Extended Abstracts of the 1998 International Conference on Solid State Devices and Materials, Hiroshima, 1998, pp. 484-485

Highly Improved Electrical Properties of Diamond MISFET Prepared by Ultrahigh-Vacuum Process

Young Yun, Tetsuro Maki, Hiroyuki Tanaka and Takeshi Kobayashi

Department of Electrical Engineering, Faculty of Engineering Science, Osaka University,
1-3 Machikaneyama, Toyonaka, Osaka 560, Japan
Phone/Fax: +81-6-850-6311-6341, E-mail: yun@sup.ee.es.osaka-u.ac.jp

1. Introduction

Owing to its good electrical properties such as low dielectric constant, wide band gap, and large break down field, diamond has recently attracted a lot of attention as a promising candidate for high temperature and high power device [1,2]. For realization of the diamond electronic device, however, the electrical stabilization of the diamond surface is indispensable. Therefore, we have been studying about electrical stabilization of diamond surface by investigating diamond metal-insulator-semiconductor (MIS) interface.

According to our results previously reported, it was found that oxygen adsorption on the diamond surface induced a number of surface states, which degraded the electrical properties of MIS interface to a great extent [3]. Therefore, the electrical performance of diamond MISFET strongly depended on to what extent the diamond surface escaped from exposure to oxygen.

In the present work, in order to exclude the oxygen contamination on the diamond surface as much as possible during the process, we introduced reduced-oxygen process [3] including ultrahigh-vacuum (UHV) technology (in our case, the vacuum level was $\sim 10^{-9}$ Torr) for the first time. In such manner, we fabricated the diamond MISFETs employing surface channel conductance [4,5], and characterized their electrical properties.

2. Experimental

In order to obtain the conducting channel region, hydrogen-terminated surface conductive layer was employed [4,5]. The fabrication step of MISFET is as follows. Undoped homoepitaxial diamond films were grown on high-pressure-synthesized (100) diamond substrates by means of the electron-cyclotron-resonance(ECR) microwave plasma-assisted chemical vapor deposition (CVD) method using a mixture of H_2 (220 sccm) and CO (12 sccm) at 800℃. It is worth noting here that oxygen contamination arising from CO source gas can be ignored almost completely because atom adhesion becomes less pronounced at temperatures as high as 800℃. For the purpose of forming source and drain electrodes, Pt/Ti bilayer (or Au) was deposited on the diamond surfaces by electron beam evaporation at room temperature and the standard lift-off technique. In order to prevent even residual oxygen adsorption on the diamond surface during annealing, this sample was annealed in UHV chamber ($\sim 10^{-9}$ Torr during annealing) at 500℃ after Pt/Ti (or Au) deposition (annealing was performed for ohmic contact and adhesion between metal and diamond surface). The non oxide CaF_2 gate insulator film was employed. We have published the role of CaF_2 gate insulator film on diamond surface in some articles [6-8]. In addition, CaF_2 gate insulator was deposited at room temperature to prevent the residual oxygen from adsorbing on the diamond surface during deposition. Finally, Al gate electrodes were formed on the insulating films at room temperature. A schematic view of the MISFET is shown in Fig. 1.

3. Results and Discussion

For device fabrication, reduced-oxygen process was employed, including UHV process. In our article [3], reduced-oxygen process was explained in detail. According to our results, even residual oxygen (oxygen included in the vacuum level of $\sim 10^{-6}$ or $\sim 10^{-5}$ Torr) was detrimental to electrical stability of diamond surface [3]. Especially, diamond surface was fatally affected by a very small quantity of residual oxygen when the diamond surface was directly exposed to the oxygen ambient (for example, when the diamond surface is annealed for ohmic contact between electrode and diamond surface). Therefore, we performed the UHV annealing as well as reduced-oxygen process in order to hinder residual oxygen adsorption on the diamond surface as much as possible.

The drain current versus drain voltage (I_D-V_D) characteristics of the MISFET is shown in Fig. 2. As is well known, hydrogen termination on the diamond surface causes upward band bending under even zero bias of gate voltage. Therefore, the MISFETs exhibited normally on characteristics and operated in both enhancement and depletion modes (only operation in enhancement mode is given in this figure). Several electrical parameters are shown in Table I. As shown in Table I, we can see that the electrical performance of the MISFET was improved to a great extent in comparison with conventional ones [1-3]. The obtained transconductance (μ_{eff}) was 400 cm^2/Vs at room temperature, which is the highest value reported until now in the diamond FET at room temperature. In addition, transconductance (g_m) and surface state density (N_{SS}) of the MISFET operation region was 5mS/mm and $\sim 10^{10}/cm^2$ eV, respectively. These values are comparable with those of conventional Si MOSFETs having the same channel length (Lg=30μm).

Considering low surface hole mobility of hydrogenated diamond surface at room temperature (it is known that the value is 30~40 cm^2/Vs [9,10]), the obtained effective mobility of 400 cm^2/Vs is a fairly high value. This result can be reasonably explained in terms of reduction of surface state as follows. Namely, reduction of surface state allowed a relatively unlimited upward band bending for applied negative gate voltage. Such an unlimited upward band bending generated the holes existing in a relatively inner region as well as outermost region of hydrogenated surface conductive layer. Therefore, it is thought that a high effective mobility of 400 cm^2/Vs is attributable to the holes existing in the inner conductive region having higher hole mobility value than outermost conductive region. According to the result estimated using drain conductance (this method was closely explained [3]), it was found that there exists surface state of ~10^{10} /cm^2 eV in the vicinity of valence band edge (MISFET operation region) of the FET.

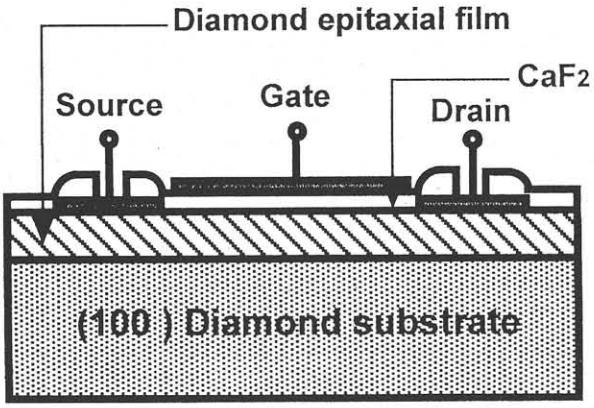

Fig. 1 Schematic view of fabricated MISFET.

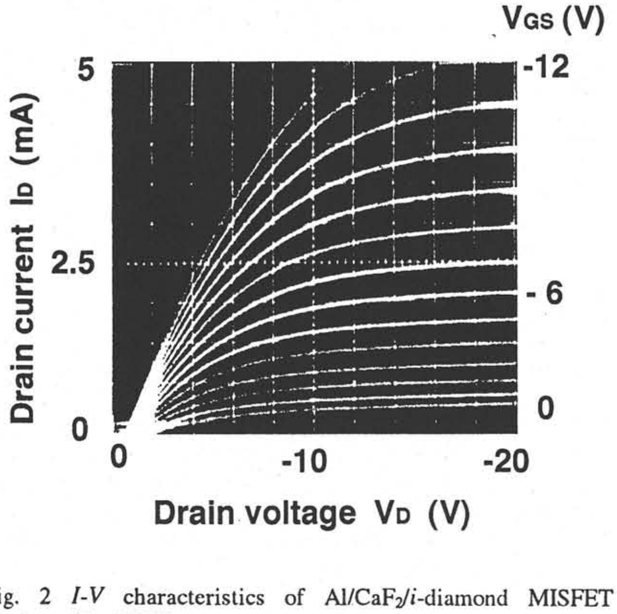

Fig. 2 I-V characteristics of Al/CaF_2/i-diamond MISFET fabricated by UHV process.

Table 1. Electrical parameters measured from Al/CaF_2/i-diamond MISFET prepared by UHV process.

μ_{eff} (cm^2/Vs)	g_m (μS/mm)	N_{SS} (/cm^2 eV)
400	5000	~10^{10}

4. Conclusions

In order to prevent the oxygen contamination on the diamond surface as much as possible during the process, we fabricated the diamond MISFET by reduced-oxygen process including UHV technology for the first time, and characterized its electrical properties. The MISFET prepared by UHV process showed a marked improvement on its electrical properties in comparison with that of conventional diamond MISFETs. According to the result, it was found that the observed g_m and N_{SS} of the device operation region was 5mS/mm and ~10^{10}/cm^2 eV for 30μm gate length, respectively. The obtained μ_{eff} was 400 cm^2/Vs at room temperature, which is the highest value reported until now in the diamond FET at room temperature.

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