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Normally-off H-diamond field effect transistors based on the multiple enlarged growth single crystalline diamond by microwave plasma chemical vapor deposition

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Abstract

The high-performance normally-off hydrogen-terminated diamond MOSFETs have been achieved on the single crystalline diamond grown in our lab by adopting UV ozone treated channel and the alumina dielectric prepared by thermal oxidation of aluminum film. The device with a 2-μm gate shows record high transconductance of 20 mS/mm, and threshold voltage of -0.65V at $V_{DS} = -6$ V, and drain current of 55.6 mA/mm and on-resistance of 65.39 Ω·mm at $V_{GS} = -4.5$ V. The high transconductance and low on-resistance of the simple and low-cost devices benefits from the short time and mild property of both normally-off channel processes.

1. Introduction

Diamond has tremendous advantages to be used as a kind of semiconductor except its low bulk doping efficiency [1], [2]. The p-type surface conductivity of the hydrogen terminated diamond (H-diamond) has greatly motivated the application of diamond in electronics devices [3]. However, most reported H-diamond FETs are the depletion mode (normally-on) devices. Most reported normally-off H-diamond devices showed much higher on-resistance and lower output current compared to the normally-on devices with the same gate lengths. Therefore, it is necessary to improve the performance of the H-diamond normally-off devices.

In this report, we report the achievement of the H-diamond normally-off MOSFETs with high performance. The devices were fabricated on the single crystalline diamond grown by microwave power chemical vapor deposition (MPCVD) in our lab. The direct current (DC) and capacitance-voltage (CV) properties of the normally-off H-diamond devices were demonstrated.

2. Experiments and results

The type-IIa single crystalline diamond (SCD) was grown on commercially available high-temperature high-pressure type-Ib (001) substrates with (100) side surfaces. The growth was performed in a 6 kW 2.45 GHz MPCVD system. we braze all the substrates on a molybdenum holder using 25-μm-thick gold foil to obtain the stable thermal exchange between the substrates and the holder in growth. The samples placed apart from each other were marked, as shown in Fig. 1(a). During growth the pressure, temperature and microwave power are 290 mbar, 920 °C and 3.8 kW, respectively. The total gas flow rate of 200 sccm and the methane concentrations of and 5% were used. To keep the sample surface temperature at a constant level, we reduce the height of the sample by 10 μm when the temperature reaches 920 °C. Our growth method does not change any growth parameters. Thus, little stress or dislocations would be induced. The as-grown samples are shown in the inset of Fig. 1(a). After growth, the quality of the sample was characterized by HORIBA JOBIN YVON Raman spectrometer with 514 nm laser and a grating of 1800 grooves/mm (Fig. 1(b)). Then, the samples were separated from the seeds and polished to the roughness below 1 nm (inset of fig. 1(b)).

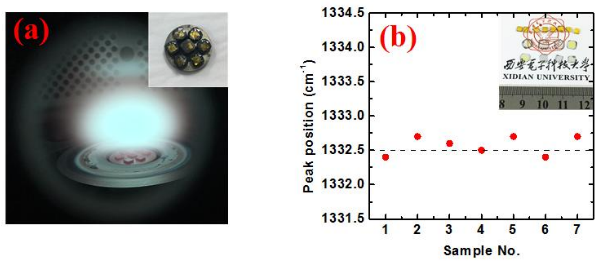

Fig. 1. (a) Interior scene of the CVD chamber during growth, and inset is the as-grown samples; (b) the peak positions of the Raman characteristic peak of diamond of the CVD SCDs inset picture shows the substrates and the CVD SCDs after cutting and polishing.

The H-diamond surface was obtained by treating the SCD in the MPCVD chamber with hydrogen plasma for 20 min. During treatment, the hydrogen flow, microwave power and temperature are 600 sccm, 2 kW and 890 °C, respectively. The device process flow is shown in Fig. 2 and similar in details to that in Ref. [4], except two points aiming to realize a low on-resistance normally-off MOSFET channel. The first is that after defining the gate window and wet-etching of gold using KI/I_2, the exposed H-diamond surface is treated by UV ozone for 2 min (Fig. 1(b)). The second is that we use the gate dielectric of alumina prepared by annealing a thin aluminum layer in air (Fig. 1(c)) at 80 °C for half an hour.

Fig. 3 summarized the recently reported L_G-dependent device parameters of normally-off H-diamond MOSFETs with different gate dielectric or fabrication processes as we know [5-12]. In the L_G range of 2 ~ 40 μm, our devices show the record high g_m, and almost the lowest R_{on} except that for the 2-μm case (slightly higher than 63.5 Ω·mm of $LaAlO_3/Al_2O_3$/H-diamond MOSFET [6]), and secondary largest $|I_D|$ for $L_G \leq 4$ μm. The high g_m and low R_{on} of the devices benefits from the short time and mild property of both normally-off channel processes. Further optimization of our normally-off devices will be carried out in the near future.

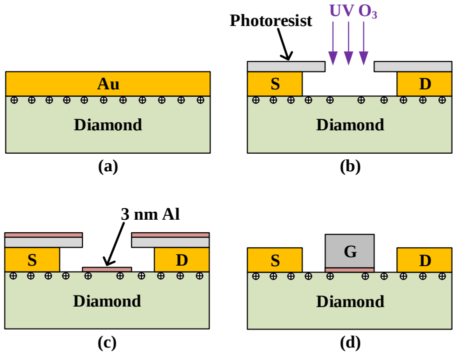

Fig. 2. Process flow of our H-diamond MOSFET

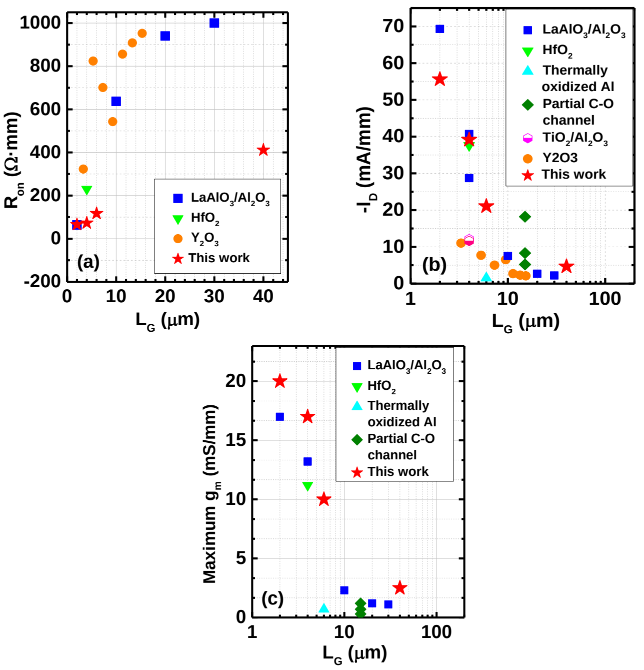

Fig. 3. (a) R_{on} and (b) $-I_D$ and (c) maximum g_m of reported normally-off H-diamond MOSFETs dependent on the gate length. The gate dielectric or the type of the channel is given.

3. Conclusions

High performance normally-off H-diamond MOSFETs were fabricated on single crystalline diamond grown in our lab. The device with 2-μm gate length shows a record high g_m of 20 mS/mm and a V_{TH} of -0.65 V, and a drain current of 55.6 mA/mm and an R_{on} of 65.39 Ω·mm at $V_{GS} = -4.5$ V. The critical device process to realize these low on-resistance normally-off MOSFETs consists of 2-min UV ozone treatment of the H-diamond surface and thermal oxidation of aluminum film in the air to form an alumina gate dielectric. This simple and low-cost device process will be optimized to further improve the performance of normally-off H-diamond devices.

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