HfAlO$_x$/Al$_2$O$_3$ Bilayer Dielectrics for a Field Effect Transistor on a Hydrogen-Terminated Diamond

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Abstract: In this work, a hydrogen-terminated (H-terminated) diamond field effect transistor (FET) with HfAlO$_x$/Al$_2$O$_3$ bilayer dielectrics is fabricated and characterized. The HfAlO$_x$/Al$_2$O$_3$ bilayer dielectrics are deposited by the atomic layer deposition (ALD) technique, which can protect the H-terminated diamond two-dimensional hole gas (2DHG) channel. The device demonstrates normally-on characteristics, whose threshold voltage ($V_{TH}$) is 8.3 V. The maximum drain source current density ($I_{DS,max}$), transconductance ($G_m$), capacitance ($C_{OX}$) and carrier density ($\rho$) are $\rho$ = 6.3 mA/mm, 0.73 mS/mm, 0.22 μF/cm$^2$ and 1.53 $\times$ 10$^{13}$ cm$^{-2}$, respectively.

Keywords: hydrogen-terminated diamond; field effect transistor; HfAlO$_x$

1. Introduction

The diamond is considered as an ultimate semiconductor with ultrawide bandgap of 5.47 eV, extremely high breakdown field of 10 MV/cm, highest thermal conductivity of 22 W/cm$^\circ$K, high carrier mobility (electrons of 4500 cm$^2$/V$\cdot$s, holes of 3800 cm$^2$/V$\cdot$s) and large carrier saturation velocity (electrons of 1.5–2.7 $\times$ 10$^7$ cm/s, holes of 0.85–1.2 $\times$ 10$^7$ cm/s) [1–4]. Since the dopants cannot be activated at room temperature with high activation energy (boron of 370 meV and phosphorous of 650 meV) [5], the application of diamonds has been greatly hindered. In this case, δ-doping comes into being. However, this technique requires the precise control of the doping thickness, and the carrier mobility is not ideal [5]. Fortunately, a hydrogen-terminated (H-terminated) diamond with two-dimensional hole gas (2DHG) channel provides a new solution to overcome these problems, which demonstrates a high carrier density of 10$^{13}$ cm$^{-2}$ and large carrier mobility of 50–200 cm$^2$/V$\cdot$s [3,6]. To date, as a promising structure of diamond-based electronic devices, the H-terminated diamond field effect transistor (FET) has aroused the great interest of researchers [7–21].

Since a H-terminated diamond is thermally and chemically instable, it is necessary to stabilize the hole carriers for a H-terminated diamond FET with a dielectric layer [8]. Furthermore, the dielectric material with high dielectric constant can control large charge responses at a small bias effectively [14]. To date, many high dielectric constant materials have been employed for the fabrication of a H-terminated diamond FET [10,15]. However, there are few reports on using HfAlO$_x$ as dielectric with a high dielectric constant, high crystallization temperature and large band gap (5.8–6.2 eV) [22].

In this work, we study a H-terminated diamond FET with HfAlO$_x$/Al$_2$O$_3$ bilayer dielectrics, and its electrical properties were evaluated by semiconductor analyzer.
2. Materials and Methods

The fabrication process of the H-terminated diamond FET with HfAlO₃/Al₂O₃ bilayer dielectrics is displayed in Figure 1. A high temperature and high pressure (HPHT) single crystal diamond substrate was cleaned by various solutions before growth [9]. Then, a 200 nm homoepitaxy layer was grown on the substrate with the dimensions of $3 \times 3 \times 0.5 \text{ mm}^3$ by the microwave plasma chemical vapor deposition (MPCVD) technique. The growth conditions were declared in our previous work [9]. Afterwards, 150 nm Au electrodes with 20 μm source drain gap ($L_{SD}$) were realized by photolithography, electron beam evaporation (EB) and the lift-off technique. Next, isolation was carried out with 20 min UV/ozone treatment. After that, a 4 nm Al₂O₃ film was deposited to protect the H-terminated channel, and a 30 nm HfAlOₓ film was deposited by the ALD technique sequentially. The atomic percentage of HfAlOₓ is Hf:Al:O = 2:23:75, evaluated by the energy dispersive X-ray spectroscopy (EDS) technique. Finally, 150 nm Al gate electrode was deposited on the gate region with 4 μm gate length ($L_C$) and 100 μm gate width ($W_C$). The electrical properties of this device were characterized by Agilent B1505A. Figure 2 demonstrates the schematic diagram of the H-terminated diamond FET with HfAlOₓ/Al₂O₃ bilayer dielectrics. The electrical contacts for the source, drain and gate electrodes are exhibited, and the hole carriers of the channel are illustrated.

![Fabrication process of the H-terminated diamond FET with HfAlOₓ/Al₂O₃ bilayer dielectrics.](image1)

**Figure 1.** Fabrication process of the H-terminated diamond FET with HfAlOₓ/Al₂O₃ bilayer dielectrics.

![Schematic diagram of the H-terminated diamond FET with HfAlOₓ/Al₂O₃ bilayer dielectrics.](image2)

**Figure 2.** Schematic diagram of the H-terminated diamond FET with HfAlOₓ/Al₂O₃ bilayer dielectrics.

3. Results and Discussion

Figure 3a demonstrates the drain source current density ($I_{DS}$) versus drain source voltage ($V_{DS}$) at different gate voltages ($V_{GS}$) of the H-terminated diamond FET with HfAlOₓ/Al₂O₃ bilayer dielectrics. The gate length ($L_C$), gate width ($W_C$) and $L_{SD}$ for the device are 4 μm, 100 μm and 20 μm, respectively. The $V_{CS}$ varies from 8 to −6 V in a step of −2 V. The absolute value of $I_{DS}$ ($|I_{DS}|$) increases as the absolute value of the $V_{GS}$ ($|V_{GS}|$) increases, indicating the existence of a p-type channel. The maximum $I_{DS}$ ($I_{DS\text{max}}$) is −6.3 mA/mm obtained at a $V_{CS}$ of −6 V and a $V_{DS}$ of −20 V. The $I_{DS\text{max}}$ is relatively large compared with our previous work [13,23], and the reason may be attributed to the undamaged 2DHG conduction channel protected by Al₂O₃.
Figure 3. Characteristics of the H-terminated diamond FET with HfAlOx/Al2O3 bilayer dielectrics: (a) output and (b) transfer.

In Figure 3b, the transfer characteristic of the H-terminated diamond FET with HfAlOx/Al2O3 bilayer dielectrics is presented. The threshold voltage \( V_{TH} \) is extrapolated to be 8.3 V at a \( V_{DS} \) of −20 V based on the relationship between \( I_{DS}^{1/2} \) and \( V_{GS} \), demonstrating normally-on characteristics [14]. The maximum transconductance \( (G_m) \) is 0.73 mS/mm.

The leakage current density \( (I_{GS}) \) in the log coordinate of the H-terminated diamond FET with HfAlOx/Al2O3 bilayer dielectrics is shown in Figure 4a. The \( I_{GS} \) changes from −6 to 8 V, and the absolute value of \( I_{GS} \) \( |I_{GS}| \) is \( 7.95 \times 10^{-7} \, \text{A/cm}^2 \) at a \( V_{GS} \) of −6 V, demonstrating a low \( |I_{GS}| \). Table 1 demonstrates the \( |I_{GS}| \) comparison with the reported H-terminated FETs. The \( |I_{GS}| \) for the MoO3, LiF/Al2O3, Ta2O5/Al2O3 and ZrO2/Al2O3 H-terminated diamond FET are \( 3.33 \times 10^{-4} \, \text{A/cm}^2 \), \( 1 \times 10^{-6} \, \text{A/cm}^2 \), \( 7.6 \times 10^{-4} \, \text{A/cm}^2 \) and \( 4.8 \times 10^{-5} \, \text{A/cm}^2 \), respectively [21,24–26]. Their values are larger than those of the HfAlOx/Al2O3 FET. As shown in Figure 4b, the relationship between \( I_{GS} \) and \( V_{GS} \) can be described by the thermionic field emission (TFE) model (1) [9]:

\[
J_{TFE} = J_S \exp(V/P)[1 - \exp(-eV/kT)]
\]

where \( J_{TFE} \) means the \( I_{GS} \) caused by TFE model; \( J_S \) represents the saturation current; and \( P \) is a parameter associated with the carrier tunneling probability and temperature [9]. In Figure 4b, the \( \ln J_{TFE}/J_S(-\exp(qV/kT)) \) and \( V_{GS} \) exhibit a linear relationship under the TFE model.

Figure 4. \( I_{GS} \) characteristics of the H-terminated diamond FET with HfAlOx/Al2O3 bilayer dielectrics: (a) \( |I_{GS}| \) and (b) TFE.
Table 1. The $|I_{GS}|$ comparison between this work and the reported H-terminated diamond FETs.

| Gate Materials | MoO$_3$ | LiF/Al$_2$O$_3$ | Ta$_2$O$_5$/Al$_2$O$_3$ | Zr$_2$O$_5$/Al$_2$O$_3$ | HfAlO$_x$/Al$_2$O$_3$ |
|----------------|---------|-----------------|------------------------|-----------------------|----------------------|
| $|I_{GS}|$ (A/cm$^2$) | $3.33 \times 10^{-4}$ | $1 \times 10^{-6}$ | $7.6 \times 10^{-4}$ | $4.8 \times 10^{-5}$ | $7.95 \times 10^{-7}$ |
| Ref. | [21] | [24] | [25] | [26] | This work |

Figure 5a displays the capacitance-voltage (C-V) curve measured at 1 MHz of the H-terminated diamond FET with HfAlO$_x$/Al$_2$O$_3$ bilayer dielectrics. Evident accumulation and depletion regions can be observed. The maximum capacitance ($C_{OX}$) is 0.22 µF/cm$^2$ at $V_{GS}$ of −2 V. Based on the method $d^2C/dV_{GS} = 0$, the flat band voltage ($V_{FB}$) is determined to be 8.5 V and 7.6 V in the forward and reverse directions, respectively [18]. The trapped charge density is evaluated to be $1.24 \times 10^{13}$ cm$^{-2}$ at $V_{GS}$ of −2 V measured at 1 MHz: (a) C-V and (b) $\rho$.

**4. Conclusions**

In summary, the electrical properties of H-terminated diamond FET with HfAlO$_x$/Al$_2$O$_3$ bilayer dielectrics were investigated. The output characteristics exhibit an evident p-type channel, and the $I_{DS,max}$ is −6.3 mA/mm obtained at $V_{GS}$ of −6 V. The transfer characteristics exhibits the $V_{TH}$ of 8.3 V, indicating normally-on characteristics. The $|I_{GS}|$ is $7.95 \times 10^{-7}$ A/cm$^2$ at $V_{GS}$ of −6 V, demonstrating a low $|I_{GS}|$. In addition, the $C_{OX}$ is 0.22 µF/cm$^2$ based on the C-V curve. Additionally, the $\rho$ is $1.50 \times 10^{13}$ cm$^{-2}$ at a $V_{GS}$ of −2 V. The results are meaningful for the research of a H-terminated diamond FET, and the electrical performance of HfAlO$_x$/Al$_2$O$_3$ FET will be further improved by optimizing the fabrication process in our future work.

**Author Contributions:** Conceptualization, M.Z., W.W. and S.F.; methodology, M.Z. and F.L.; software, M.Z. and G.C.; validation, W.W. and H.W.; formal analysis, F.W.; investigation, M.Z. and S.H.; resources, M.Z. and Y.W.; data curation, M.Z. and F.L.; writing—original draft preparation, M.Z.; writing—review and editing, M.Z., W.W. and H.W.; visualization, R.B.; supervision, W.W. and H.W.; project administration, M.Z.; funding acquisition, W.W. and H.W. All authors have read and agreed to the published version of the manuscript.
Funding: This work was funded by National Key R&D Program of China (No. 2018YFE0125900), National Natural Science Foundation of China (No. 61627812, 61804122 and 62074127), China Postdoctoral Science Foundation (No. 2019M660256 and 2020M683485), and Key R&D Program of Shaanxi Province (No. 2021GY-223).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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