Extended Abstracts of the 1997 International Conference on Solid State Devices and Materials, Hamamatsu, 1997, pp. 436–437

Electrical Properties of Metal-Insulator-Semiconductor (MIS) Interface and MISFETs Employing Hydrogenated Diamond Film Surface

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1. Introduction

Semiconducting diamond has many unique properties such as high thermal conductivity, wide band gap, and large break down field. Therefore, diamond has been expected to be a promising candidate for the application to the semiconducting device suitable for the hard-electronics. Diamond film growth is performed by various kinds of chemical vapor deposition (CVD) such as hot filament CVD and microwave plasma CVD with and without magnetic bias[1], all of which are characterized by host hydrogen plasma. In a case of hydrogen-involved CVD, the hydrogen plasma introduces a hydrogen terminated diamond surface during the diamond film growth which appears as a highly conductive *p*-type semiconducting layer.

Although the origin of this conductivity has not been clarified yet, the hydrogenated diamond surface conductive layer has been actively employed for the application to the semiconducting device.[2] With the wide application to the electron device, the electrical and optical properties of the hydrogenated diamond surface has been intensively studied and characterized by several researchers.[3,4] However, there is scarcely any investigation about electrical properties of MIS interface employing hydrogenated diamond surface. As is well known, silicon device (especially MOSFET) have progressed with improvement of the MOS interface (mainly reduction of the surface states). From this point of view, the investigation of the electrical properties of MIS interface employing hydrogenated diamond surface is very important for the application to the electron device in the hard-electronics field.

In the present work, from the Al/CaF_2/*i*-diamond MIS diode and MISFET, we characterized the electrical properties of the MIS interface employing hydrogenated diamond surface for the first time.

2. Experimental

Test specimens were fabricated on homoepitaxial (100) diamond films throughout the work. The films were grown on high-pressure-synthesized (100) diamond substrates by means of the electron-cyclotron-resonance (ECR) microwave plasma-assisted CVD method using a mixture of H_2 (220 sccm) and CO (12 sccm) at 800℃. For the purpose of forming an ohmic contact, Pt/Ti bilayer electrodes were made on the diamond surfaces by electron beam evaporation at room temperature and the standard lift-off technique, followed by sintering at 500℃ for 10 min in vacuum. CaF_2 films were deposited at room temperature to protect the hydrogenated diamond surface from the fluorine termination. Finally, Al electrodes were formed on the insulating films. The MIS fabrication techniques stated above were applied for fabrication of diamond MISFETs as well as the MIS diode.

3. Results and Discussion

The *C-V* characteristics measured from Al/CaF_2/*i*-diamond MIS diode, and the surface state density estimated by Terman method[5] are plotted by solid and open circles in Fig. 1, respectively. From this figure, we can see an efficient electrical modulation of surface band from the accumulation to at least the flat-band condition, where the pinning of surface band and hysteresis indicating a very high density of surface states are not observed.

For the clear analysis about the electrical properties of the MIS interface, we estimated the surface state density distributions by Terman method, and the result is also shown in Fig. 1, where the energy is measured from the

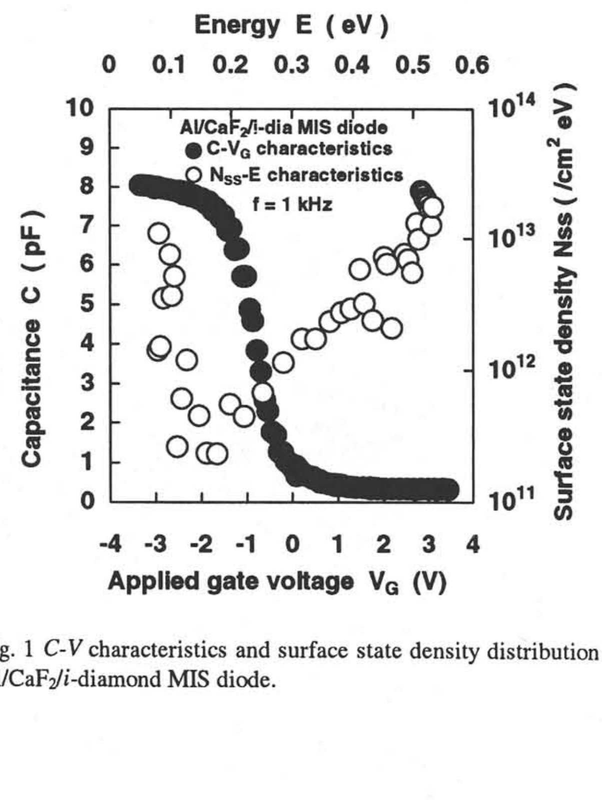

Fig. 1 *C-V* characteristics and surface state density distribution of Al/CaF_2/*i*-diamond MIS diode.

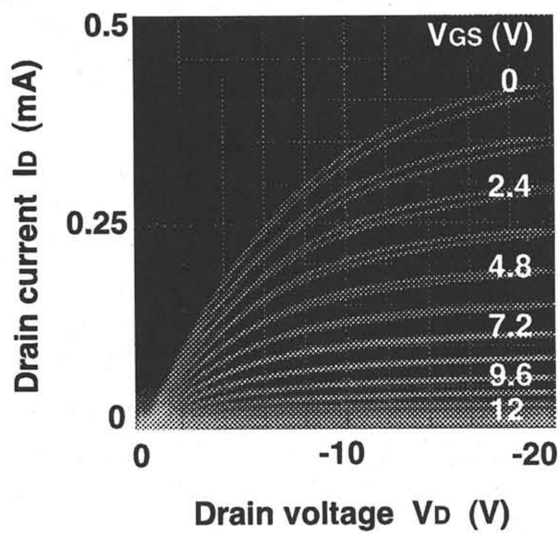

Fig. 2 I_D-V_D characteristics of the Al/CaF_2/*i*-diamond MISFET.

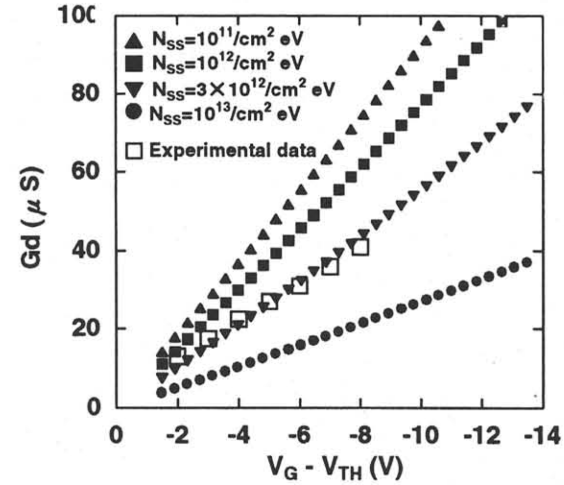

Fig. 3 Theoretical and experimental drain conductance G_D of Al/CaF_2/*i*-diamond MISFET.

valence band edge into the forbidden band. From this figure, we can see that surface state density existing on the MIS interface is from $\sim 10^{11}$ to $\sim 10^{13}$/cm^2 eV, which is one to three orders of magnitude larger than that of the silicon MOS interface in practical use ($\sim 10^{10}$/cm^2 eV). About the origin of the surface state, we can consider two factors. One is intrinsic factor such as defects inherent in diamond surface and crystalline imperfections. The other is extrinsic factor (for example, contamination on the diamond surface during the process). Really, we demonstrated surface states related to extrinsic factor, where the oxygen contamination produced a number of surface states on fluorine-terminated *i*-diamond surface as well as *p*-diamond surface.[6] Accordingly, the present data of the surface state density distribution are not necessarily taken as the intrinsic defects inherent in diamond surface. In other words, the observed surface states on the hydrogenated diamond surface might be originated partly from the extrinsic factors such as the oxygen adsorption, for instance. Further study concerning this point is underway. In the case of surface states related to extrinsic factor, they can be reduced more and more by introducing the clean process, etc.

However, we should pay caution to the result of surface states, the reason being in the following. From the general point of view, the surface state density at the energy of 0.1 eV or lower (from the valence band edge) strongly affects the performance of MISFETs because surface Fermi level is located at the position during the on-stage (current-flowing condition). Therefore, the surface state density near the valence band edge gives very important information for the MISFET operation. Unfortunately, however, it is well known that there arises a large error in estimation of the surface state density near the band edge as far as Terman method is employed for its estimation. Therefore, to ensure the result of surface states near the valence band edge, we fabricated diamond MISFET employing hydrogenated surface, and deduced the surface state density using the drain conductance (G_D) related to surface states.[7] The drain current vs drain voltage (I_D-V_D) characteristics of MISFET is shown in Fig. 2, and the results of theoretical and experimental G_D including surface state effect is shown in Fig. 3, where the experimental data of G_D were obtained from the slope of I_D-V_D curve of Fig.2. As shown in Fig. 3, it was found that the surface states of 3×10^{12}/cm^2 eV are located in the vicinity of valence band edge (0.05-0.1eV), which is in a fairy good agreement with the result estimated by Terman method. This result confirms the reliability of the data near the valence band edge estimated by Terman method.

4. Conclusions

Al/CaF_2/*i*-diamond MIS diodes and MISFET employing hydrogenated diamond surface were prepared, and the electrical properties of the diamond MIS interface were investigated for the first time. An efficient electrical modulation of surface band from the accumulation to at least the flat-band condition was observed from the MIS diode. From the estimation of surface state density, it was found that surface state density existing on the MIS interface employing the hydrogenated diamond surface was from $\sim 10^{11}$ to $\sim 10^{13}$/cm^2 eV, and the surface state density existing near the valence band edge (FET operation region) was 3×10^{12}/cm^2 eV.

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