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Research On Structural Design and Performance Optimization of Diamond Transistors

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Abstract. With the increasing demand for transistors that work in high-power, high-frequency, and high-voltage environments, diamond transistors are set to become an indispensable part of future transistor development. This article reviews the development history of hydrogen-terminated diamond transistors and silicon-terminated diamond transistors. Specifically, this article summarizes the invention of hydrogen-terminated and silicon-terminated diamond transistors, along with recent structural innovations and data analysis. From the recent findings on hydrogen-terminal diamond transistors, this paper finds that the structure of hydrogen-terminated diamond transistors is already mature. However, silicon-terminated diamond transistors are still in the development stage, and scientists are still looking for a new structure to make the output of silicon-terminated diamond transistors more stable and improve the efficiency of silicon-terminated diamond transistors. Last but not least, diamonds are also used to build FinFETs. Although there are few studies on this type of diamond transistor, significant progress has still been made in the development of diamond transistors.

Keywords: Hydrogen-terminal diamond transistor; Silicon-terminal diamond transistor; Diamond MOSFETs; P-doped diamond.

1. Introduction

Since the invention of the first transistor in 1947, the exploration of semiconductor materials for making transistors began. With the development of technology, various types of transistors have been discovered, including dual bipolar crystal transistors, metal oxide metal tubes, complementary metal oxide semiconductors, and the latest discovery of a three-dimensional field effect transistor called FinFETs. Moreover, the materials available for transistors have also varied, including Silicon, Gallium Arsenide, and Gallium Nitride. However, the performance of Silicon, Gallium Arsenide, and Gallium Nitride significantly decreases in high-temperature and high-pressure environments. As a result, scientists are keen to find a new material with a wider bandwidth to support its functionality under extreme conditions.

As a special semiconductor, diamond has a wide bandgap, high thermal conductivity, high electron mobility, Chemical Stability, and high breakdown electric field compared to other semiconductors. The bandgap of the diamond reaches 5.5 eV. The wide bandgap of diamond enables diamond transistors to maintain stable output under high temperature, high pressure, and high frequency. Secondly, the high thermal conductivity of diamond of 2000 W/m·K allows diamond transistors to dissipate heat when working at high power, effectively avoiding overheating. Thirdly, diamond has a high electron mobility of 4500 $cm^2/V\cdot s$, which also means that diamond has high electrical conductivity. In other words, the electrons on diamond devices can move faster than other semiconductor material devices under the same electric field, so they can respond to rapidly changing electric fields, allowing electrons to move quickly under high-frequency electrical signals. This ensures that it can work in a high-frequency environment. In addition, diamonds are chemically very stable and cannot react with other materials. The high corrosion resistance of diamonds allows the equipment to endure extreme working environments. Last but not least, the breakdown electric field of the diamond can reach 10MV/cm, which gives it a larger breakdown voltage. This property allows diamond devices to output stably under high-voltage situations. In conclusion, transistors made of diamond materials have unparalleled advantages under extreme situations. The following paragraphs will show the development process of diamond transistors and data analysis of different types of diamond transistors.

2. Fabrication and Principle of Diamond Transistor

2.1. Hydrogen-terminal diamond transistor

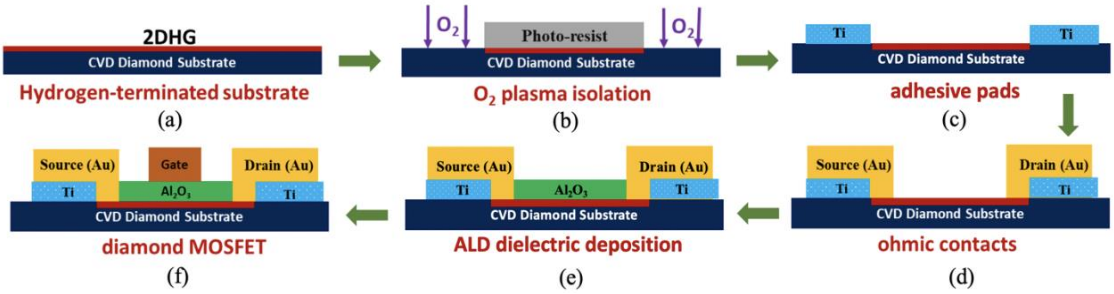

Figure 1. Diagram for fabrication of hydrogen-terminated diamond transistor [1].

Figure 1 shows the whole fabrication process of the hydrogen-terminated diamond transistors in detail [1]. Initially, the diamond surface undergoes hydrogen plasma treatment to create a hydrogen-terminated surface. Subsequently, a layer of photoresist is applied to safeguard the hydrogen-terminated surface, followed by the use of oxygen plasma treatment to achieve device isolation. The next step involves the deposition of gold for the source and drain via ohmic contacts, along with the deposition of Al2O3 (alumina) on the surface. After all these processes, the final stage is the deposition of the gate.

For the hydrogen terminal diamond transistor, there is a two-dimensional hole gas (2DHS) on the surface of the diamond substrate. Therefore, the source and drain are still connected by 2DHS when Vgs is zero. Thus, the hydrogen terminal diamond transistor operates in depletion mode by default. When Vgs voltage is negative, more holes will be attracted to the channel. Thus, the current in the channel will increase. However, when the Vgs is positive, the electrons will be attracted to the channel and fill the holes. This creates a depletion region. As soon as the depletion region fills the channel, the source and drain will be disconnected.

2.2. Silicon-terminal diamond transistor

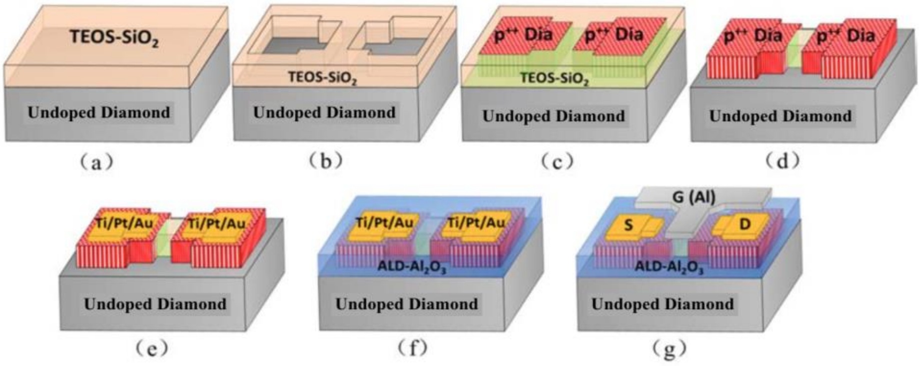

Figure 2. Diagram for fabrication of silicon-terminated diamond transistor [2].

Figure 2 indicates the fabrication processes of silicon-terminated diamond transistors [2]. First, a thin layer of silicon dioxide is applied to the surface of the diamond, and then a portion of this layer is selectively removed to induce P-type doping in the diamond. Next, a portion of the silicon dioxide layer is selectively removed to induce P-type doping in the diamond. The process in section C utilizes MPCVD technology to achieve P-type doping in the diamond and establishes a silicon-terminated interface between the silicon dioxide and diamond. In section D, device isolation is achieved by removing most of the silicon dioxide and conducting an oxygen termination procedure. Subsequently, in section E, metal is coated onto the P-type diamond to create a Schottky contact. Section F involves the deposition of an aluminum oxide film. The final step involves depositing gate metal.

When Vgs is equal to zero, because of the negative voltage difference between the drain and source, the gate voltage is larger than that in the drain and creates an electric field from gate to drain. Therefore, the electrons will be attracted to the region between the gate and the drain. Thus, the p-type channel connected will be destroyed. Consequently, the silicon-terminated diamond transistor operates in enhancement mode.

3. Innovation of Diamond Transistor

3.1. The first hydrogen-terminal diamond transistor

As early as 1994, Hiroshi Kawarada and his team reported for the first time hydrogen-terminated semiconductor transistors [3]. Rather than using boron-doped diamond as a substrate, this hydrogen-terminated semiconductor transistor uses a combination of hydrogen and carbon to create a layer of two-dimensional holes gas on the surface of the undoped diamond to create a p-type effect. In this case, the diamond substrate is oriented 001. Because they made MESFETs transistors, the source and drain of the transistor are directly formed using gold. On the gate part, the aluminum metal is directly connected to the surface of the two-dimensional hole gas.

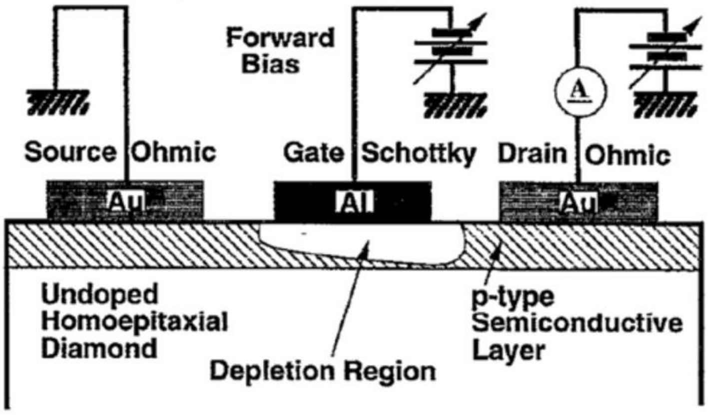

Figure 3. Diagram of the first hydrogen terminal diamond transistor [3].

The first hydrogen terminal diamond transistor was created by Kawarada, H and his teams, as shown in Figure 3 [3]. Its operating mode is enhancement mode, meaning when Vgs is equal to zero, no current flows through it. The transistor only starts to work normally when Vgs is less than -2 volts, which exceeds its threshold voltage. The transistor can work normally. When Vgs is equal to zero, the reason why the transistor cannot work is the width of the two-dimensional hole gas is too narrow. In this case, the depletion region provided by the electric field from the gate to the drain will cover the two-dimensional hole gas, making the channel disconnected.

3.2. The first silicon-terminal diamond transistor

In May 2020, Wenxi Fei and her team at Waseda University in Japan first reported a gray-terminated diamond field-effect transistor. [2] This report provides a detailed introduction to the manufacturing process of silicon-terminated diamond field-effect transistors. (as shown in Figure 4) The first step is a thin silica film deposited on top of the diamond substrate. Next, part of the silica film is etched for growth of a p-type doped Diamond. Then, the Microwave plasma chemical vapor deposition (MPCVD) is used to grow boron-doped diamonds. Therefore, the silica and Diamond interface is formed which becomes a silicon-terminated diamond. The device isolation is achieved by etching most of the silica and performing oxygen termination treatment. The last step is metal deposition on the p-type diamond and making a Schottky contact.

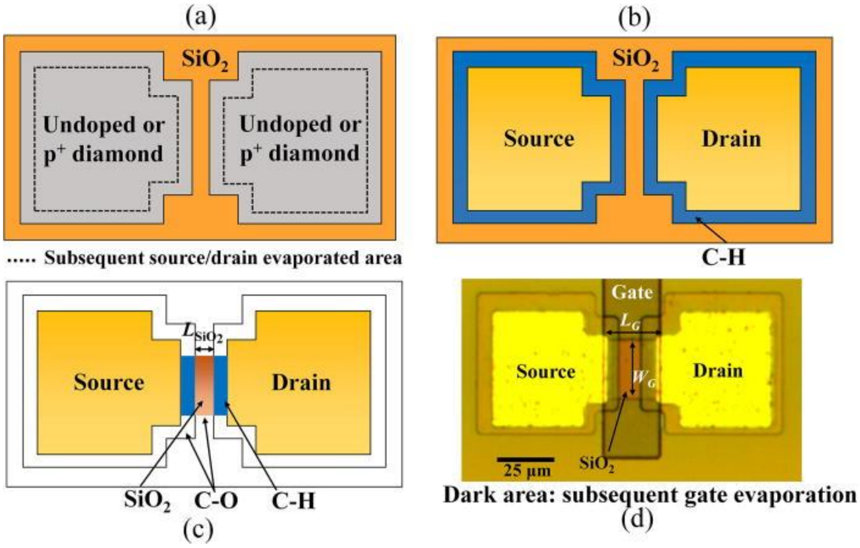

Figure 4. The manufacturing process for silicon terminal transistors [2].

4. The Improvement of Fabrication for Diamond Transistor

4.1. Performance of hydrogen-terminated diamond field-effect transistors at high frequencies

In August 2001, H. Kawarada and his team reported on the performance of hydrogen-terminated diamond field-effect transistors at high frequencies [4]. The transistors used in the study were hydrogen-terminated diamond Mesfets with a gate length of 2 µm and a gate width of 50 µm. The study found that when Vds is -5 volts and Vgs is -1.5 volts, the drain current reaches its maximum value. Additionally, when Vgs is -1.5 volts, the maximum transconductance is 70 mS/mm. In terms of the microwave performance of the transistor, the cutoff frequency reached 2.2GHz and the maximum oscillating frequency reached 7 GHz. Through research and calculations, it was found that the parasitic resistance from source to gate is 60 ohms. The capacitance is 1.3pF, and the depth of the depletion region is 4nm. Thanks to the lower dielectric coefficient of diamond, the transistor can produce stable output with greater efficiency. In conclusion, this article's measurement of diamond hydrogen terminal transistor data provides a theoretical basis for the optimization of diamond manufacturing processes in the future.

4.2. Boron delta-doped p-channel transistor

A. Aleksov and his team in 2003 republish an essay about two different kinds of diamond transistors [5]. One is a boron delta-doped p-channel transistor, and the other is a hydrogen-terminated surface channel transistor. The article indicates that the current boron delta-doped p-channel transistor technology is not mature. This article reports in detail the performance of boron-hybridized diamond transistors. They found that both a boron delta-doped p-channel transistor and a hydrogen-terminated surface channel transistor can produce better output in high-frequency and high-power working environments. Moreover, the article proposes that this diamond transistor with boron-doped p-channels can improve its structure to maximize its power. Therefore, because of the excellent performance of diamond transistors under high power input and high frequency, they can play an important role in the field of high-frequency communications or radar systems.

4.3. Diamond transistor with high breakdown voltage

In September 2014, Hitoshi Umezawa and his teams from Japan's National Institution of Advanced Industry and Technology reported their research about high breakdown voltage diamond transistors with Corbino geometry [6]. The process mentioned in this paper is different from the hydrogen-terminated diamond transistor in that the two-dimensional hole gas part in the hydrogen-terminated transistor is replaced by a boron-doped diamond layer. The most obvious improvement of this transistor in the essay compared to other diamond transistors was that its intrinsic transconductance changed drastically with changes in temperature. For instance, at 300°C, the intrinsic transconductance increased to 143 μS/mm, which is room temperature. 5.9 times lower intrinsic transconductance. Moreover, the breakdown voltage increases with the increase of length from gate to drain. As long as the length from gate to drain is 30 μm, the maximum breakdown voltage can be 1530 volts, which is much larger than the normal diamond transistors' breakdown voltage (Figure 5).

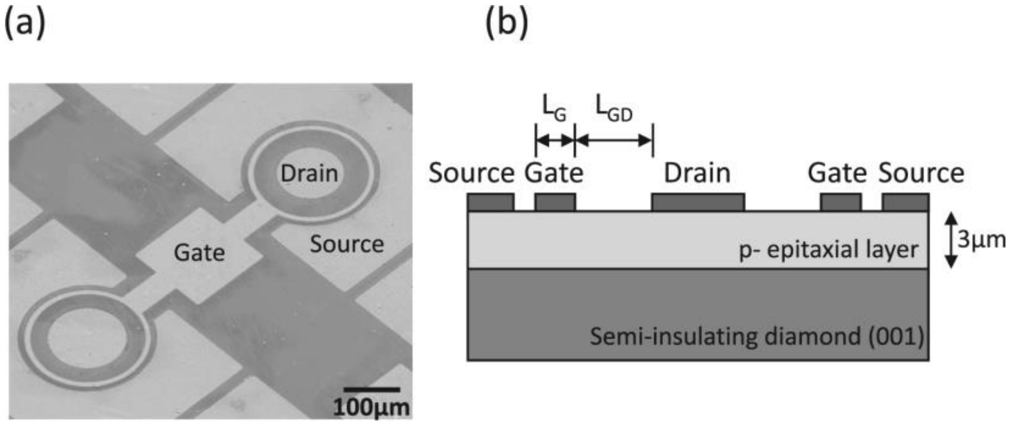

Figure 5. Diagram for diamond MESFET with Corbino geometry [6].

4.4. Diamond field effect transistor with high-k ZrO2

In 2014, Jiangwei Liu and his team reported that their diamond field effect transistor with high-k ZrO2 can achieve a large current output and a high extrinsic transconductance [7]. The paper reports that the main improvement is achieved by adding a thin oxide layer to the hydrogen-terminated diamond transistor. The reason why the author chose Zirconium dioxide as the oxide layer is that Zirconium dioxide has high-k (25), a wide band gap (5.8eV), and a large breakdown field (15–20MV·cm-1). The author's research found that the ratio of zirconium atoms and oxygen atoms on the surface of H-diamond is one to two. The energy gap of this oxide layer reaches about 5.6 eV. Furthermore, the K value of a single layer of zirconium dioxide is 15.4, which is larger compared to the double layer of zirconium dioxide and alumina, which is 12.8. Therefore, this kind of hydrogen-terminated transistors with high-k ZrO2 perform better on high-power machines than traditional hydrogen-terminated transistors (Figure 6).

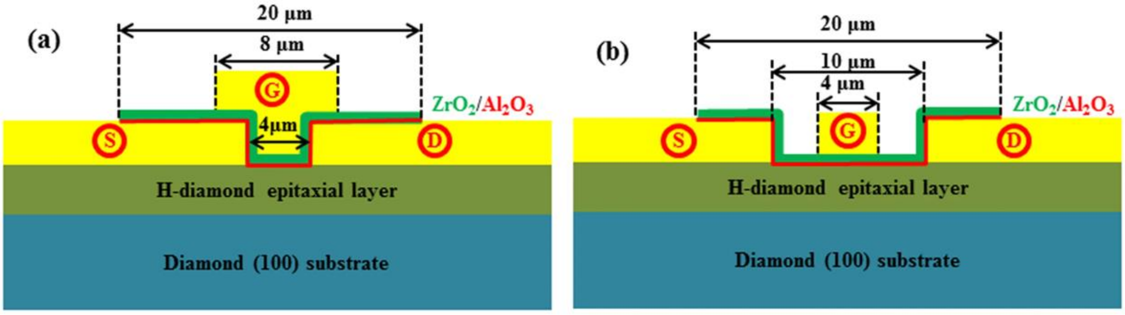

Figure 6. Diagram of the diamond field effect transistor with ZrO2/Al2O3 layer with different source-drain lengths [7].

4.5. Normally off operation in the vertical diamond MOSFETs by an oxidized silicon-terminated diamond channel

In September 2023, Kosuke Ota and his team published an essay claiming to have fabricated an oxidized silicon-terminated diamond transistor that is normally off-operating [8]. The main difference between this oxidized silicon-terminal transistor and the traditional silicon-terminal transistor is that the channel is composed of carbon, silicon, and oxygen. Figure 7 shows the structure of the oxidized silicon-terminal transistor. This kind of C-Si-O channel can keep a high current density. The C-Si-O diamond surface interface with Al2O3 has weaker negative electron affinity than the C-H diamond surface. Therefore, the band bending decreases, the difference between Fermi l energy and valence band energy increases, and the threshold voltage shifts towards the negative direction. The most important achievement achieved in this paper is the creation of the first normally-off operation in the vertical diamond transistor under stably high current density.

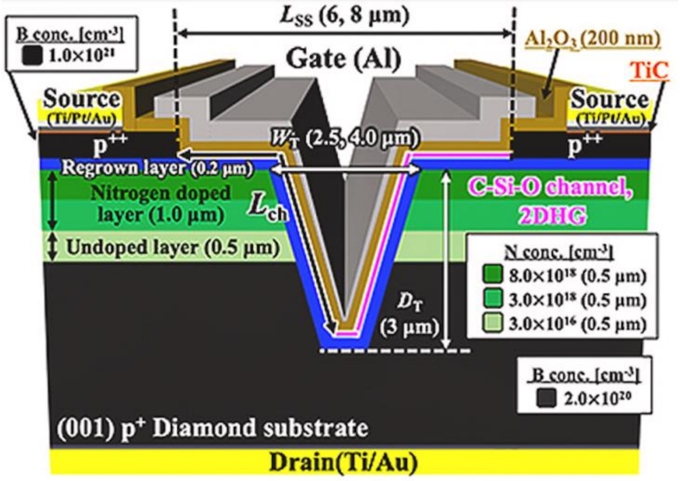

Figure 7. Structure of oxidized silicon-terminated diamond transistor [8].

4.6. Diamond fin field-effect transistors

In 2018, Biqin Huang and his team designed the first diamond FinFET without a hydrogen-terminated channel. Holes can be accumulated in the MOS structure on the fin [9]. The author uses fins to control the magnitude of the channel current and its conductivity. The channel will be pinched off when the device's voltage on the gate is zero. In addition, the transistor can reach a maximum current density of 30mA/mm at 150 degrees. The author found through repeated experiments that the current density at 150 degrees Celsius is 35 times higher than at room temperature. This shows that this transistor has great potential. It is reasonable to infer that when the doping concentration is high, the transistor may be able to achieve a stronger current density at a higher temperature, thereby exhibiting better conductivity. The most important achievement of this article is that it published the first diamond fin transistor, completely abandoning the two-dimensional hole gas like the hydrogen terminal transistor and instead using a diamond doped with boron (Figure 8).

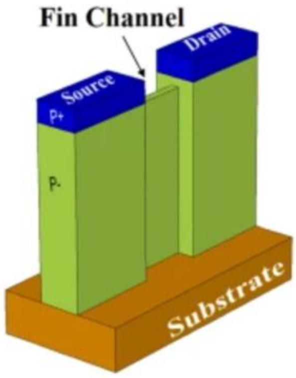

Figure 8. Diagram of Diamond FinFET [9].

4.7. Hydrogen-terminated diamond with hexagonal boron nitride heterostructures

In 2022, Yosuke Sasama and his team claimed that p-channel wide-bandgap heterojunction field-effect transistors could be created by utilizing a hydrogen-terminated diamond channel and a hexagonal boron nitride gate insulator instead of surface transfer doping [10]. Therefore, the transistors can have lower sheet resistance and larger conductivity. Moreover, the transistor author designed exhibits normally off behavior. The ratio of on and off is 108. Under the experiment, the author indicates that their p-channel FETs have a high mobility of 680cm2/V/s, the sheet resistance is 1.4 kΩ, and the operation current is 1,600 μm mA/mm. These good properties indicate that this diamond has better performance in high-frequency electronic devices.

5. Conculsion

In conclusion, hydrogen-terminated diamond transistors can meet most of the requirements for operating in high-temperature, high-pressure, and high-frequency environments. Multiple institutions have improved two-dimensional hole structures in hydrogen-terminated diamond transistors, and new results have been achieved. Moreover, scientists have discovered other oxides that enhance the efficiency of hydrogen-terminated diamond transistors. However, increasing carrier mobility can further improve transistor reliability and power output of hydrogen-terminated transistors.

The technology of silicon-terminated diamond transistors is immature. While silicon-terminated diamond transistors already provide strong and stable current output, there is still significant potential for further development. In addition, achieving stability in high-voltage environments is crucial for the future development of silicon-terminated diamond transistors. Therefore, scientists can try to enhance the efficiency of silicon-terminated transistors by adjusting the gate width and the material of the oxide. The concentration of carriers in p-typed doped diamonds in silicon-terminated diamonds also needs to be increased to achieve higher efficiency.

Until now, most of the research on diamond transistors has been concerned with p-type doped transistors, while n-type doped diamond transistors are still in the innovation stage. Scientists must address the issues of high activation energy, low electron mobility, and surface stability in n-type doped diamond transistors.

In summary, diamond is a high-bandgap semiconductor with great potential. Numerous scientific research institutions and experts will dedicate their efforts to this field to further enhance the efficiency of diamond transistors. These transistors' great properties can be utilized in high-frequency communications and high-speed computing in the future.

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