Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp1261-1262

Thermally Stable Operation of Diamond Field-Effect Transistors by NO_2 Adsorption and Al_2O_3 Passivation

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1. Introduction

Diamond has remarkable semiconductor properties, such as the highest thermal conductivity (22 W/cmK), high breakdown field (>10^7 V/cm), and high carrier velocity (>10^7 cm/sec) [1]. Therefore, diamond appears promising for high-power and high-frequency devices. On hydrogen-terminated (H-terminated) diamond surface, a two-dimensional hole channel with sheet carrier concentration of ~ 1×10^{13} cm^{-2} forms without impurity doping. For H-terminated diamond field-effect transistors (FETs) with the two-dimensional hole channel, high-frequency (> 100 GHz) and high-power (~ 2 W/mm) operations have already been demonstrated [2-4]. To date, several models for the hole channel have been proposed, and it is known that some adsorbed molecules on the H-terminated diamond surface are essential for hole-channel formation [5,6]. Recently, we showed that the hole carriers are mainly generated by nitrogen-dioxide (NO_2) adsorption on the H-terminated surface, and we increased the hole carrier concentration to ~ 1×10^{14} cm^{-2} during NO_2 exposure [7]. Very recently, in order to solve the thermal stability problem of the NO_2 adsorbates on H-terminated diamond surface, we passivated the NO_2-adsorbed diamond surface with an Al_2O_3 layer and successfully stabilized the hole channel up to 200 °C [8].

In this work, we applied the NO_2 adsorption and Al_2O_3 passivation technique to H-terminated diamond FETs, which is based on our successful stabilization of the conductivity for the NO_2-adsorbed diamond surface by using an Al_2O_3 passivation layer. The passivated diamond FETs exhibit stable operation at 200 °C in a vacuum. Furthermore, using this technique, we obtained high maximum drain current (I_{DSmax}) of -1000 mA/mm for a passivated diamond FET.

2. Experimental

We fabricated diamond FETs on IIa-type single-crystal diamond (001) substrates. The residual boron acceptor concentration in the IIa-type diamond is less than 1×10^{16} cm^{-3} and the thermal activation energy of the boron acceptors is as high as 0.37 eV. We confirmed by Hall-effect measurement that the bulk conduction in the IIa-type diamond substrate is negligible at least up to 300 °C. H-termination was performed by exposing the diamond surface to microwave-generated hydrogen plasma. Au was deposited on the H-terminated surface. Next, the Au patterning and isolation were performed. After electron-beam (EB) resist patterning for the gate electrode area, the Au was etched in KI solution through the EB resist mask. In this process, the Au was separated to form the source and drain electrodes. Here, we exposed the H-terminated diamond surface between the source and drain contacts to highly concentrated NO_2 gas (2% in N_2). Then, we covered the NO_2-adsorped H-terminated diamond surface with Al_2O_3 using the atomic-layer-deposition (ALD) technique. The Al_2O_3 thickness is 8 nm. To avoid NO_2 desorption from H-terminated surface, Al_2O_3 was deposited at low temperature of less than 150 °C. Finally, the gate electrode was formed by Al deposition and the lift-off technique. The Al_2O_3 acts as a passivation layer and gate insulator.

3. Results and Discussion

First, we performed Hall-effect measurements of the H-terminated diamond surface covered with Al_2O_3 in a vacuum. At room temperature (RT), sheet resistance was 6000 Ω/sq. with sheet hole concentration of 1.9×10^{13} cm^{-2} and hole mobility of 60 cm^2/Vs. At 200 °C, the sheet resistance was 7200 Ω/sq. with the sheet hole concentration of 1.9×10^{13} cm^{-2} and the hole mobility of 45 cm^2/Vs. The sheet hole densities remain almost constant at RT and 200 °C. This means that the Al_2O_3 passivation layer can suppress the desorption of adsorbates at least up to 200 °C.

The stability of passivated diamond FETs was evaluated in a vacuum (3×10^{-3} Pa). Figure 1 shows the long-term stability of drain current (I_{DS}) for a passivated diamond

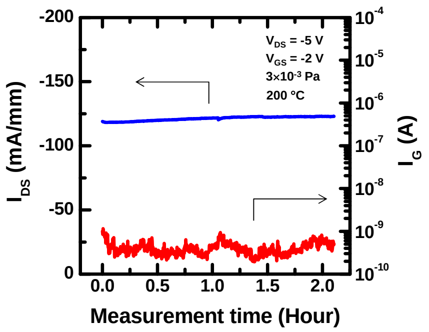

Fig. 1. Long-term stability of I_{DS} and I_G for a passivated diamond FET.

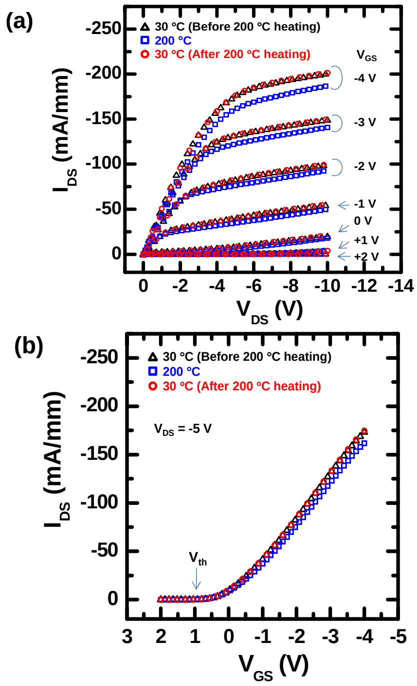

Fig. 2. (a) I_{DS}-V_{DS} and (b) I_{DS}-V_{GS} characteristics of a 0.4-μm-gate-length diamond FET with the passivation layer.

FET at 200 °C. The gate length (L_G) and width (W_G) were 0.4 and 25 μm, respectively. The applied gate-source and drain-source voltage (V_{GS} and V_{DS}) were -2 and -5 V, respectively. During the 200 °C heating, the I_{DS} remained almost constant (-120 mA/mm) for more than two hours and an increase in gate leakage current (I_G) was not observed. This result means that the desorption of the adsorbates and reactions between the adsorbates and H-terminated diamond surface do not progress under the Al_2O_3 layer at 200 °C [9].

Figure 2(a) shows the I_{DS}-V_{DS} characteristics of a 0.4-μm gate-length diamond FET at 200 °C and RT before and after the 200 °C heating in a vacuum. At 200 °C, the I_{DS}-V_{DS} characteristics were measured after a one-hour period of temperature stabilization. V_{GS} was varied from + 2 V to -4 V in steps of -1 V. Before the 200 °C heating, the I_{DSmax} at RT was -200 mA/mm. At 200 °C, the I_{DSmax} decreased to -180 mA/mm. After the 200 °C heating, the I_{DSmax} increased to the initial value of -200 mA/mm at RT. Before and after the heating, I_{DS} values at every V_{GS} clearly agree well with each other.

Figure 2(b) shows the I_{DS}-V_{GS} characteristics of a passivated diamond FET at V_{DS} = -5 V. From RT to 200°C, the passivated diamond FET showed normally-on operation. The threshold voltage (V_{th}) remained constant (+1 V), which means that the hole concentration under the gate electrode stayed exactly the same value after the heating cycle below 200 °C. Therefore, the I_{DS} decrease at 200 °C is attributed to the temperature dependence of hole mobility, as observed in the Hall-effect measurement. These results reveal that the Al_2O_3 passivated diamond FETs can be operated without thermal degradation at least up to 200 °C.

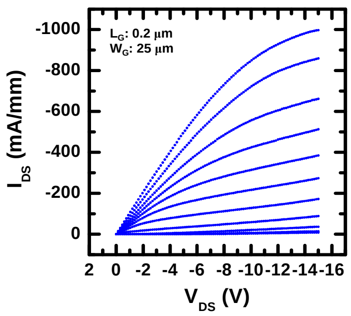

Fig. 3. I_{DS}-V_{DS} characteristics (V_{GS}= + 4.5 – -5.5 V; ΔV_{GS}= -1 V) of a passivated diamond FET at RT in air.

Figure 3 shows the I_{DS}-V_{DS} characteristics of a passivated diamond FET with L_G of 0.2 μm measured at RT in air. V_{GS} was varied from + 4.5 to -5.5 V in steps of -1 V. The I_{DSmax} and maximum transconductance (g_{m_max}) are -1000 mA/mm and 200 mS/mm, respectively [9]. The I_{DSmax} is the highest ever reported for diamond FETs on diamond (001) substrates. The reason for the high I_{DSmax} is the low sheet resistance in the gate-source and gate-drain spacing, which is due to the NO_2 adsorption under the Al_2O_3 passivation layer [7].

4. Conclusions

The thermal stability of H-terminated diamond FETs was improved by the NO_2 adsorption and Al_2O_3 passivation technique. For the first time, stable and heating-cycle-resistive FET operation from RT to 200 °C was demonstrated for H-terminated diamond FETs. With this technique, the I_{DSmax} and g_{m_max} of the diamond FETs were also improved to -1000 mA/mm and 200 mS/mm. The I_{DSmax} is the highest ever reported for diamond FETs on diamond (001) substrates. This technique will open a way to high-temperature applications of diamond FETs.

Acknowledgements

We thank Dr. T. Makimoto for helpful discussions and Drs. N. Maeda and Y. Yamauchi for experimental support.

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