J-3-5

Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp942-943

High-temperature Operation of Boron-implanted Diamond FETs

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1. Introduction

Diamond has excellent physical properties, such as the highest thermal conductivity (22 W/cmK), high electric breakdown field (>10 MV/cm), and high carrier mobility (4500 cm^2/Vs and 3800 cm^2/Vs for electrons and holes, respectively). These are advantageous for high-frequency and high-power transistors. Recently, using hydrogen-terminated CVD diamond field effect transistors (FETs), we achieved a transition frequency (f_T) and maximum frequency of oscillation (f_{max}) of 45 and 120 GHz, respectively [1], and a maximum output-power density of 2.1 W/mm at 1 GHz [2], which are sufficient for high-frequency power amplifiers in wireless communications systems.

Ion implantation is the most widely used doping technology for semiconductors. However, it can not be used for diamond because the doping efficiency is quite low. We have achieved one-order of magnitude higher doping efficiency in ion implantation by using high-pressure and high-temperature (HPHT) annealing [3]. Here we examine the characteristics of ion-implanted diamond FETs at elevated temperatures. There have only been a few reports on the high-temperature characteristics of diamond FETs [4-5].

2. Experimental

CVD homoepitaxial diamond films were grown on Ib (100) substrates by microwave plasma CVD. Then, boron (B) ions were implanted in the films at an acceleration energy of 60 keV with a dose of 10^{15}-10^{16}cm^{-2}. HPHT annealing of the B-implanted films was performed at ~7 GPa and 1350°C for activation of the implanted B. FETs were fabricated from these diamond films. The source and drain contacts were formed by evaporating Ti/Au and annealing in vacuum at 600° C. The gate recess structures were formed by reactive ion etching (RIE). The thickness of the B-implanted layers under the gate recess was fixed at ~30 nm, at which channel modulation is possible. Gate Schottky contacts were formed by evaporation of Pt and lift-off process. The current-voltage characteristics of the diamond FETs were measured in vacuum up to ~600° C.

3. Results and Discussion

We obtained a higher hole concentration for a dose of 1 ~ 5×10^{15} cm^{-2} while maintaining high mobility. For a dose of 3×10^{15} cm^{-2}, we obtained a hole sheet concentration and mobility at 300 K of 1.6×10^{13} cm^{-2} and 41 cm^2/Vs, respectively. The hole concentration is slightly higher than that of H-terminated diamond (~10^{13} cm^{-2}).

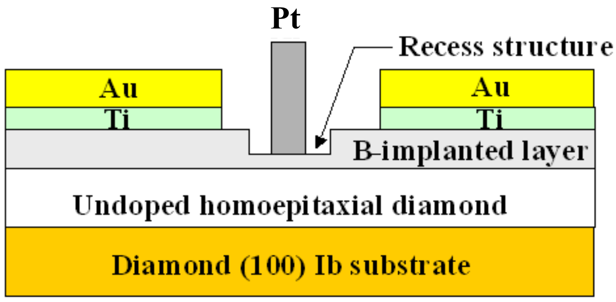

Fig. 1. Schematic cross-section of a B-implanted diamond FET.

Using this film with a dose of 3×10^{15} cm^{-2}, we fabricated FETs (Fig. 1). The gate length and the width were 5 μm and 100 μm, respectively. Figure 2 shows DC drain current (I_{DS})- voltage (V_{DS}) characteristics for different gate-source voltage (V_{GS}) measured at 25, 250, 400 and 500°C. Current saturation and pinch-off characteristics were clearly observed. The maximum I_{DS} of 0.16 mA/mm was obtained at V_{GS} of -2 V at 25°C. The maximum I_{DS}

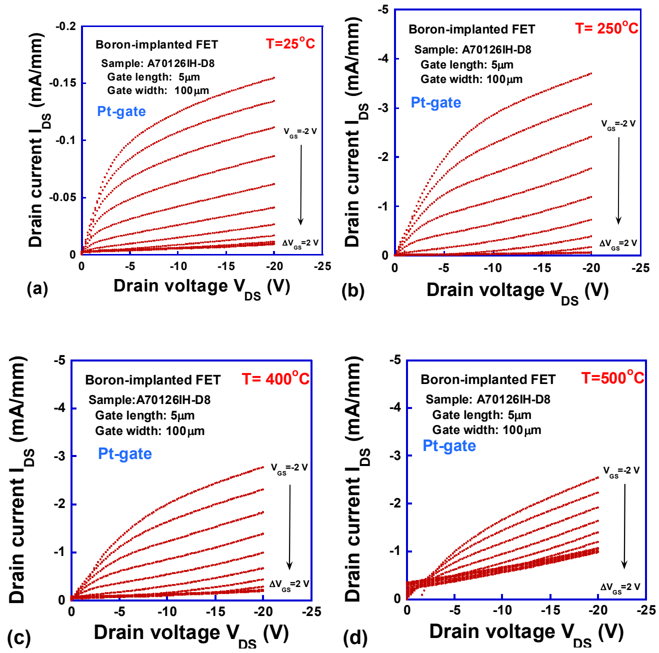

Fig. 2. Drain current-voltage characteristics of a B-implanted diamond FET measured at (a) 25°C, (b) 250°C, (c) 400°C and (d) 500°C.

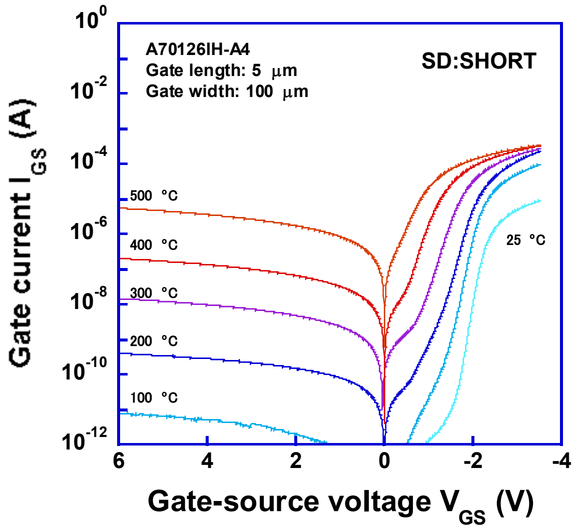

Fig. 3. Gate current-voltage characteristics of B-implanted diamond FET measured from 25 to 500°C.

increased as temperature increased up to ~250°C, and became 3.7 mA/mm at 250°C [Fig. 2 (b)]. The increase of the I_{DS} is caused by the activation of B at higher temperature. However, above 300°C, the maximum I_{DS} gradually decreased as temperature increased. This is because drain bulk leakage current gradually increased above 300°C. Current saturation and pinch-off characteristics were clearly observed up to 500°C, though drain bulk leakage current was observed. Further at ~550°C, severe bulk leakage occurred and current modulation could not be observed above that temperature.

Figure 3 shows the gate current (I_{GS})-voltage (V_{GS}) characteristics for the B-implanted diamond FETs. The reverse leakage current is lower than the detection limit (~10^{-12} A), with a high rectification ratio of more than ~7 orders of magnitude at 25°C. However, the reverse leakage current systematically increased as temperature increased. This is in contrast to Vescan et al.'s results, which showed low leakage current up to ~500°C in a diamond Schottky diode [6]. Strong thermal activation of reverse leakage current is commonly associated with thermally stimulated currents across defects at the interface [7]. We think the strong thermal activation of the leakage current of our diamond FETs is due to residual damage induced by implantation and/or deterioration of the surface by RIE.

Forward current increased as temperature increased because of a B activation at higher temperature; however, it almost saturated at around 250°C. These behaviors agree well with the I_{DS}-V_{DS} characteristics of the B-implanted diamond FETs, which showed maximum I_{DS} of 3.7 mA/mm at ~250°C [Fig. 2(b)]. Above 550°C, severe drain bulk leakage occurred [Fig. 2 (d)]. These results indicate that thermal activation of reverse leakage current of Schottky gate electrodes determines the high temperature characteristics of the B-implanted diamond FETs. To suppress the strong thermal activation of the reverse leakage current and achieve FET operation at higher temperature, crystal quality of the B-implanted diamond films and interfacial properties between the diamond films and electrodes must be improved.

4. Conclusions

By combining ion-implantation and high-pressure and high-temperature (HPHT) annealing, we have obtained boron (B)-implanted diamond layers with high hole concentration and mobility. We have succeeded in fabricating diamond FETs using the B-implanted layers. For a B dose of 3×10^{15} cm^{-2}, a sheet hole concentration and mobility of 1.6×10^{13} cm^{-2} and 41 cm^2/Vs at 300 K were obtained. Diamond FETs fabricated on the B-implanted layer showed maximum I_{DS} of 0.16 mA/mm at gate voltage of -2 V at room temperature. The maximum I_{DS} increased as temperature increased and became 3.7 mA/mm at ~250°C. The operation of the B-implanted diamond FETs was possible up to ~ 500°C without severe drain bulk leakage.

Acknowledgements

The authors thank Dr. H. Kageshima for fruitful discussions and Dr. K. Nishiguchi for experimental support. This work was partly supported by the SCOPE "Diamond RF Power Amplifier" project of the Ministry of Internal Affairs and Communications, Japan.

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