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Normally Off Diamond Metal-Oxide-Semiconductor Field-Effect-Transistor with Inversion Mode

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Abstract

We successfully fabricated inversion channel diamond metal-oxide-semiconductor field-effect transistors (MOSFETs) with normally off characteristics and high on/off ratios of over 10^{10} by using a high-quality insulated phosphorus doped n-type diamond body, a low-resistive heavily boron doped p-type diamond layer that shows hopping conduction, and a high-quality diamond MOS interface [1]. For the inversion channel diamond MOSFETs, we precisely controlled phosphorus doping for the n-type diamond body, selective growth of boron doping for source and drain regions, and wet annealing for the diamond MOS interface using ALD-Al_2O_3 as a gate oxide.

1. Introduction

Diamond semiconductor has a strong potential for use in the field of high-power and high-frequency electronics because its breakdown electric field, thermal conductivity, and carrier mobility are higher than those of Si, SiC, GaN and Ga_2O_3.

At present, Si MOSFETs and insulated gate bipolar transistors (IGBTs) with inversion channels are widely used because of their high controllability of electric power, high reliability, and its simple device structure. Therefore, MOSFETs using wide-bandgap semiconductors such as SiC, GaN, Ga_2O_3 and diamond attract attention as next-generation power devices. Although many inversion channel SiC and GaN MOSFETs were reported [2-5], high channel mobility over 300 cm^2/Vs was not obtained. On the other hand, as a same MOSFET structure, accumulation channel Ga_2O_3 MOSFETs and diamond MOSFETs with H-terminated p-type surface conduction channel, which is difference from inversion channel showed high drain current and high breakdown voltage [6-8]. However, for these Ga_2O_3 and diamond MOSFETs, it is difficult to realize normally off characteristics without additional techniques about MOS interface control. In addition, electron μ_e and hole mobility μ_h of diamond bulk are greater than 3,000 cm^2/Vs at room temperature (μ_e = 7,300 and μ_h = 5,300 cm^2/Vs by time-resolved cyclotron resonance and μ_e = 4,500 and μ_h = 3,800 cm^2/Vs by time-of-flight) [9, 10]. Generally, when a high-quality MOS interface is used, μ_{FE} of approximately one half of μ_e and μ_h can be obtained in the case of Si MOSFETs. Therefore, μ_{FE} greater than 1,000 cm^2/Vs is expected in inversion channel diamond MOSFETs.

In this study, we precisely controlled phosphorus doping for a high-quality insulated n-type diamond body, selective growth of boron doping for a low-resistive source and drain regions, and wet annealing for a high-quality diamond MOS interface using ALD-Al_2O_3 as a gate oxide. We introduce fabrication processes of the inversion channel diamond MOSFETs and discuss the FET characteristics in more detail.

2. Experimental

Device structure and measurements

First, phosphorus doped n-type diamond body was deposited using a microwave plasma-assisted chemical vapor deposition (MPCVD) system using a mixture of CH_4 and H_2 gas on high-pressure and a high-temperature (HPHT) synthetic Ib (111) single-crystal diamond substrate (3 × 3 × 0.3 mm^3) with a misorientation angle of approximately 2.5°. Second, a selective p+-type layer was grown on the n-type body through a metal mask (Ti/Au: 10 nm/200 nm) by MPCVD. The process parameters shown in Table 1 were used for deposition. Third, to obtain OH terminations on diamond surface, the diamond was annealed in a quartz tube in an electric furnace at 500°C for 60 min. The wet annealing was performed under an atmosphere of N_2 with flow of 400 sccm gas bubbled through ultrapure water. Then, an Al_2O_3 layer with thickness of 34 nm was deposited onto the diamond by atomic layer deposition (ALD) at 300°C. After the deposition of the Al_2O_3 layer, the diamond surface termination changed from OH to O, same as that in the ALD mechanism. The gate, drain and source electrodes (Ti/Pt/Au: 30 nm/30 nm/100 nm) were fabricated by photolithography and lift-off processes. Figure 1 shows top-view image of the planar diamond MOSFET.

The current–voltage (*I*–*V*) characteristics of the MOSFETs were measured using a parameter analyzer (KEIT-

Table 1. Growth condition of n-type diamond body and selective p$^+$-type layer

	n-type body	selective p$^+$-layer
CH_4 conc. (%)	0.4	0.2
plasma power (kW)	3.6	1.2
chamber pressure (Torr)	150	50
thickness (μm)	~3	~0.05
Impurity conc. (cm^{-3})	[P] ~3×10^{16}	[B] ~1×10^{20}

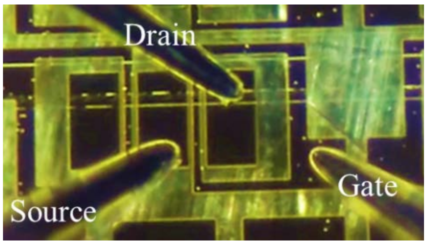

Fig. 1 Top-view image of diamond MOSFET.

HLEY 4200-SCS). The *I*–*V* measurements were conducted at room temperature in air.

Results and Discussions

Figure 2 shows the drain current (I_d) and drain voltage (V_{ds}) characteristics at gate voltages (V_g) ranging from 0 to −11 V with a voltage step of −1 V, gate length (L_g) of 5 µm and gate width (W_g) of 150 µm for a diamond MOSFET at room temperature. The MOSFET shows normally off and clear saturation characteristics.

Figure 3 shows the I_d and the gate current (I_g) in the logarithmic scale vs V_g characteristics at V_{ds} = −0.1 V and V_g from 0 to −11 V with a voltage step of −0.1 V for a diamond MOSFET with L_g = 5 µm and W_g = 150 µm at room temperature. From the I_d–V_g characteristics, the maximum field-effect mobility, the subthreshold swing value, and the interface-state density were ~3 cm^2/Vs, 630 mV/dec, and ~10^{13} $cm^{-2}eV^{-1}$, respectively. These values were almost same as previous values [1]. The high interface state density and high gate leakage current are essential problem for inversion channel diamond MOSFETs. On the other hand, normally off characteristics and high on/off ratio are obtained at high reproducibility.

3. Conclusions

We successfully fabricated inversion channel diamond MOSFETs with normally off characteristics and high on/off ratios using a high-quality insulated phosphorus doped n-type diamond body at high reproducibility. Although the inversion channel diamond MOSFETs show clearly normally off characteristics, the high interface state density and high leakage gate current are essential problem.

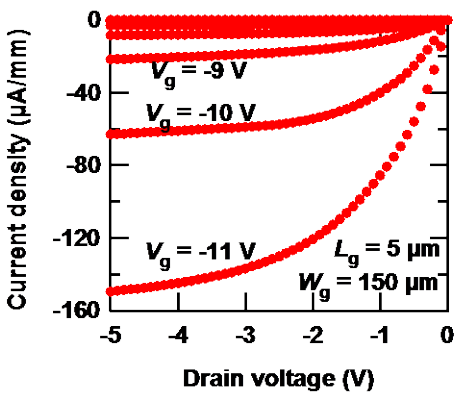

Fig. 2 I_d–V_{ds} characteristics of diamond MOSFET with L_g = 5 µm and W_g = 150 µm at room temperature. Applied V_g and V_{ds} range from 0 to −11 V with a voltage step of −1 V and from 0 to −5 V with a voltage step of −0.1 V, respectively.

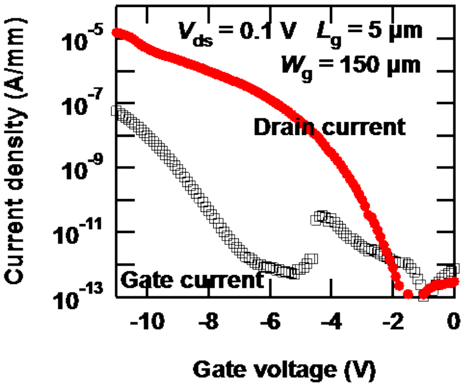

Fig. 3 I_d and I_g in logarithmic scale vs V_g of diamond MOSFET with L_g = 5 µm and W_g = 150 µm at room temperature. Applied V_g ranges from 0 to −11 V with a voltage step of −1 V, and applied V_d is a constant value of −0.1 V.

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