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Normally-off hydrogen-terminated diamond field-effect transistor with Al_2O_3 dielectric layer formed by thermal oxidation of Al

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ABSTRACT

Fabrication of normally-off hydrogen-terminated diamond field-effect transistors (FET) has been carried out by using 3 nm Al_2O_3 dielectric layer, which was formed by thermally oxidizing 3 nm Al in air. 100 nm Al was covered on the 3 nm Al_2O_3 dielectric layer to form Al/Al_2O_3 gate. The leakage current density of FET with 6 μm gate length kept smaller than 5×10^{-7} A·cm^{-2}, while the gate voltages swept from 3 to −5 V. The capacitance-voltage characteristic indicated low-trapped charge densities in Al_2O_3 dielectric layer. For comparison, FET with only 3 nm Al_2O_3 gate and with 100 nm Al/3 nm Al_2O_3 gate was fabricated, which showed normally-on and normally-off characteristic respectively, indicating that 100 nm Al/3 nm Al_2O_3 gate could deplete hole densities in FET channel due to the difference of work function between Al and hydrogen-terminated diamond.

1. Introduction

Diamond exhibits many outstanding properties such as good light transmittance, effective resistance to radiation damage, large bandgap, high breakdown voltage, high thermal conductivity, high carrier mobilities etc., making it having potential applications in the fields of wide range optical transparent window material, coating tools, especially in the field of electron devices which can work in high frequency, high power, high temperature as well as corrosive environment [1–15]. However, because of high activation energies of boron (380 meV) and phosphorous (570 meV) in diamond, few dopants can be activated at room temperature (RT) [16]. In order to solve this problem, δ-doping technique has been used. However, this method required the strict thickness of doping and the carriers mobility in the δ-doping area was behind expectation [17–19]. Fortunately, when single crystal diamond surface is treated by hydrogen plasma and produced hydrogen-termination bonds, an accumulation layer of hole carriers will be formed 10 nm below the diamond surface, resulting in a p-type conduction layer with 10^{13} cm^{-2} sheet carrier density and 50–150 cm^2 V^{-1} s^{-1} carrier mobility [20–21]. Up to now, many researchers have successfully fabricated metal oxide semiconductor field effect transistors (MOSFETs) using hydrogen-terminated single crystal diamond, which are normally-on operation [4–6,11–12,30–34]. However, fail-safe systems strongly require normally-off operation in hydrogen-terminated diamond MOSFETs [22–23].

Recently, several groups reported that normally-off MOSFETs have been fabricated in diamond field. Yuya Kitabayashi et al. have successfully realized normally-off hydrogen-terminated diamond MOSFET, whose hydrogen-terminated conductive channel under the gate electrode was partially treated by UV/Ozone to form partially oxygen-terminated non-conductive areas [24]. The dielectric layer of Al_2O_3 film with a thickness of 200 nm was deposited by ALD at 450 °C. Hitoshi Umezawa et al. also used partially oxygen-terminated channel to realize MOSFET with normally-off property [25]. J.W. Liu et al. used 27.4 nm $LaAlO_3/Al_2O_3$ dielectric layer to form normally-off hydrogen-terminated diamond MOSFETs by annealing the sample at 180 °C for 10 min [26]. To the authors' knowledge, few investigations on normally-off MOSFETs using Al gate to deplete hole carriers in p-type channel has been reported, which was due to the difference of working function between gate metal and hydrogen-terminated diamond.

In this work, normally-off hydrogen-terminated diamond MOSFETs with 3 nm Al_2O_3 dielectric layer formed by thermal oxidation of Al were successfully fabricated. The electrical properties of the normally-off MOSFETs were investigated.

2. Materials and methods

Two CVD synthesized (001) IIa single crystal diamonds (Elemetsix Corp.) in dimension of $3 \times 3 \times 0.5$ mm^3 were used as substrates for sample A and B, respectively. The schematic of the processes for

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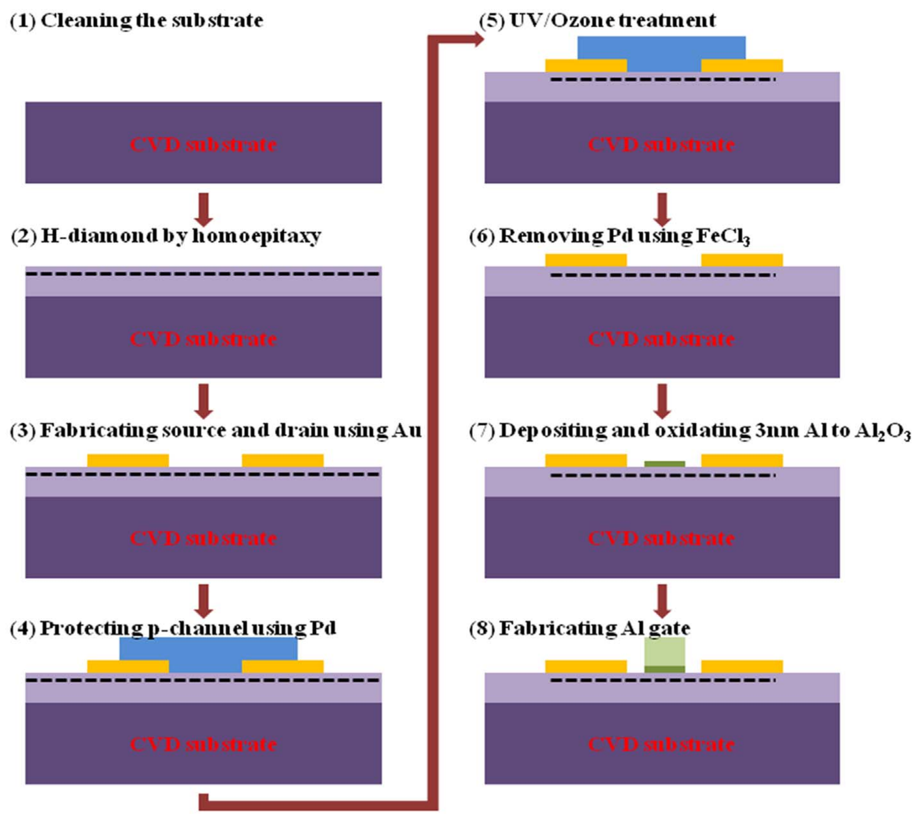

Fig. 1. Schematic of the process for fabricating normally-off hydrogen-terminated single crystal diamond MOSFETs of both sample A and B.

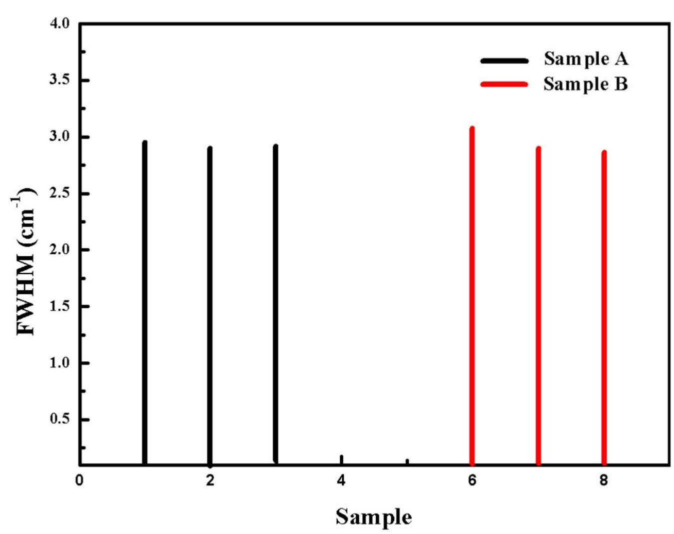

Fig. 2. Raman measurement results of sample A, B. Three random points are measured on each sample.

fabricating normally-off hydrogen-terminated single crystal diamond MOSFETs of both sample A and B are shown in Fig. 1.

To fabricate samples, the substrates were cleaned by an acid mixture H_2SO_4 : HNO_3 : $HClO_4H_2SO_4$: HNO_3 : $HCLO_4$ = 31.2 : 36 : 11.4 at 250 °C for 1 h and then treated with a mixed alkali of NH_4OH : H_2O_2 : H_2ONH_4OH : H_2O_2 : H_2O = 4 : 3 : 9 at 80 °C for 10 min to remove non-diamond phase. On the substrates, microwave plasma CVD system (AX5200 Seki Technotron Corp.) was used to grow 200 nm homoepitaxial single crystal diamond film with H-termination bonds. During growth progress, the CH4/H2 ratio, pressure and temperature were 5%, 90 Torr and 1000 °C. To pattern source and drain for each sample, photolithographic and electron beam evaporation (EB) technique were used to form 100 nm Au electrodes spaced 20 μm. The pressure, temperature and deposition rate for EB process were 5×10^{-4} Pa, 300 K and 0.5 nm/s, respectively. Once the Au electrodes done, the channel area between source and drain for each sample was covered by 150 nm palladium (Pd) deposition. After that, the sample A and B were treated 1 h by UV/ozone at RT for device isolation. Then sample A and B were soaked in ferric chloride ($FeCl_3$) solution respectively to remove the patterned Pd at RT. Photolithographic technique was used to form patterned gates, and EB technique was used to deposit 3 nm Al on diamond surface then oxidized in air at 100 °C for 10 h to form Al_2O_3 dielectric layer before 100 nm Al gate was covered on the 3 nm Al_2O_3 dielectric. For comparison, sample A has the gate width (W_G) kept at 100 μm and the gate lengths (L_G) of 6, 10 and 15 μm, respectively. The interspacing between source/drain contact and gate was fixed at 7, 5 and 2.5 μm, respectively. For sample B, the differences were the W_G of 2 and 3 μm, the L_G kept at 10 μm, and the interspacing between source/drain contact and gate was fixed at 5 μm. The electrical properties of sample A and B were measured under a dark condition.

3. Results and discussion

In order to investigate crystal quality of diamond, micro-Raman spectroscopy with a 20 × objective lens has been carried out for these two samples after 200 nm undoped homoepitaxial single crystal diamond films were deposited. The Raman excitation laser wavelength is 532 nm and resolution is 0.40 cm^{-1}/pixel. Fig. 2 shows Raman measurement results of sample A and B. For sample A, Raman results of three random measurement points were 2.9 cm^{-1}, 2.9 cm^{-1} and 2.9 cm^{-1}, respectively. While for sample B, Raman results of three random measurement points were 3.1 cm^{-1}, 2.9 cm^{-1} and 2.9 cm^{-1}, respectively.

Fig. 3 shows (a) leakage current density (J) and (b) C-V curve for the 3 nm Al_2O_3 MOSFET on sample A with 6 μm gate length. When the gate bias was larger than 0 V, the J value of the MOSFET was smaller than 5×10^{-8} A·cm^{-2}, as shown in Fig. 3(a). And also, the absolute J value