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Interface Properties of Diamond MOS Diodes Studied by Capacitance-Voltage and Conductance Methods - NO_2 Hole Doping Effect -

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Abstract

Hydrogen terminated diamond metal-oxide-semiconductor (MOS) structures with and without NO_2 hole doping were studied by measuring capacitance-voltage (C-V) characteristics. Higher carrier concentrations of NO_2 hole doped MOS diode led to positive gate voltage shift to deplete carriers and sharper C-V curves. Hysteresis behavior in both cases shows interface states. Interface state density was measured by the conductance method.

1. Introduction

Diamond is the best electronic material for the high-power operation due to its high band-gap (5.47 eV), and high break down field (>10 $MVcm^{-1}$) [1]. Hydrogen termination on the diamond form two-dimensional hole gas (2-DHG) near the surface without impurity doping [2]. Hydrogen terminated diamond used in field effect transistor (FET) and achieved high RF output power density of 2 W/mm at 1 GHz [3], transition frequency (f_T) of 45 GHz and maximum frequency of oscillation (f_{MAX}) of 120 GHz [4]. When it is exposed to NO_2 gas, it exhibits high surface carrier concentrations. It was also reported that, exposure to NO, SO_2, O_3 gases generate holes on the hydrogen terminated diamond surface [5]. Al_2O_3 passivation is required for the thermally stable operation of hydrogen terminated diamond surface [6]. NO_2 adsorbed and Al_2O_3 deposited FET also reported high drain current density of 1350 mA/mm [7].

However, the mechanisms of hole doping and MOS interface are not clearly understood. Al_2O_3/diamond interface properties of such FET's were measured by fitting obtained capacitance-voltage (C-V) curves taking continuum U-shaped state distributions into account. Gate C-V characteristics were measured at 1 MHz, and were compared to ideal C-V curve in order to extract negative fixed charge density in the oxide layer (7.5×10^{12} cm^{-2}). Variation of assumed U-shaped interface state distributions from band edge to mid-band gap were ~10^{13} eV^{-1} cm^{-2} and ~10^{11} eV^{-1} cm^{-2} respectively [8].

In this work, we fabricated diamond MOS diodes with and without NO_2 hole doping. By measuring parallel conductance and estimating interface states density, we investigated and compared effect of NO_2 hole doping in the diamond MOS structure.

2. Fabrication Process

We fabricated and compared MOS diode samples with and without NO_2 hole doping. Fabrication processes of both samples were the same except NO_2 hole doping. Fig. 1 shows a schematic structure of the diamond MOS diode with NO_2 hole doping. We used ~1 μm-thick homo-epitaxial layer grown by microwave chemical vapor deposition (CVD) method simultaneously with H_2 plasma to perform hydrogen termination on diamond (001) single crystal substrates. NO_2 hole doping was done by exposing hydrogen terminated diamond to 2% NO_2 gas. Au was deposited as ohmic contact. After Au etching from the gate portion, remaining photoresist was removed and again exposed to the NO_2 gas before depositing of 32 nm-thick Al_2O_3 layer using atomic layer deposition (ALD) method as the oxide layer. Al_2O_3 insulating layer in MOS structure also works as surface passivation to stabilize the hole channel. Al was deposited over Al_2O_3 layer as the gate electrode metal. 200 nm-thick circular shape Al gate electrode with a diameter of 205 μm was formed. Gap between ohmic contact and gate contact was 10 μm.

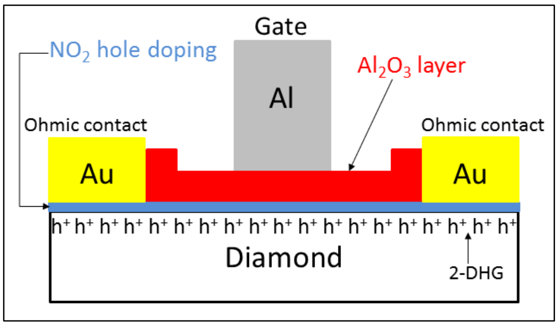

Fig.1 Schematic cross section of NO_2 doped diamond MOS diode. NO_2 hole doping is made on hydrogen terminated diamond. Al_2O_3 layer is used as an insulating layer of MOS diode.

3. Results and Discussion

Fig.2 shows C-V characteristics of MOS diodes with and without NO_2 hole doping. Measurements were performed at room temperature in dark. Measurement frequency was 1 kHz. Typical C-V responses were observed for both MOS diodes, where holes accumulated at the Al_2O_3/diamond interface. In comparison with the ideal C-V curve, C-V curve of NO_2 hole doped diode shifted to the positive gate voltage side by ~5 V. This positive gate voltage shift is consistent with that, NO_2 hole doping increases hole concentration.

Applied gate bias was swept from positive to negative (inversion to accumulation) followed by reverse direction to observe the hysteresis behavior. C-V hysteresis in the bidirectional C-V measurements were 0.27 V and 0.68 V for MOS

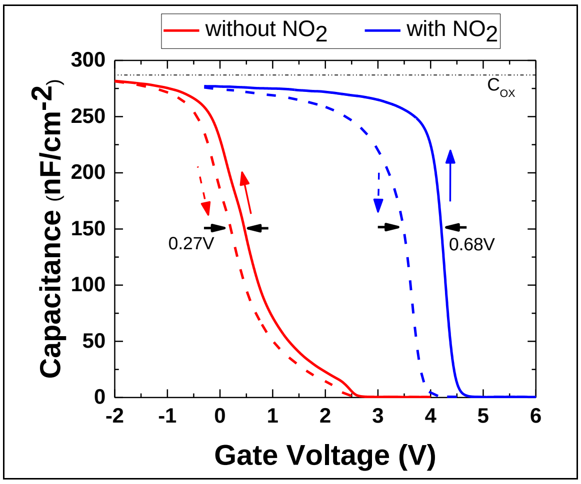

Fig. 2 C-V characteristics of MOS diodes without NO_2 hole doping (red) and with NO_2 hole doping (blue). Measurement frequency is 1 kHz.

diodes without and with NO_2 hole doping respectively. Hysteresis behavior can be regarded as existence of trapped charges at the Al_2O_3/diamond interface.

Fig.3 shows depth profile of hole concentrations derived from obtained C-V characteristics. Maximum hole concentrations were ~10^{21} cm^{-3} and ~10^{19} cm^{-3} at the interface for MOS diodes with and without hole doping, respectively [9]. NO_2 hole doping resulted in high carrier density at the interface. Sheet carrier concentrations of MOS diode with NO_2 hole doping was calculated to be 1.73 x 10^{13} cm^{-2}, which is one order in magnitude higher than 4.5 x 10^{12} cm^{-2} of the sample without NO_2 hole doping. Kasu *et al.* also reported sheet carrier concentrations of 1.9 x 10^{13} cm^{-2} for similar structure [8]. Previously increased surface concentration was also confirmed by Hall measurements of NO_2 hole doped sample [5, 6, 11].

C-V characteristics of NO_2 hole doped diode also showed sharper behavior as shown in Fig.2. Diode may face less defects at the surface for high hole concentrations, due to which we found sharper C-V curves. As well, high hole carrier density requires high reverse bias voltage to deplete. This positive gate voltage shift of C-V curve of NO_2 hole doped diode also indicates negative fixed charges in the Al_2O_3 layer. NO_2 hole doping before Al_2O_3 deposition could be one of the reasons to increase negative fixed charge in the Al_2O_3 layer.

Interface state was investigated by measuring parallel conductance as a function of frequency (1 kHz – 5 MHz) at different gate biases by conductance method. All the measurements were done at room temperature. During the measurements, amplitude of AC signal of capacitance meter was kept around 50 mV. Then, we fitted statistically G_p/ω-f curves considering surface potential fluctuations [10]. Here, G_p is parallel conductance and angular frequency, $\omega = 2\pi f$. Interface state density (D_{it}) is proportional to $(G_p/\omega)_{max}$ in G_p/ω versus f curves. Obtained D_{it} values of the MOS diode with NO_2 hole doping were varying from ~10^{14} $cm^{-2}eV^{-1}$ to 10^{12} $cm^{-2}eV^{-1}$ near the valence band. Reduced amounts of D_{it} were

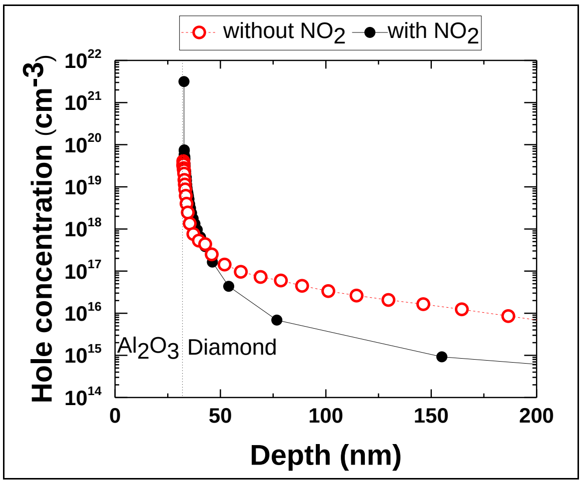

Fig. 3 Depth profile of the hole concentrations of the MOS diodes with and without NO_2 hole doping obtained from C-V measurements.

found for the MOS diode without NO_2 hole doping, varied from ~10^{12} $cm^{-2}eV^{-1}$ to 10^{10} $cm^{-2}eV^{-1}$ near the valence band. Thus, interface state density is two orders of magnitude higher in NO_2 hole doped MOS diode. It is expected that higher density of holes may trap at the interface due to higher surface concentrations of NO_2 hole doped MOS diode, which results in higher interface state density and C-V hysteresis.

4. Conclusions

We fabricated and compared hydrogen terminated diamond MOS diodes with and without NO_2 hole doping, and measured C-V curves. We found that interface state density and carrier concentration were higher in NO_2 hole doped MOS diode. NO_2 hole doped MOS diode also showed sharper capacitance-voltage curves.

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