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Comparison and analysis of gate dielectrics for SiC MOSFET

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Abstract. SiC MOSFET has been widely used for its characteristics of lower on-off resistance, less switching loss, higher working frequency, and high-temperature resistance. With the scale down of Moore's Law, better gate dielectrics should be selected to improve the breakdown voltage and reduce the gate-drain current to ensure a good working mode of MOSFETs. The traditional gate dielectric is SiO_2 but their dielectric constant is low and the interface characteristics at the junction of SiO_2 and SiC are poor so various emerging materials have been created to replace the traditional SiO_2. Emerging gate dielectrics such as high-k gate dielectrics are receiving a lot of attention today, they can increase breakdown voltage and decrease gate-drain current while maintaining oxide thickness. Among many emerging gate dielectrics, Al_2O_3, HfO_2, and HfSiON have been noticed due to their good characteristics and a lot of research on them. This paper will focus on the analysis of the characteristics of these three materials and their applications in MOSFET. Finally, after a detailed analysis of the three materials, they three materials are compared to understand their differences.

Keywords: SiC MOSFET, gate dielectrics, dielectric constant.

1. Introduction

The growth of the power electronics business has been significantly influenced by semiconductor technology [1]. Power semiconductor devices have historically been regarded as a crucial part of power electronic equipment. Power silicon devices have a well-established field of use, but as industry demand has increased, silicon devices' physical restrictions have caused them to become less suitable for a variety of applications requiring high power density, high efficiency, high temperature, and high voltage. SiC materials are a very desirable candidate for applications requiring high power and high temperature [2, 3]. Because SiC MOSFET have substantially lower on-resistance and switching losses than Si MOSFET with identical power levels, they are suited for higher operating frequencies.

SiC MOSFETs have long employed silicon dioxide as the gate dielectric layer, although this material has drawbacks as well [4]. Especially, two issues come up. SiO_2 can create a 2.5 times greater electric field than SiC because it has a lower dielectric constant by 2.5 times. Moreover, the SiO_2 and SiC contact has a high density of surface traps. To overcome this, the likely low-SiO_2 materials should be replaced by high-dielectric materials as the alternate gate oxide, such as HfO_2, Al_2O_3, HfSION, ZrO_2, Ta_2O_5, La_2O_3, $LaLuO_3$, NiO, TiO_2, CeO_2, GaF_2, AlN, Si_3N_4, etc.

This article will introduce several main emerging high-k dielectric layer materials, and compare and analyze the influence of dielectric layers of different materials on SiC MOSFET characteristics.

2. SiC MOSFET and its gate dielectrics

2.1. SiC MOSFETs

The new SiC material has drawn a lot of interest since it has better physical characteristics than Si material [5]. The energy needed to attract electrons from a material's valence band to its conduction band is known as the bandgap. The band gap of Si is 1.1 eV, while that of SiC is 3.26 eV. SiC devices perform better in terms of electric field breakdown than Si because of the higher energy needed for electrons to migrate to the conduction band. For the same drift area thickness, SiC devices have a greater blocking voltage because their critical breakdown electric fields are roughly ten times larger than those of silicon. As a result, for devices with the same blocking voltage, a greater critical breakdown electric field allows for a reduction in the thickness of the lightly doped drift zone, as well as a reduction in the drift region's resistance and conduction loss in the SIC device. SiC devices are appropriate for high switching frequency applications because the saturation drift speed of the material is twice as fast as that of Si. Moreover, the release of stored charge from the diode's depletion zone can proceed more quickly due to the increased saturation drift speed. SiC diodes have reduced reverse recovery loss and a faster reverse recovery time as a result. Finally, SiC materials have a thermal conductivity that is around three times that of Si. High thermal conductivity allows for more power to be generated inside the semiconductor material while also making system cooling components (such as heat sinks and fans) simpler to use, which lowers system cost and volume.

Since its birth, SiC MOSFET has drawn a lot of attention in the field of power electronics due to its great performance [6]. Compared to silicon-based MOSFETs, SiC MOSFETs are better suited for applications that have voltage, frequency, temperature, and density of very high values. SiC MOSFET offers the clearest high-temperature properties when compared to other power electronic devices. The thermal breakdown junction temperature of SiC MOSFETs can reach 300 degrees Celsius, which is higher than that of conventional silicon-based MOSFETs, which only reach 170 degrees Celsius. The development of SiC MOSFET has significantly increased the efficiency of power electronic devices by allowing them to operate in high-demand conditions settings. Simultaneously, power electronic devices' volume is lowered and the advancement of power electronic devices toward miniaturization and high efficiency is encouraged due to SiC MOSFETs' lower loss. SiC MOSFET applications are gradually becoming larger and larger. Compared with traditional silicon device applications, the use of silicon carbide power devices has higher operating efficiency, lower loss, and smaller volume. It can be better applied to high voltage and high power fields such as smart grids, solar photovoltaic power generation, electric traction, new energy electric vehicles, and industrial motors.

2.2. Gate dielectrics of SiC MOSFETs

Between the transistor's channel region and the MOSFET's gate electrode, there is a layer of insulation called the gate dielectric [2]. In use, an electric field is produced by the voltage at the gate in the channel area, which stops current flow. But in recent decades, as silicon transistors have shrunk in size, insulating layers made of silicon dioxide have had to get thinner and thinner to control current with less voltage, reducing energy consumption. Eventually, the insulating barrier becomes so thin that electric charges can pass through it, causing current to leak and waste energy. So various new gate dielectric layer materials began to appear, the most typical ones are high-κ dielectrics (HfO_2, Al_2O_3, HfSION, ZrO_2, Ta_2O_5, TiO_2, CeO_2, etc.) However, various high performance of -k dielectrics is also different. Al_2O_3 is drawing the most attention as a potential SiO_2 replacement among them because of its superior lattice matching to SiC, compatibility with 4H-SiC, high-k value, strong thermal stability, a fairly wide dielectric bandgap, and a conduction band offset that is not excessively high. The high k value of HfO_2 makes it appear as another intriguing possibility for 4H-SiC MOS devices. Zirconia (ZrO_2), which is nearly identical to HfO_2, has a dielectric constant close to 25 and its bandgap is about 5.8–7.8 eV, and it also has excellent thermal stability when near the Si substrate [7]. Because of its high refractive index, chemical and thermal resilience, high dielectric constant, compatibility with microelectronics operations, and high refractive index, Ta_2O_5 has already drawn considerable interest as the gate dielectric for high-

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density memory cells and MOS field-effect transistors [8]. Then, for TiO_2, even if its electrical bandgap is very tiny (3.5 eV), it is nevertheless possible to change its dielectric constant from 40 to 110, which has a significant impact on the ability to start MOSFET [9]. Moreover, CeO_2 has a broad bandgap, a low interface state density, a high dielectric constant, and strong thermal stability. It has been used as a gate insulator and storage capacitor in many applications. [10]. The extraordinarily high (40) dielectric constant of metal oxides like HfO_2 makes them appealing, but they also have drawbacks including lower mobility and unstable threshold voltage brought on by charge trapping [11]. The use of silicates, which have substantially lower threshold voltage fluctuations than silicon-based media and form a more stable interface with silicon, is one possible solution. Among silicate materials, HfSION is a relatively ideal silicate for use as a grid dielectric.

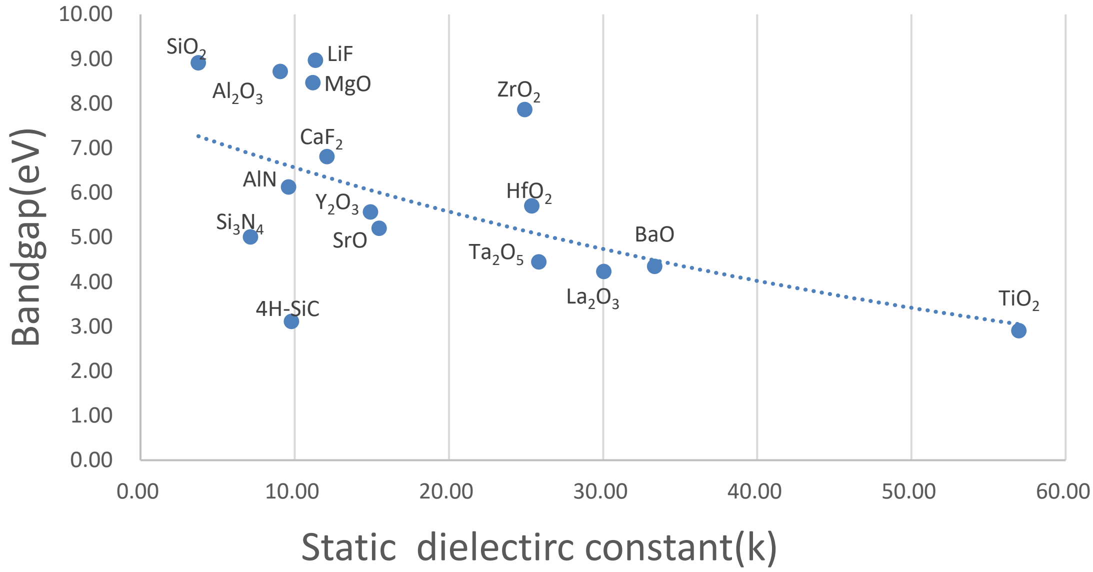

Figure 1. The bandgap of different static dielectric constant.

Figure 1 shows the bandgap of different static dielectric constant, it visually shows the bandgap corresponding to a different gate dielectric.

The following section of this article will concentrate on these three gate dielectrics (Al_2O_3, HfO_2, and HfSION), examine how they affect MOSFET performance, and then compare and contrast the three.

3. Al_2O_3 as gate dielectric layer

3.1. Al_2O_3 material properties and general behavior as a dielectric layer

In-depth research into Aluminum oxide (Al_2O_3) for use as a possible gate oxide in SiC MOS technology. has recently been conducted [12]. Al_2O_3 has a broad bandgap of about 7.0 eV, which is its primary benefit as a gate dielectric. It is anticipated that the 1.6 eV Al_2O_3 conduction band offset to 4H-SiC will be adequate for n-channel MOSFET functioning. Alumina (Al_2O_3) has been thoroughly researched for numerous uses and is a very stable and durable material. Al_2O_3 has numerous advantageous characteristics that make it useful as a substitute gate dielectric, the capacity to become amorphous under the desired circumstances, a high bandgap, and the thermodynamic stability of Si at high temperatures. The disadvantage is that Al_2O_3 only possesses k8–10, which limits its applicability as a long-term solution for industry (1-2 generations) [13].

3.2. Performance evaluation of Al_2O_3 dielectric layer SiC MOSFETs

According to research on MOS structures using 4H-SiC produced by sublimation and gate dielectrics of Al_2O_3 and SiO2 [14], both the dielectric and the substrate type have a significant impact on the types of charges that affect the electrochemical characteristics of the samples.

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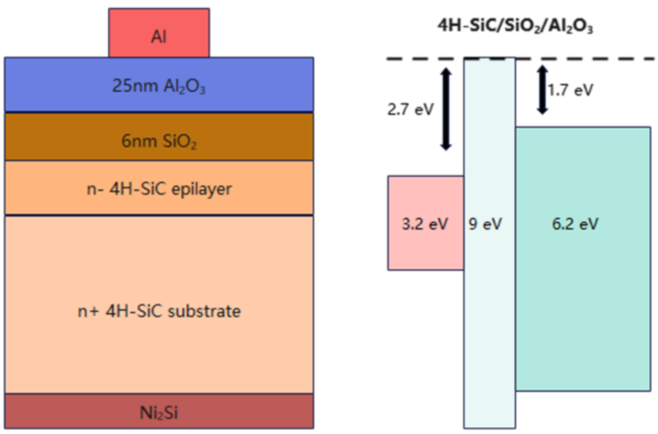

Figure 2. Diagram of the band alignment and cross-section of a schematic MOSFETS capacitor for an Al_2O_3, SiO_2, and 4H-SiC system.

Figure 2 shows the structure of 4H-SiC MOS with Al_2O_3 as the main gate dielectric and it also shows the band alignment in Al_2O_3, SiO_2, and 4H-SiC system. The structure shows the width of the main gate dielectric and the position of Al_2O_3 , it is halfway between Al and SiO_2. 4H-SiC is 2.7eV from SiO_2 while Al_2O_3 is 1.7eV from SiO_2 from the band diagram in the system.

The n-type 4H-SiC/SiO_2 structures display exceptional performance on the C-V curves with a low density of interface states and net oxide charge. The findings show that donor-type slow phases, which greatly increase C-V curve hysteresis in severe depletion, are the principal sources of weakness in these systems. Al_2O_3 on n-type SiC exhibits a sizable quantity of interface, slow, and positive net charges in the samples. The slow states in this scenario are acceptor type and cause hysteresis in depletion, in contrast to SiO_2 structures. Considering how these conditions affect the mobility of the carrier channel, this distinction may be crucial. In comparison to samples with SiO_2 deposits, samples with Al_2O_3 deposits on p-type 4H-SiC exhibit better C-V characteristics. For 4H-SiC-MOSFETs with Al_2O_3 gate insulators made at low temperatures via metal-organic chemical vapor deposition, ultrahigh channel mobility has been observed [15].

4. HfO_2 as gate dielectric layer

4.1. HfO_2 material properties and general behavior as a dielectric layer

High-K material HfO_2 fits the gate's requirements by having a substantial offset from silicon's conduction band (>l eV), a broadband gap (5.7 eV), and a large dielectric constant (25) [16,17]. One of the most promising substitutes for SiO_2 at the moment is HfO_2, which is gradually being employed in modern integrated circuits. Because of HfO_2's high dielectric constant, which reduces the channel-to-gate direct tunnel current, the gate width can be raised while still exerting the same control over the channel. HfO_2 has taken the position of SiO_2 as the favored high-K dielectric material due to its steady thermodynamic characteristics on silicon. The gate's corresponding oxide layer thickness can be kept constant in this way, and the initial working performance can be preserved. In addition, the tunneling current of the gate can be effectively reduced, and the control ability of the gate under high electric field strength can be improved.

4.2. Performance evaluation of HfO_2 dielectric layer SiC MOSFETs

Although having a higher dielectric constant than SiO_2, HfO_2 has a narrower bandgap, which leads to reduced conduction band offsets for SiC materials [2].

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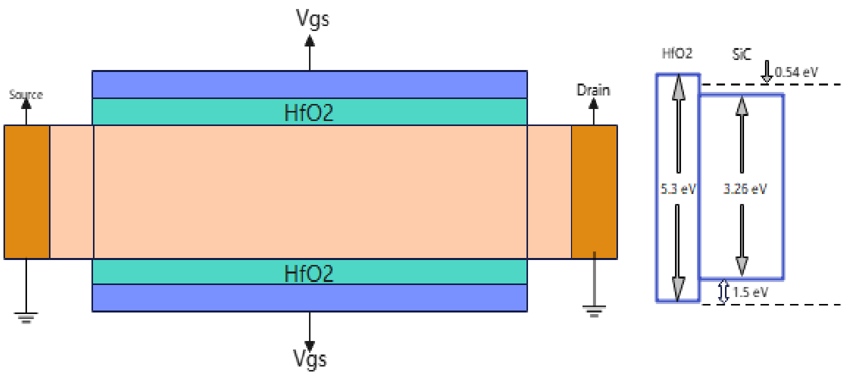

Figure 3. Structure diagram of HfO_2 as gate dielectric in MOSFETS and the schematic band alignments for HfO_2/SiC system**.**

Figure 3 shows the structure diagram of HfO_2 as gate dielectric in MOSFETS and the schematic band alignments for HfO_2/SiC system. In this system, HfO2 alone acts as the gate material to start the MOSFET. It can be seen from the band diagram that the bandgap of HfO2 is higher than that of SiC. Carrier tunnelling through into the dielectric is far more likely at very low conduction band offset levels, which may restrict the uses of this high-k material. Little conduction band offset and enhanced surface trap density at the HfO_2/SiC interface have been found to cause significant leakage current densities, which may affect the MOSFET's electron transport characteristics. The dielectric constant of HfO_2 is very high so it makes a good gate oxide for Si-MOSFETs in low-power devices. Yet, the 5.7 eV low bandgap value of 4H-SiC-based MOSFET makes them seem prohibitively expensive. The increased dielectric constant values of the dielectric material result in a substantial decrease in the electric field. The narrow band offsets at the dielectric/SiC interface for SiC-based MOS devices have recently been resolved by the addition of an ultrathin SiO_2 interface layer between SiC and high-k HfO_2 dielectrics.

5. HfSION as gate dielectric layer

5.1. HfSION material properties and general behavior as a dielectric layer

The extraordinarily high (40) dielectric constant of metal oxides like HfO_2 makes them desirable, but they also have drawbacks including lower mobility and unstable threshold voltage brought on by charge trapping [18]. Due to their more stable silicon interface and significantly lower threshold voltage instability, silicates are a potential partial replacement for Si-based dielectrics. The drawback is those metal oxides, often known as "mid-k" dielectric materials, have a substantially greater dielectric constant than silicate. Although the dielectric constant of the hafnium silicate layers utilized in this work, 11, is only three times that of SiO_2, it is believed that this will allow for the construction of layers that are thick enough to address the leakage current issue.

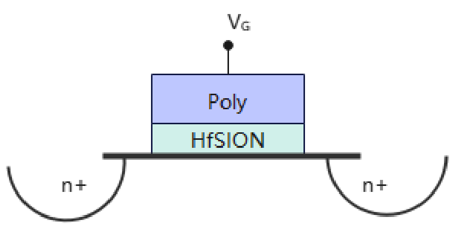

Figure 4. Structure diagram of HfSION as gate dielectric MOSFETS.

Figure 4 shows the structure of HfSION as gate dielectric MOSFETS. HfSION alone acts as the gate dielectric material, and its thickness is larger to reduce leakage current.

5.2. Performance evaluation of HfSiON dielectric layer SiC MOSFETs

Low leakage current compared to SO_2, low specific trap density, electron, and hole carrier mobilities at 80% of the universal curve at Eff > 0.8 MV/cm, and low interfacial trap density are just a few of HfSiON's superior electrical characteristics. It can also adapt to an equivalent oxide layer thickness of less than 10A. Additionally, this substance is significantly more effective in blocking boron than SiO_2 and SiON when in contact with polysilicon, and it is thermally stable up to 1100 °C [19]. HfSiON gate dielectrics subjected to positive biased temperature stress revealed charge trapping rates that were satisfactory and met reliability standards [20]. For ten years, HfSiON gate dielectrics can be safely used at 1.2 V at 105 °C without significantly changing the threshold voltage or driving current. In contrast to conventional SiO_2-based dielectrics, charge trapping in HfSiON exhibits a logarithmic trend over time. HfSiON is a viable choice for high-k gate dielectrics since it demonstrates good material and electrical attributes in addition to appropriate electrical stability.

6. Evaluation and comparison of these three gate dielectrics

High dielectric constant materials include Al_2O_3 and HfO_2. Both materials were successful in reducing the gate's tunneling current and enhancing gate control in high electric fields. HFO_2 and SiC materials have highly different band gaps and the narrower band gap of HFO_2 results in less conduction band migration than SiC materials [2]. The use of such high k materials may be constrained by the fact that carriers are substantially more likely to pass through the dielectric with very low band offsets. However, Al_2O_3 has a larger band gap and a conduction band offset of around 1.6 eV than 4H-SiC, which are projected to be sufficient for N-channel MOSFET operation. Al_2O_3 has superior properties over HfO_2 in this comparison. Because of their extraordinarily high permittivity, metal oxides (such as HfO_2 and Al_2O_3) are suitable, but they also have charge capture, reduced mobility, and threshold voltage instability issues. Silicate and silicon forms are an option that can be utilized as a partial replacement for silicon-based dielectrics since they have substantially lower threshold voltage instability and can build a more stable interface. Silicate HfSION will enable the creation of layers thick enough to address leakage current issues because its dielectric constant is substantially lower than that of metal oxides. HfSiON thus outperforms HfO_2 and Al_2O_3 in this regard.

7. Conclusion

This paper focuses on the analysis and detailed introduction of the characteristics of three gate dielectrics and their application in SiC MOSFET analyzes the effects of different gate dielectrics on SiC MOSFET and obtains their advantages and disadvantages. Finally, compare and analyze the three materials, and discuss their respective advantages and disadvantages.

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