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ARTICLE

Electrical Characteristics of MISFETs with Al_2O_3 Atomic Layer Deposited as Hydrogen-Terminated Diamond Protective Layer

Zhang Pengfei[1,2], Chen Weidong[1,3], Zhang Shaopeng[2], Yan Shufang[1,3], Ma Wen[1,3], Wang Hongxing[2]

[1] College of Materials Science and Engineering, Inner Mongolia University of Technology, Hohhot 010051, China; [2] Institute of Wide Band Gap Semiconductors, Xi'an Jiaotong University, Xi'an 710049, China; [3] Inner Mongolia Key Laboratory of Thin Film and Coatings, Hohhot 010051, China

Abstract: The interface properties of Zr-Si-N/hydrogen-terminated diamond (H-diamond) metal insulator semiconductor field transistors (MISFETs) with and without Al_2O_3 protective layer were studied. The Al_2O_3 protection layer and Zr-Si-N insulation layer were deposited by atomic layer deposition (ALD) and radio frequency (RF) sputter methods, respectively. The transfer characteristics of the MISFETs show that the gate threshold voltage varies from -2.5 V to 3 V with and without Al_2O_3 layer, which indicates that the devices switch from normally off to normally on operation. The output and transfer properties reveal the preservation of hydrogen termination because of the Al_2O_3 layer.

Key words: field-effect transistor; protective layer; Zr-Si-N/Al_2O_3

It is well-known that diamond is a wide-band-gap semiconductor that is suitable for high power and high-frequency electron devices because of its large band gap energy (5.5 eV), high carrier mobility (hole: 3800 cm^2/V·s, electron: -4500 cm^2/V·s), and high breakdown field (>10 MV/cm) [1-5]. However, the large activation energies of dopants and carrier concentrations in the diamond are very low, restricting the further development of the diamond-based electronic devices[6,7]. In recent years, diamond-based FETs focus on the epitaxial layer of the hydrogenated surface[8-10], which can be regarded as a suitable p-type channel layer with a sheet hole density and hole mobility of 10^{14} cm and 50~150 cm^2·V^{-1}·s^{-1} [11,12], respectively. For H-terminated diamond FETs with dielectric layers, the device performance can be rapidly improved[13,14]. H-diamond metal insulator semiconductor field transistors (MISFETs) have normally-on characteristics because of the 2DHG channel, while in terms of safety, normally-off MISFETs operation is usually required[15]. Nevertheless, the two-dimensional hole gas (2DHG) existing near the diamond surface is chemically and thermally unstable and vulnerable to the ambient environment[16]. Besides, during the sputtering deposition dielectric layer, 2DHG is easy to be damaged by the plasma discharge[17]. Therefore, a buffer layer is necessary to protect the 2DHG in the H-diamond. Fortunately, ALD-Al_2O_3 reported, showing a large valence band offset with H-diamond, has been used as a buffer layer and exhibits excellent characteristics in H-diamond MISFETs[18,19]. Consequently, ALD-Al_2O_3 can be deposited on the H-diamond surface as a protective layer.

In this work, normally-off H-diamond MISFET was fabricated with dielectrics of Zr-Si-N using Al_2O_3 as a protective layer, and its electrical properties were investigated. For comparison, H-diamond MISFET without Al_2O_3 was also fabricated.

1 Experiment

Undoped homoepitaxial films were grown on a CVD

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Corresponding author: Chen Weidong, Ph. D., Professor, College of Materials Science and Engineering, Inner Mongolia University of Technology, Hohhot 010051, P. R. China, E-mail: weidongch@163.com

synthesized [100] IIa single-crystal diamond substrate with a dimension of 3 mm×3 mm×0.5 mm in AsteX 5200 reactor (Seki Technotron Corp). Before growth, the single crystal diamond was dipped into alkali and hot-acid to remove the non-diamond phase. Then, the substrate was loaded into a microwave plasma chemical vapor deposition system for diamond epitaxial. During growth, the total-flow rate was 500 mL/min, with 2% CH_4 diluted in purified H_2. The growth temperature, process pressure, and microwave power were 980 ℃, 12.6 MPa, and 1 kW, respectively. After growth, the substrate was kept in hydrogen plasma for 10 min at 900 ℃ and then cooled to generate a hydrogen-terminated surface.

In order to acquire the quality of H-diamond film, Raman measurements with 532 nm excitation laser and 0.4 cm^{-1}/pixel resolution in 20× objective lenses were carried out. For good adhesion and low specific resistance[20], a carbon soluble metal palladium (Pd) was patterned as electrodes by photolithography and electron beam evaporation (EB) techniques. First, the Al_2O_3 films were deposited on the H-diamond with a thickness of 14.3 nm at 150 ℃, and the precursor and oxidant used in ALD were trimethyl aluminum and H_2O, respectively. Some device's channels were not covered with Al_2O_3 for comparison. Next, the Zr-Si-N layer with 28.6 nm in thickness was deposited by the sputtering technique. Then, the sample was isolated by irradiation of O_3 and UV rays at room temperature (RT) for 15 min. W as the gate metal was finally patterned by the EB technique on Zr-Si-N. The complete fabrication process of the MISFET is shown in Fig.1. The gate length (L_G) and gate width (W_G) for both devices were 2.5 μm and 100 μm, respectively. The electrical properties of the devices with and without the Al_2O_3 protective layer were then investigated.

2 Results and Discussion

To investigate the quality of single-crystal diamond, micro-Raman spectroscopy with 20× objectives was used before the MISFET fabrication process. As shown in Fig. 2, the Raman excitation laser wavelength is 532 nm, and the resolution is 0.40 cm^{-1}/pixel. The narrow symmetrical sharp peak and Raman FWHM result of the diamond substrate are 1333 cm^{-1} and 4.9 cm^{-1}, respectively. The optical microscope images of as-deposited diamond epitaxial films are shown in Fig. 3. It shows the full scale of the growth film with a dimension of 3 mm×3 mm. No point defect pits and steps are found on the surface, which indicates great quality for electronic device fabrication.

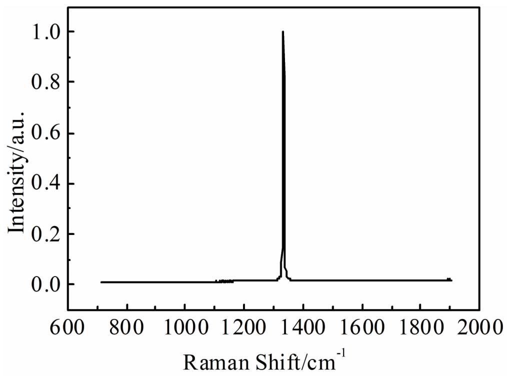

Fig.2 Raman spectrum of single crystal diamond

Fig.4 shows the leakage current density (J) for the Zr-Si-N/H-diamond MISFET for gate voltage ranging from -5 V to 5 V. When the gate bias is -5 V, the J value is smaller than 5.0×10^{-7} $A\cdot cm^{-2}$. With the change of the gate bias from positive to negative, the J value of the MISFET increases to 2.0×10^{-6} $A\cdot cm^{-2}$ at 1.5 V, indicating very low driving leakage current density. We conclude that the Zr-Si-N/H-diamond MIS gate structure with Al_2O_3 applies to the fabrication of MISFETs.

Fig. 5 displays C-V characteristics of the Zr-Si-N/H-diamond MISFET with and without Al_2O_3 protective layer. All the C-V curves show distinct accumulation and depletion regions, which suggest that a high-quality insulator is fabricated on the H-diamond surface. The depletion regions of the C-V curves for the capacitors with and without Al_2O_3 strongly depend on gate bias, which indicates that the H-diamond interface has low fixed charge density.

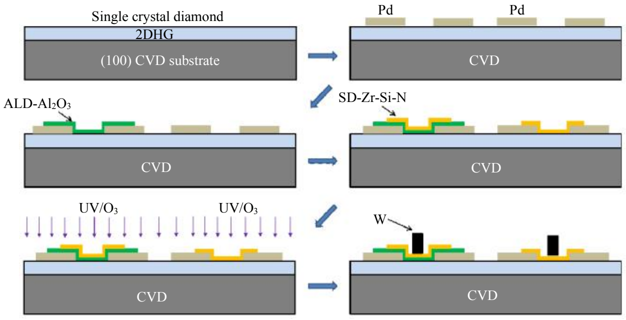

Fig.1 Outline of the process used for fabricating MISFET

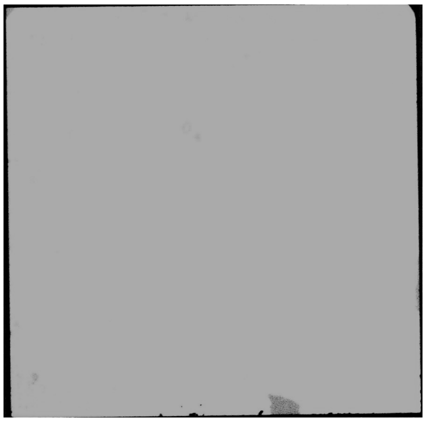

Fig.3 OM image of as-deposited diamond epitaxial films (5×)

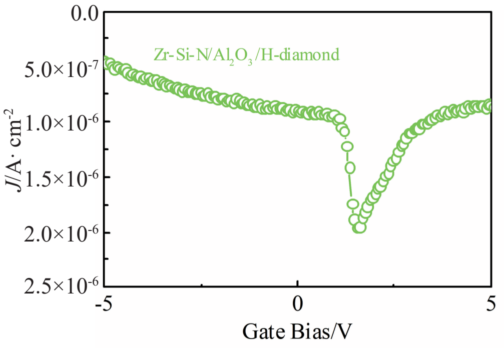

Fig.4 Leakage current density of the device with Al_2O_3 layer

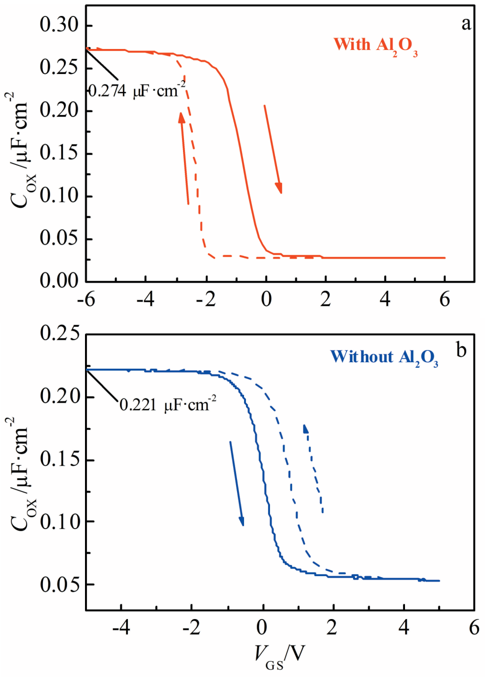

Fig.5 *C-V* curves for the devices with (a) and without (b) Al_2O_3

Based on the C max values, the Zr-Si-N thickness (28.6 nm) and the Al_2O_3 thickness (14.3 nm), the dielectric constants of the Zr-Si-N films with and without Al_2O_3 protective layer were calculated to be 13.3 and 7.1, respectively, because of the different dielectric materials. Another reason for the higher dielectric constants is believed to be the high quality of the ALD-Al_2O_3 protective layer. We also observed hysteresis in the bidirectional *C-V* characteristics; the hysteresis values are 1.16 V for MISFET with Al_2O_3.

Drain-source current versus voltage (I_{DS}-V_{DS}) characteristics for Zr-Si-N/H-diamond MISFET with and without Al_2O_3 are presented in Fig.6. The gate-source voltage (V_{GS}) varies from -4 V with voltage steps of +1 V. All the MISFETs show good operation and p-type channel characteristics. Transparent linear regions are observed at low V_{DS} in all of the I_{DS}-V_{DS} curves, which indicates that good ohmic contact is formed between Pd/Zr-Si-N/Al_2O_3 and the H-diamond surface. The maximum I_{DS} (I_{DSmax}) of the MISFET without Al_2O_3 is -1.2 mA/mm, while that of the MISFET with Al_2O_3 is -2.0×10^{-3} mA/mm. Thus, the Zr-Si-N/H-diamond interface is significantly improved by Al_2O_3.

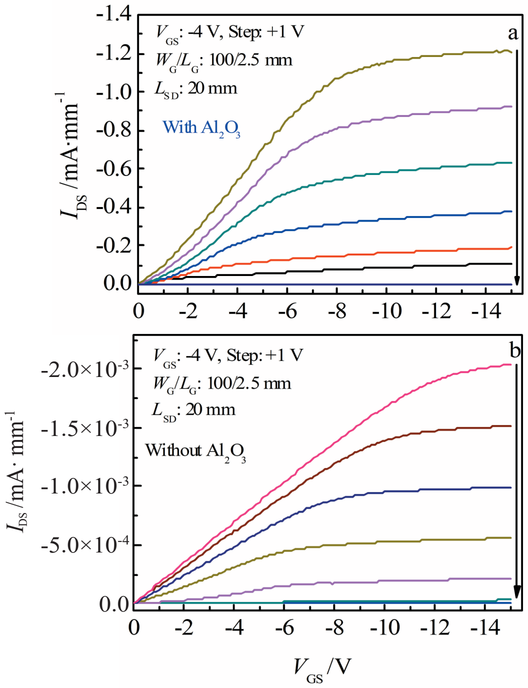

Fig.6 Output characteristics of the device with (a) and without (b) Al_2O_3 layer

The room temperature transfer and transconductance (G_m) characteristics for the MISFET with and without Al_2O_3 are presented in Fig.7. The threshold voltage (V_{TH}) can be determined according to the linear part of the G_m-V_G plot. Without the Al_2O_3 layer, V_{TH} is 3 V for the MISFET with normally on characteristics. However, with the Al_2O_3 layer, V_{TH} changes to -2.5 V with normally off characteristic due to different fixed charge densities. The fixed charge density with and without Al_2O_3 layer are calculated to be 3.4×10^{12} and 4.0×10^{11}cm^{-2}, respectively. Al_2O_3 protective layer can change the operation of the MISFET from normally on to normally off characteristics. This pheno-menon indicates that the holes in the H-diamond layer at the equilibrium stage disappear with the Al_2O_3 protective layer[21,22]. Besides, the maximum value (G_m) with and without Al_2O_3 protective layer is 0.23 mS·mm^{-1} and 2.81 mS·mm^{-1}, respectively. The threshold voltage (V_{TH}) is extrapolated from the linear part of G_m-V_{GS} plot, showing the value of 2.2 V.

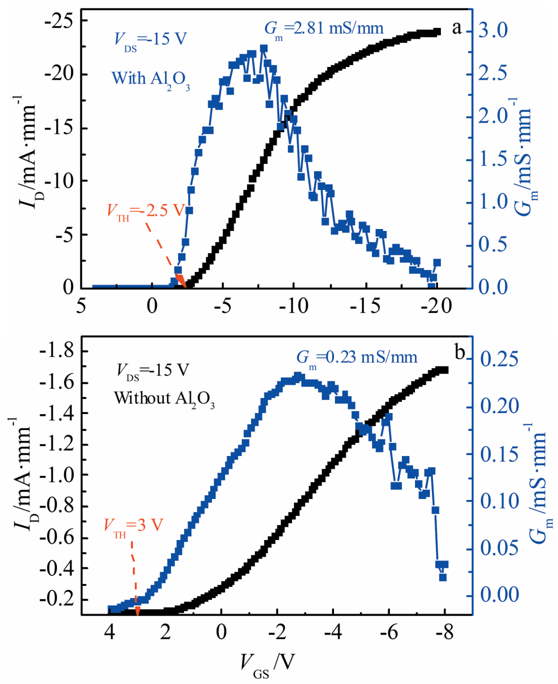

Fig.7 Transfer and transconductance of the device with (a) and without (b) Al_2O_3 layer

3 Conclusions

1) The transistor output and transfer characteristics conform to the presence of 2DHG existing near the diamond surface. The gate leakage current of the device with the Al_2O_3 layer is lower than 5.0×10^{-7} A·cm^{-2} and V_{GS} changes from -5 V to 5 V. The maximum I_{DS} of the MISFET with and without Al_2O_3 are -2.0×10^{-3} mA/mm and -1.2 mA/mm, respectively.

2) The channels can be protected by the Al_2O_3 layer. Al_2O_3 protective layer can change the operation of the MISFET from normally on to normally off characteristics.

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原子层沉积Al_2O_3保护层氢终端金刚石MISFETs的电学特性

张鹏飞[1,2]，陈伟东[1,3]，张少鹏[2]，闫淑芳[1,3]，马 文[1,3]，王宏兴[2]
(1. 内蒙古工业大学 材料科学与工程学院，内蒙古 呼和浩特 010051)
(2. 西安交通大学 宽禁带半导体材料与器件研究中心，陕西 西安 710000)
(3. 内蒙古自治区薄膜与涂层重点实验室，内蒙古 呼和浩特 010051)

摘 要：研究了Zr-Si-N氢终端金刚石（H-diamond）绝缘栅场效应晶体管（MISFET）在有无Al_2O_3保护层情况下的电学特性。分别采用原子层沉积法（ALD）和射频溅射法（RF）制备了Al_2O_3保护层和Zr-Si-N栅介质层。MISFETs的转移特性曲线表明，其栅阈值电压在有无Al_2O_3保护的情况下从-2.5 V变化到3 V，表明器件从常关型转换为常开型。输出和转移特性曲线揭示了氧化铝的存在保护了氢终端，使其免受磁控溅射过程的损伤。

关键词：场效应晶体管；保护层；Zr-Si-N/Al_2O_3

作者简介：张鹏飞，男，1992年生，博士，内蒙古工业大学材料科学与工程学院，内蒙古 呼和浩特 010051，E-mail：pfzhang.kk@foxmail.com