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Normally-Off 2DHG Diamond Al_2O_3/SiO_2 MOSFETs without Deteriorating Drain Current Density

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Abstract

Two-dimensional hole gas (2DHG) diamond metal-oxide-semiconductor field-effect transistors (MOSFETs) show normally-on characteristic and comparable performance with other n-channel wide band gap semi-conductors. However normally-off operation is required from the viewpoint of safety operation. We introduce SiO_2 thin film to the interface between Al_2O_3 and hydrogen-terminated (C-H) diamond to control threshold voltage of 2DHG diamond MOSFETs. Here, we demonstrated that theSiO_2 inserted MOSFETs showed gate threshold voltage (V_{th}) of from −6 to −2 vindicating normally-off without deteriorating drain current density.

1. Introduction

Wide band gap semiconductors such as SiC, GaN and diamond are expected to be next generation power devices. Especially, diamond has wide band gap energy (5.5 eV), high thermal conductivity (20 W/cm・K) [1, 2] and high breakdown field (10 MV/cm). Furthermore, diamond has a unique property that the 2DHG is induced by the negative electron affinity (NEA) when diamond surface is hydrogen-terminated. The 2DHG formed on C-H diamond surface has some useful aspects such as high carrier density (~10^{13} /cm^2) [3] and simple fabrication of FETs. Then, C-H diamond has been applied to 2DHG diamond MOSFETs by the passivation of Al_2O_3 insulator deposited by high-temperature atomic layer deposition (ALD) method [4]. We have reported high breakdown voltage characteristics ~2000 V [5] and operations in wide temperature range from 10 to 673 K [6]. Generally, 2DHG diamond MOSFETs have normally-on operation because 2DHG channel is induced by surface negatively charged adsorbates without negative bias voltage. But, power devices are required normally-off for safety operations. Normally-off diamond FETs have been already reported such as partially oxidized (C-O) diamond metal-insulator-semiconductor field-effect transistors (MISFETs) [5,7], HfO_2-gated diamond FETs [8], Junction FETs with submicrometer channel [9] and Inversion channel diamond MOSFETs [10].

In this study, we demonstrated normally-off operation by the insertion of thin SiO_2 layer between diamond/Al_2O_3 interface and improved the adhesion of Al_2O_3 to the C-H diamond surface by chemical bonding between SiO_2 and Al_2O_3.

2. 2DHG diamond Al_2O_3/SiO_2 MOSFETs

The cross-sectional schematic image of the 2DHG diamond Al_2O_3/SiO_2 MOSFETs is shown in Fig. 1. The fabrication process is as follows. First, undoped layer was deposited on Ib (001) single diamond substrate by chemical vapor deposition (CVD) method and Ti/Au (30 nm/100 nm) were deposited as source and drain electrodes. Second, the diamond surface was hydrogen-terminated by remote plasma. The isolation was performed by O_2 plasma ashing. Third, Al_2O_3 film (32 nm) was deposited as mask by high-temperature ALD method (Oxidant: H_2O, Temperature: 450 ℃) [4]. Forth, Si thin film (1 nm) was deposited by electric heating evaporation at 450 ℃. Then, Si was partially oxidized by atmospheric exposure. Al_2O_3 film (200 nm) was deposited as insulator and passivation by high-temperature ALD method again. Finally, Al (100 nm) was deposited as gate electrode.

Fig. 2 shows the sheet resistivity after hydrogen-termination, SiO_2 formation and Al_2O_3 deposition measured by the van der Pauw method. After hydrogen-termination, sheet resistivity showed 1 - $3 \times 10^4\ \Omega/\text{sq}$. After SiO_2 formation, sheet resistivity rose to $\sim 10^5\ \Omega/\text{sq}$ because of thermal desorption of negatively charged adsorbates. Fig. 3(a) shows the X-ray photoelectron spectroscopy (XPS) at SiO_2/Si formation. After Al_2O_3 deposition, sheet resistivity showed $\sim 10^6\ \Omega/\text{sq}$. 2DHG was not induced by SiO_2 in spite of negative charge in Al_2O_3 [11] because of negative charge in Al_2O_3 far from C-H diamond. Negative charge in Al_2O_3 was screened by SiO_2 insulator. Therefore, sheet resistivity showed $\sim 10^6\ \Omega/\text{sq}$. In addition, SiO_2/Si was completely oxidized to SiO_2 to form 2nm thick film through high temperature (450℃) ALD. It was confirmed by XPS shown in Fig. 3(b).

Fig. 4 shows the on state $I_{\text{DS}} - V_{\text{DS}}$ characteristics with the drain current V_{GS} from −40 to 28 V, and the step (ΔV_{GS}) of 4 V. The maximum drain current density $I_{\text{DSmax}} = -55$ mA/mm was achieved ($V_{\text{DS}} = -50$ V, $V_{\text{GS}} = -40$ V). Here, the size of the device was respectively $L_{\text{SG}} = 2\ \mu\text{m}$, $L_{\text{G}} = 10\ \mu\text{m}$ and $L_{\text{GD}} = 15\ \mu\text{m}$. Fig. 5 shows the $\sqrt{I_{\text{DS}}} - V_{\text{GS}}$ characteristics, where Threshold voltage $V_{\text{th}} = -6$ V (normally-off) was achieved. Obtained I_{DSmax} is reciprocally related to the V_{th}. V_{th} of −2 V produces

I_{DSmax} of 140 mA/mm, which is one of the highest in normally-off MOSFETs.

3. Conclusions

We demonstrated the 2DHG was reduced by SiO_2 formed between Al_2O_3 and diamond surface. In addition, we fabricated 2DHG diamond Al_2O_3/SiO_2 MOSFETs and confirmed the gate threshold voltage shift. The MOSFETs exhibited the threshold voltage of from −6 to −2 V (normally-off) with high I_{DSmax} from 55 to 140 mA/mm

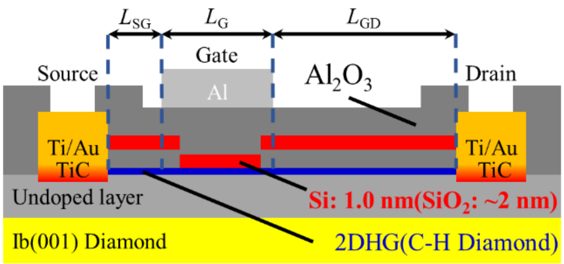

Fig. 1 The cross-sectional illustration of the 2DHG diamond Al_2O_3/SiO_2 MOSFETs

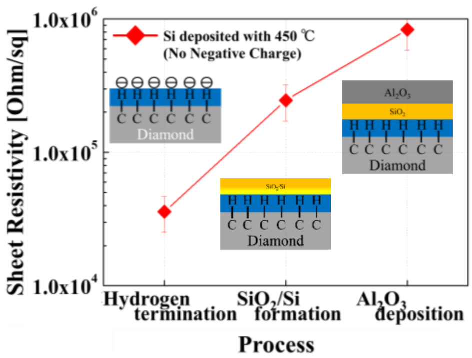

Fig. 2 The sheet resistivity after hydrogen-termination, SiO_2 formation and Al_2O_3 deposition

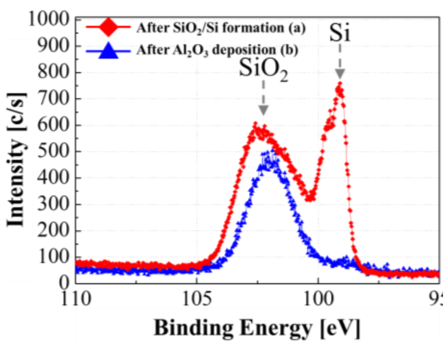

Fig. 3 The XPS spectra of 1nm deposited Si on C-H diamond (001) surface

(a) after Si deposition of 1nm and air exposure. SiO_2 and Si coexist.

(b) after Al_2O_3 ALD process at 450°C and removed only Al_2O_3

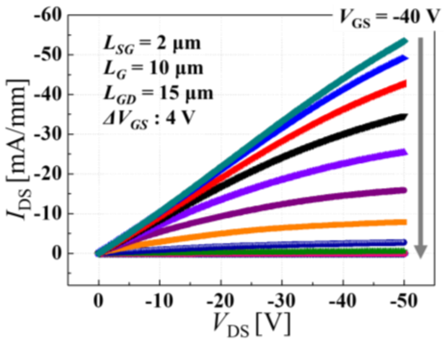

Fig. 4 $I_{DS} - V_{DS}$ characteristics

The maximum drain current density (I_{DSmax}) is −55 mA/mm

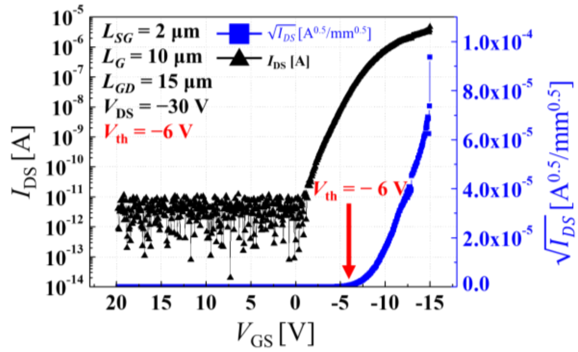

Fig. 5 $\sqrt{I_{DS}} - V_{GS}$ characteristics

The threshold voltage (V_{th}) is −6 V

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