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High hole current achievement of hydrogen-terminated diamond MOSFETs coated with Poly-tetra-fluoro-ethylene

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1. Introduction

It is well known that hydrogen-terminated (H-terminated) diamond has a hole accumulation layer however its origin has not been completely understood, and various models have been proposed [1,2]. (However,) In most of models these, the hole accumulation layer is obtained via the adsorption of molecules from the air onto C-H bonds on the H-terminated diamond surface.

The hole accumulation layer can also be induced, in a similar method, by other insulating materials [3,4]. For example, it has been reported that fuluoro-fullerene induces the conductivity of the H-terminated diamond surface and that its conductivity is higher than that of air adsorbates [5]. Herein, H-terminated diamond Metal-oxide-semiconductor field-effect transistors (MOSFETs) have been coated with Poly-tetra-fluoro-ethylene (PTFE), which has a comparable structure to fluoro-fullerene, and the enhancement of conductivity and drain current value has been investigated.

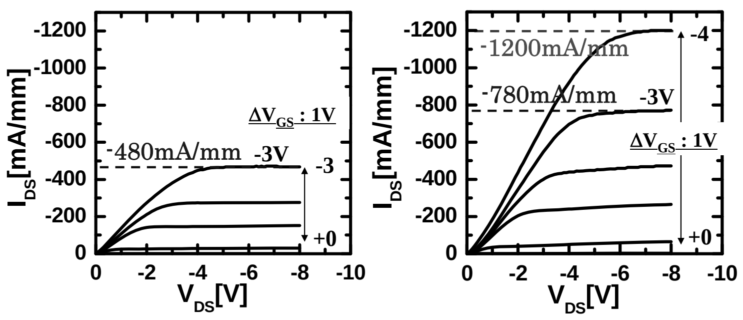
2. Experimental

IIa-type (111) diamond substrates have been used to obtain high drain current value on the MOSFETs. The MOSFETs are expected to show high performance drain current because of the sheet resistance of the H-terminated (111) surface (~5kΩ/sq.) of diamond is lower than that of (001) surface (~10kΩ/sq.). This lower sheet resistance is due to high the C-H dipole density [6]. The C-H density on (111) substrates ($1.8\times10^{15}cm^{-2}$) is 1.13 times higher than (001) substrates. Furthermore, considering the C-H bond of the (001) surface is angled, the C-H dipole density on (111) substrates is 1.2 times higher than (001) substrates. The IIa-type diamond substrates have been exposed to hydrogen plasma resulting in H-terminated surfaces.

The MOSFETs have been fabricated on H-terminated diamond surface by using the self-alignment process [7]. First, gold (Au) is deposited on an H-terminated diamond substrate by resistive heating evaporation. The gold is used as the ohmic metal for the source and drain electrodes, with a thickness of 100nm. The MOSFETs pattern is drawn by EB lithography, and the Au is patterned via wet chemical etching to separate the source and drain electrodes. Next to fabricate the gate, employing the lift off process Aluminum (Al) is thinly (3nm) deposited on the channel area, and then is oxidized into aluminum oxide (Al_2O_3) to serve as the gate insulator. Al (100nm) is then deposited onto the aluminum oxide to act as the gate electrode. The insulator and gate electrode are deposited through the same resist mask used for the Au etching. The unneeded part of Al/Al_2O_3 layer is then lifted-off. Finally, The H-terminated diamond MOSFETs are coated with PTFE. This PTFE is in the form of a dispersion liquid of 0.3um particles in iso-propyl alcohol. The MOSFETs are spin coated with the PTFE, and the drain current of the MOSFETs are compared with the MOSFETs operating under in-air conditions.

3. Results and Discussion

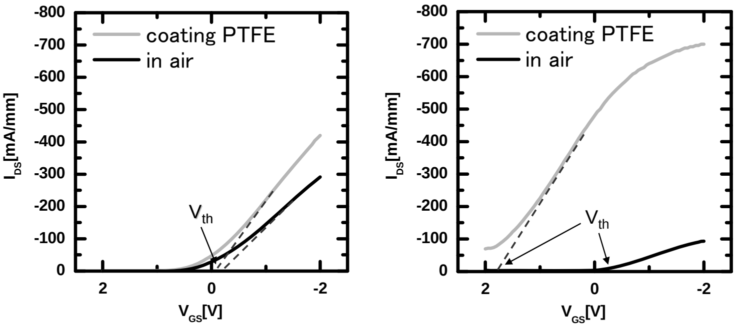
Fig.1 shows typical drain current-voltage (I_{DS}-V_{DS}) characteristics of the H-terminated diamond MOSFET in air (a) and coated with PTFE (b). The gate length (L_g) of the MOSFET is 0.5 μm. For in-air exposure, the drain current of the MOSFET is -480 mA/mm at a drain voltage (V_{DS}) of -8V, and a gate voltage (V_G) of -3V. After coating with PTFE, the drain current of MOSFET is -780 mA/mm at the same V_{DS} and V_G. The Drain current of the H-terminated diamond MOSFET is enhanced by approximately 1.6 times following PTFE coating. Transconductance (g_m) of the MOSFET is -200 mS/mm at V_{DS} = -8V and V_G = -3V. After PTFE coating, g_m = -300 mS/mm at the same V_{DS} and V_G, thence the g_m of the H-terminated diamond MOSFET is enhanced 1.5 times after PTFE coating. The maximum drain current (I_{DSmax}) and transconductance (g_{mmax}) of MOSFET coated with PTFE are -1.2 A/mm and -430 mS/mm. This drain current of -1.2 A/mm is the highest value reported in diamond field-effect transistors (FET) to date.



(a) (b)

Fig.1 (a) V_{DS}-I_{DS} characteristics of a 0.5μm gate-length H-terminated diamond MOSFET on IIa type (111) substrate without PTFE. (b) Same device after PTFE coating.

Fig.2 shows I_{DS}-V_{GS} characteristics at a V_{DS} of -4V of the MOSFET with L_g of 0.5 μm (a) and 0.2 μm (b). Threshold voltage (V_{th}) is obtained at the crossing point of the extrapolarated tangent and x-axis. The V_{th} shifts little (0 V) and g_m increases (140 mS/mm to 210 mS/mm) at L_G = 0.5 μm. However, V_{th} shifts to normally-on operation (- 0.3 V to + 2 V) and g_m increases (60 mS/mm to 260 mS/mm) at L_G = 0.2 μm.



(a) (b)

Fig.2 (a) I_{DS}-V_{GS} characteristic of a 0.5μm gate-length diamond MOSFET on IIa-type (111) substrate (in-air and PTFE coating). (b) I_{DS}-V_{GS} characteristic of a 0.2μm gate-length diamond MOSFET on diamond substrate (in-air and PTFE coating).

PTFE is a polymer that has a structure of two fluorine atoms sandwiching a carbon atom. PTFE is globally neutral, however, it is considered that the difference in electronegativity between the fluorine (3.98) and carbon (2.55) atoms polarizes carbon with +δ and fluorine with –δ. And hole accumulation layer is induced on the H-terminated diamond surface by the –δ of the fluorine that are nearest to diamond surface as shown in Fig.2. So, the enhancement of drain current of MOSFETs fabricated on (111) H-terminated diamond is probably caused by a reduction of R_S and R_D (that are the parasitic resistances in H-terminated diamond MOSFET) due to the effect of PTFE enhancing a hole accumulation layer.

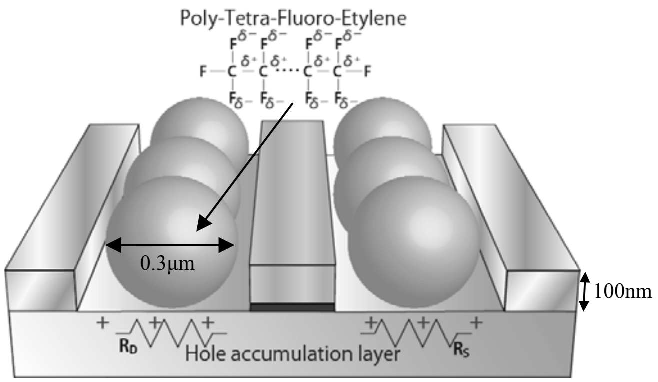


Fig.3 Hole induction model of a H-terminated (111) diamond MOSFET coated with polarized PTFE that is 0.3μm particle.

Several hypotheses are considered to explain cause of these results. One is the increase of the hole carriers in the hole accumulation layer. It can reasonably explain the reduction of the resistances (R_D and R_S) and the V_{th} shifts in fig.2 (b) wherein the hole carriers traverse under the gate-electrode from source-gate and drain-gate drift region. Conversely, another one is that PTFE increases the carrier mobility because the electrical charge of fluorine atoms in PTFE is weak and its coulomb scattering center is remote compare with that of air adsobates. Finally, it could be the effective channel-length is shortened by some kind of influence, and short channel effect comes to the surface.

These results imply that the output performance of H-terminated diamond MOSFETs is indeed linked to the condition of H-terminated diamond surfaces. Compared to the MOSFETs in air, the performance of H-terminated diamond MOSFETs is enhanced by coating with PTFE. Thus, PTFE can be used to increase drain current of H-terminated diamond MOSFETs.

4. Conclusions

In this work, the characteristics of H-terminated diamond MOSFETs operated under in air conditions and with PTFE coating have been compared. The H-terminated diamond MOSFET coated with PTFE shows higher drain current than the same MOSFET with air adsorbates. As a result, the drain current of the (111) diamond MOSFET achieves I_{DSmax} = -1.2 A/mm and g_{mmax} = 430 mS/mm.

PTFE is polarized due to the difference of electronegativity between C and F, and therefore enhances a hole accumulation layer. Several hypotheses are considered to explain about these results.

References

[1]F. Maier, M. Riedel, B. Mantel, J. Ristein and L. Ley, *Physical Review Letters* 85-16 (2000) 3472

[2] V. Chakrapani, J. C. Angus, A.B. Anderson, S. D. Wolter, B. R. Stoner, and G. U. Sumanasekera, *Science* 318 (2007) 1424.

[3]S. Miyamoto, H. Matsudaira, H. Ishizaka, K. Nakazawa, H. Taniuchi, H. UmezawaM. Tachiki and H. Kawarada, *Diamond Related Materials* 12 (2003) 399-402.

[4] M. Kubovic and M. Kasu, *Applyed Physics Express* 2 (2009) 086502.

[5] P. Strobel, M. Riedel, J. Ristein, L. Ley, O. Boltalina, *Diamond Related Materials* 14 (2005) 451-458.

[6] K. Hirama, K. Tsuge, S. Sato, T. Tsuno, Y. Jingu, S. Yamauchi and H. Kawarada, *Applyed Physics Express* 3 (2010) 044001

[7] K. Hirama, T. Koshiba, K. Yohara, H. Takayanagi, S. Yamauchi, M, Satoh and H. Kawarada, *2006 IEEE International Symposium on Power Semiconductor Devices and ICs*, pp. 1-4