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Improvements in Thermal Stability of Hydrogen-terminated Diamond FETs

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1. Introduction

The hydrogen termination of diamond surface results in a two-dimensional hole gas (2DHG) p-type conductive channel of high carrier density [1] in close proximity to the surface. This unique property of the diamond surface combined with the exceptional electrical and thermal properties [2, 3] of this wide band-gap material has been used for the fabrication of diamond based electronic devices, such as FETs [4]. Operation of such devices with 0.1 µm gate lenght at microwave frequencies showed cut-off frequencies f_T of 45 GHz and f_{max} of 120 GHz [5], and output power density of 2.1 W/mm at 1 GHz [6]. The increasing performance of these devices brought new challenges in terms of high power, high frequency and high temperature. However, the origin of the hole channel is still under discussion, and for the future development of diamond electronics it is important to understand the channel formation mechanism and the condition affecting its properties. In this work, the influence of temperature and adsorbates from air on the channel conductivity has been investigated. Here, the improvement which allowed stable operation of the FETs up to 280 °C is reported.

2. Experimental

High-temperature high-pressure (HTHP) synthesized (001) single-crystal diamond substrates have been used for epitaxial growth of nominally undoped diamond layers by microwave plasma CVD. The as-grown surface has been in-situ exposed to hydrogen plasma, and after the subsequent exposure to air a p-type conductive layer with the sheet charge carrier density of about 10^{13} cm^{-2} can be observed.

Schematic view of the FET device structure is shown in fig. 1. The FETs were fabricated using thermally evaporated Au for the ohmic and Al for the Schottky contacts, respectively. A thin dielectric layer has been formed between the conductive channel and the Al metal contact as confirmed by CV measurements [7] and TEM observations [8]. Local oxygen termination has been used for the electrical isolation between devices (surface potential pinning of the O-terminated diamond results in a highly insolating surface).

3. Results and discussion

Typical DC output characteristic of a FET is shown in fig. 2. The long-term stability of such devices employing the H-induced channel is of particular interest. Hydrogen termination is necessary but not the sole condition required for the formation of the conductive channel. Adsorbates from the air are also necessary as illustrated in fig. 3, where with increasing vacuum and the interconnected desorption of the surface adsorbates into the vacuum, a reduction of the current level can be observed. The following ventilation of the system and the exposure of the H-terminated diamond surface to air led to an adsorption of the species from the air back to the surface, which led to a full recovery of the current. Thus, the surface conductivity is dependent upon the environmental conditions and a correlation between the electrical properties and the surface adsorbates is still under investigation.

In order to trap these species (acceptors) on the diamond surface and to improve the long-term stability of these devices, some kind of passivation needs to be used. A photoresist can act as a simple passivation, preventing desorption from the diamond surface and thus preserving the p-type conductivity even at high vacuum levels as shown in fig. 3. In this case, the current level remains the same during the evacuation of the measurement chamber, and no change has been observed after a week long measurements at 10^{-3} Pa, or after the subsequent exposure to air. The main advantage of this kind of passivation is that you can apply it at room temperature and atmospheric pressure.

Thermal stability is another important aspect concerning high performance devices. To fully utilize diamond's highest thermal conductivity of all materials, an investigation of the thermal stability of the hydrogen terminated diamond surface has started. So far, successful operation of FETs up to 100 °C has been shown [9], where the small signal performance remained essentially unchanged, while small decrease in the DC current with increasing temperatures has been observed. Fig. 4 shows sheet charge density (n_s) dependence on the substrate temperature as obtained from Hall measurements. In air, a slight decrease of the n_s with increasing temperature can be observed while increasing the temperature from R.T. to 400 °C, while a strong degradation of the sheet charge density occurs above 400 °C. In vacuum, a strong degradation is observed above 1000 °C. Here, the desorption of the hydrogen atoms results in a permanent degradation of the surface conductivity. Recent devices using the photoresist passivation can operate at temperatures up to 280 °C without significant degradation (see fig. 5), although at higher temperatures this passivation becomes ineffective and another kind of passivation will be necessary to take the full advantage of the unique properties of diamond.

4. Conclusions

Hydrogen induced p-type channel has been successfully employed in FET devices. In vacuum, the conductive channel disappears, while it fully recovers after exposure to air. This undesirable effect can be suppressed by a suitable passivation of the surface adsorbates. On the other hand, temperature affects the properties of the channel as well. The use of the device passivation enabled a successful FET operation up to 280 °C without significant degradation. Further investigation of the influence of the growth parameters, and environment conditions on the channel may lead to an improvement of the channel properties, and lead to an improved device performance.

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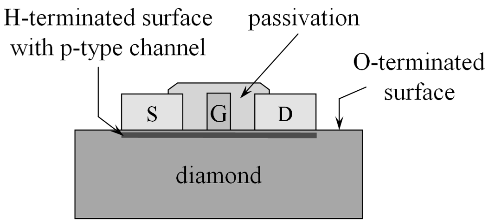

Fig. 1 Cross-section of diamond FET with a hydrogen induced p-type channel.

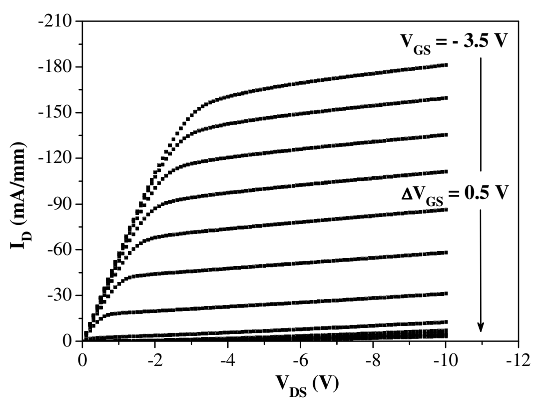

Fig. 2 Output characteristics of a FET with self-aligned gate (L_G = 1 µm, W_G = 100 µm).

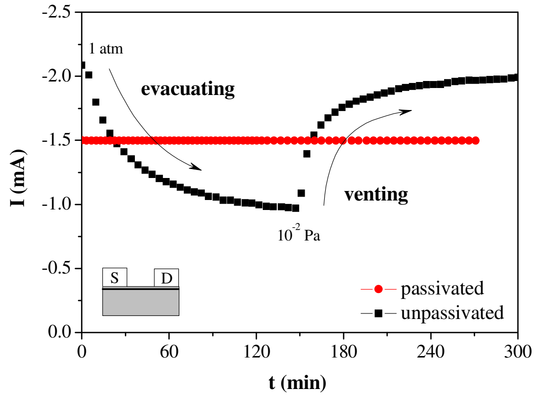

Fig. 3 Change of the current level (at 1 V bias) of an unpassivated and passivated device (ungated FET). During the pumping down process, a decrease of the current can be observed for the unpassivated device, while no change of current can be observed for the passivated device. After subsequent venting of the system, the current of the unpassivated device starts to recover, while the current of the passivated device remains unchanged.

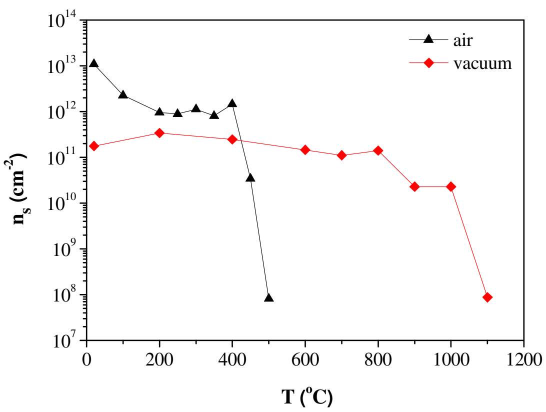

Fig. 4 Sheet charge density dependence on the temperature. In air a slow decrease of n_S with increasing temperature to 200 °C can be observed. This can be attributed to a desorption of the adsorbates from the surface. On the other hand, a rapid decrease of n_s can be observed above 400 °C. In vacuum, a strong degradation of n_S can be observed above 1000 °C. This can be attributed to a desorption of the hydrogen atoms.

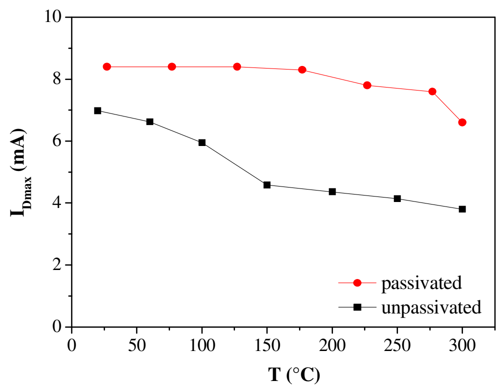

Fig. 5 Temperature dependence of maximum drain current (measured at V_{DS} = - 10 V and V_{GS} = - 3.5 V) for a passiveted and an previously measured unpassiveted FET.