Normally-Off 2DHG Diamond Al$_2$O$_3$/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-off characteristic and comparable performance with other n-channel wide band gap semiconductors. However normally-off operation is required from the viewpoint of safety operation. We introduce SiO$_2$ thin film to the interface between Al$_2$O$_3$ and hydrogen-terminated (C-H) diamond to control threshold voltage of 2DHG diamond MOSFETs. Here, we demonstrated that the SiO$_2$ inserted MOSFETs showed gate threshold voltage ($V_{th}$) of from $-6$ to $-2$ indicating 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 ($\sim 10^{13}$/cm²) [3] and simple fabrication of FETs. Then, C-H diamond has been applied to 2DHG diamond MOSFETs by the passivation of Al$_2$O$_3$ insulator deposited by high-temperature atomic layer deposition (ALD) method [4]. We have reported high breakdown voltage characteristics $\sim$2000 V [5] and operations in wide temperature range from 10 to 673 K [6]. Generally, 2DHG diamond MOSFETs have normally-on operation because 2DHG channel is induced by surface negatively charged adsorbates without negative bias voltage. But, power devices are required normally-off for safety operations. Normally-off diamond FETs have been already reported such as partially oxidized (C-O) diamond metal-insulator-semiconductor field-effect transistors (MISFETs) [5,7], HfO$_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$_2$O$_3$ interface and improved the adhesion of Al$_2$O$_3$ to the C-H diamond surface by chemical bonding between SiO$_2$ and Al$_2$O$_3$.

2. 2DHG diamond Al$_2$O$_3$/SiO$_2$ MOSFETs

The cross-sectional schematic image of the 2DHG diamond Al$_2$O$_3$/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$_2$O$_3$ film (32 nm) was deposited as mask by high-temperature ALD method (Oxidant: H$_2$O, Temperature: 450 °C) [4]. Forth, Si thin film (1 nm) was deposited by electric heating evaporation at 450 °C. Then, Si was partially oxidized by atmospheric exposure. Al$_2$O$_3$ 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$_2$O$_3$ deposition measured by the van der Pauw method. After hydrogen-termination, sheet resistivity showed $1 \times 3 \times 10^8$ Ω/sq. After SiO$_2$ formation, sheet resistivity rose to $\sim 10^5$ Ω/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$_2$O$_3$ deposition, sheet resistivity showed $\sim 10^6$ Ω/sq. 2DHG was not induced by SiO$_2$ in spite of negative charge in Al$_2$O$_3$ [11] because of negative charge in Al$_2$O$_3$ far from C-H diamond. Negative charge in Al$_2$O$_3$ was screened by SiO$_2$ insulator. Therefore, sheet resistivity showed $\sim 10^6$ Ω/sq. In addition, SiO$_2$/Si was completely oxidized to SiO$_2$ to form 2nm thick film through high temperature (450 °C) ALD. It was confirmed by XPS shown in Fig. 3(b).

Fig. 4 shows the on state $I_{DS} \sim V_{DS}$ characteristics with the drain current $V_{GS}$ from $\sim$40 to 28 V, and the step ($\Delta V_{GS}$) of 4 V. The maximum drain current density $I_{DS,max} = 55$ mA/mm was achieved ($V_{DS} = -50$ V, $V_{GS} = -40$ V). Here, the size of the device was respectively $L_S = 2$ μm, $L_G = 10$ μm and $L_{GD} = 15$ μm. Fig. 5 shows the $\sqrt{I_{DS} \sim V_{GS}}$ characteristics, where Threshold voltage $V_{th} = -6$ V (normally-off) was achieved. Obtained $I_{DS,max}$ is reciprocally related to the $V_{th}$. $V_{th}$ of $-2$ V produces
$I_{DS\text{max}}$ 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$_2$O$_3$ and diamond surface. In addition, we fabricated 2DHG diamond Al$_2$O$_3$/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 $I_{DS\text{max}}$ from 55 to 140 mA/mm

Fig. 1 The cross-sectional illustration of the 2DHG diamond Al$_2$O$_3$/SiO$_2$ MOSFETs

Fig. 2 The sheet resistivity after hydrogen-termination, SiO$_2$ formation and Al$_2$O$_3$ deposition

Fig. 3 The XPS spectra of 1 nm deposited Si on C-H diamond (001) surface
(a) after Si deposition of 1 nm and air exposure. SiO$_2$ and Si coexist.
(b) after Al$_2$O$_3$ ALD process at 450°C and removed only Al$_2$O$_3$

Fig. 4 $I_{DS} - V_{DS}$ characteristics
The maximum drain current density ($I_{DS\text{max}}$) is $-55$ mA/mm

Fig. 5 $\sqrt{I_{DS}} - V_{GS}$ characteristics
The threshold voltage ($V_{th}$) is $-6$ V

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References