on (111) substrate in the present study were about +3.0 V, while V_{th} were about +1.5 V in (001) diamond FETs. These observations indicated that there are more holes beneath the gate oxide in the floating state in the (111) substrate due to the high sheet carrier density in the (111) substrate. The differences in the maximum value of drain current density and the threshold voltage between (111) and (001) substrates were due to the differences in carrier density in the hole accumulation layer. The present study clarified that the differences in the surface influenced the characteristics of diamond MOSFET.

Fig. 6 shows the RF characteristic with gate length of 0.3 μm and gate width of 25 μm, where f_T = 22 GHz and fmax = 25 GHz were obtained in the RF measurement. The values are expected to be improved by gate shrinkage and T-shaped gate structure.

5. Conclusion

In the present study, diamond MOSFET were fabricated on IIa-type (111) substrate. The maximum value of the drain current density, –850mA/mm, was achieved as a result of fabricating the diamond MOSFET with a gate length of 0.3 μm.

Acknowledgments

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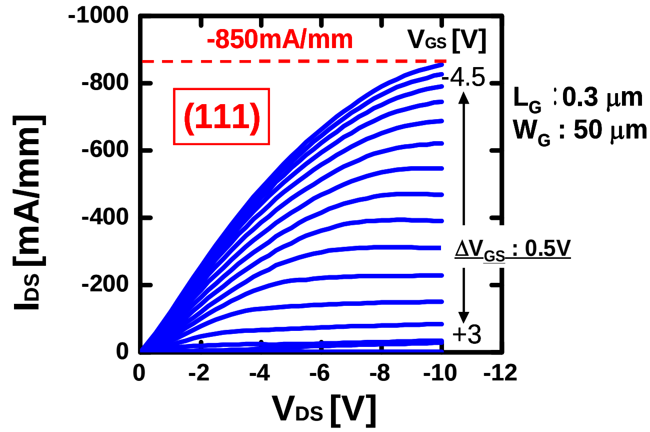

Fig. 4 I_{DS}-V_{DS} characteristics of diamond MOSFET on (111) substrate.

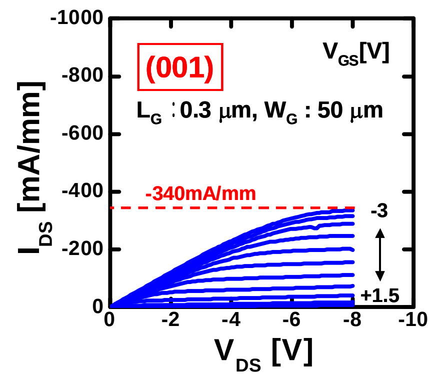

Fig. 5 I_{DS}-V_{DS} characteristics of diamond MOSFET on (001) substrate.

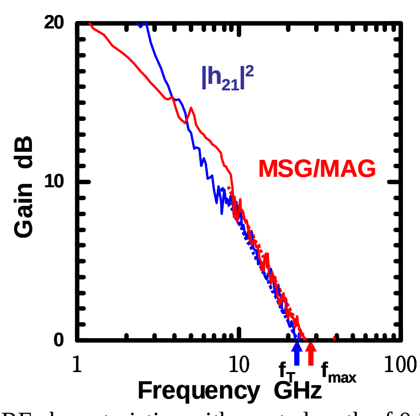

Fig.6 RF characteristics with a gate length of 0.3 μm and width of 25 μm. Current gain ($|h_{21}|^2$), maximum stable gain (MSG), and maximum available gain (MAG) as functions of frequency.