Comparative study of dielectric thin films for GaN HEMTs

Haoyang Zhang

School of Materials Science and Engineering, Central South University ,932 South Lushan Rd, Changsha, Hunan, 410083, China

8404200230@csu.edu.cn

Abstract. As a typical representative of the third generation of semiconductor materials, attracts wide attention, wide band-gap semiconductor gallium nitride (GaN) has many advantages that silicon materials do not have, now it has been used to fabricate many devices. And as one of the heterojunctions MESFET, GaN HEMTs have many excellent properties, e.g., high electric breakdown field, large saturation velocity, and low ON-resistance (Ron), wide band gap, and high mobility. The material can be employed in several fields as a result of its good qualities. All these amazing properties make it an excellent semiconductor material for communication, radar detection, guidance and other civilian and military fields. Specifically, there are mobile phones, satellite television receivers, voltage converters and radar equipment, power adapter and car charging. However, in the high-power application, the current collapses affected the performance of the devices badly. The article will discuss both high dielectric constant and low dielectric, which are used for reducing the current collapse, and improve the device's performance.

Keywords: HEMT, high-k dielectric, low-k dielectric.

1. Introduction

Semiconducter is one of the most influential technologies in human history. The first-generation semiconductor materials are germanium (Ge) and silicon (Si). In 1947, the first transistor in the world was made of Ge material at Bell Laboratories in Murray Hill, New Jersey, which was soon put into the application of integrated circuits. It is still playing an important role in the semiconductor industry. Compared with Si material, the second-generation semiconductor material Ga as has a higher band-gap width and higher electron mobility and electron saturation drift speed. Therefore, the devices made of GaAs materials have a higher breakdown voltage and are competitive candidates for high frequency work, and high-power microwave devices and integrated circuits such as radar and wireless communication.

The third generation of semiconductor materials led by silicon carbide and gallium nitride gradually come into people's sight. Gallium nitride high-electron mobility transistors (HEMTs) is one of the heterojunctions MESFET, whose properties are excellent. E.g., high electric breakdown field, wide band gap and high mobility. They indicate that this device could be a good technology for high-power microwave devices and high-power switching [1-3].

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Even though AlGaN/GaN HEMT has numerous benefits, it still has a number of drawbacks, including current collapse, which reduces the devices' stability at relatively high temperature and switching properties, the reverse leakage current of HEMT Schottky gate due to large dislocation density, or high electric fields and junction temperatures for microwave power applications, which can increase the reverse leakage of conventional Schottky grids [4-7]. Among these various drawbacks, currents collapse is a server issue because it brings about frequency dispersion when operating voltages are high [8,9].

Dielectric can be used to adjust I-V character of HEMT.The properties of dielectric material with different dielectric comstant 'k' vary considerably. Low-k material acts as an interlayer medium for reducing capacitance, RC signal delay is thus reduced, and the device operating frequency is optimized. Thus, if the parasitic resistance is reduced, then the problem of RC delay is alleviated. The parasitic capacitance is proportional to the dielectric constant 'k' of the circuit layer isolation medium, so the purpose of reducing the parasitic capacitance can be achieved by using low k material ($k<3$) as the isolation medium in devices.

On the other hand, high k is usually used to raise the grid oxide layer, improve the grid oxygen thickness, inhibit the tunneling leakage current, improve the storage charge density.

Additionally, apart from these advantages, both high-k and low-k dielectric can effectively reduce current collapse. This article compares different dielectric material using on GaN HEMTs.

2. GaN HEMT

GaN material has the characteristics of high critical breakdown electric field, high electron saturation velocity, low intrinsic carrier concentration, low dielectric constant, high thermal conductivity, etc., which has great advantages in some special fields like high temperature, high frequency. GaN is a material with a bandgap around 3.4 eV, which leads to some charming properties. GaN based device exhibits high breakdown field, low ON resistance and high saturation velocity [10]. HEMT devices are three-terminal voltage control devices. There are three electrodes on it, which are gate, source. Gate electrode is Schottky contact electrode while the other two form Ohmic contacts. Figure. 1 demonstrates the design layout of the device, first GaN and AlGaN are deposited on substrate for example SiC, sapphire by heteroepitaxial growth techniques (such as MOCVD) to form heterostructure, then AlN Buffer layer grows on the AlGaN, next a layer of intrinsic GaN and a layer of intrinsic AlGaN are grown on top. To protect Intrinsic layer, AlN layer is added, and 2-dimensional gas flowing between AlN and i-GaN, thanks to the spontaneous and polarization on the carrier confinement heterostructure interface [11], and the density of the 2DEG can be determinded by applied grid voltage. With the addition of AlN layer, there is a two-dimensional gas flow between AlN and i-GaN due to the spontaneous and polarizing effects of carrier confinement at the interface of the heterostructure. Three or two degrees of density can be applied by grid voltage. When the drain-source voltage VDS is raised in the channel, a transverse electric field is generated in the channel. Under the action of the transverse electric field, two-dimensional electron gas is transported along the heterojunction interface to form drain output current Ids. Schottky contact is made between grid and AlGaN barrier layer, and the depth of potential well in AlGaN/GaN heterojunction is controlled by the size of grid voltage VGS, and the two-dimensional electron gas surface density in the channel is changed, so as to control the drain current in channel.

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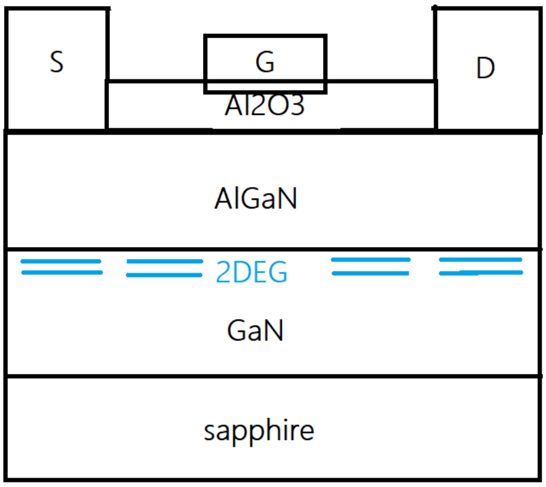

Figure 1. Cross section of the E-model HEMT.

3. Comparison of high-K dielectric used for reducing current collapse

High-k dielectrics have a higher dielectric constant than conventional SiO_2 [12]. The basic electrical requirements for the device gate media are high dielectric constant, large band gap width, large conduction band offset and high-quality interface. High dielectric constant media will increase the gate capacitance, so that the device has good channel charge control. In the development of devices, it is necessary first to have a matching gate dielectric material, which can form an interface with low interfacial state density with the underlying semiconductor. High density interfacial states can lead to Fermi pinning. Fermi pinning occurs when the interfacial states are dense enough to exchange charge with the underlying semiconductor so that the gate cannot control the device's conducting channels. These interface states also trap charges and do not respond to high frequency signals, which leads to current collapse.

Drain current collapses seriously harm the high temperature performance and switching performance because it is difficult and slow to charge surface [13,14]. So, in order to increase the stability and transport properties of AlGaN/GaN MOS-HEMTs, high-insulating materials, such as HfO_2 [15], have been utilized recently. As the high-dielectric permittivity can reverse to a better gate modulation.

Because of the maximum microwave output power can be expressed by the formula $Pmax = Imax \times (Vbreak - Vknee)/8$, Pmax becomes lower if the maximum current decreases or knee voltage increase which is so-called current collapse. Surface dielectric film can effectively reduce current collapse [16,17].

The main reason for current collapse is the surface traps in area between the electride and the electrode, and the electrons are trapped by these traps forming a virtual gate and depleting the underlying channel and the electrons are then caught by the trap from the edge of the gate to the surface area between the gate source and the gate and the drain [18]. When the negative bias on the grid gradually increases, the energy alignment in the barrier layer will be steeper, while the longitudinal electric field will be larger. Under the combined action of the transverse and longitudinal electric fields, the electrons at the edge of the grid can escape to the grid source and the grid leakage surface. Therefore, the probability of electron penetration can be reduced by designing a new device structure to reduce the electric field in the whole potential layer, so as to reduce the current collapse. Surface passivation is an effective way to reduce the current collapse [12].

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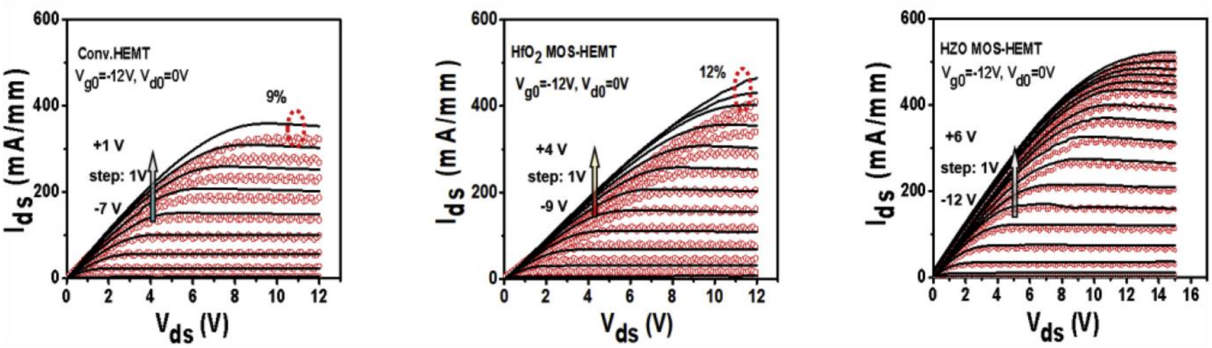

(a) (b) (c)

Figure 2. In DC and pulsed measurement, (a) ids-vds curve of traditional HEMTs, (b) ids-vds curve of HfO_2 HEMTs and (c) HZO HEMTs.

Figure. 2(a-c) compares the DC and pulsed measurement of all three-type devices [13]. During these measurements, the traditional HEMTs and HfO_2 HEMTs exhibit considerable current collapse. Particularly, the HfO_2 HEMTs exhibits a degradation of 12% while for the conventional unpassivated HEMTs, there is a degradation of 9%. Using these new generation dielectrics clearly reduces the issues of current collapse and gate leakage. On HfO_2 insulated gate device, reverse-bias gate leakage current improves an order of magnitude compared to reference Schottky devices.

Although HfO_2 has gained popularity in the field-effect transistors [19], the thermodynamic instability of the transistor heterojunction still exists. Several novel materials, such as HfAlOx and HfSiOx, together referred to as HZO terpolymer as the dielectric layer, have been used in research to address this issue and enhance the thermal stability of the field effect transistor [20-22]. They proposed the hypothesis that because these compounds have a higher dielectric constant and a more perfect surface, they can significantly reduce current collapse and improve device performance [23,24].

In fact, HEMTs equipped with HZO grid dielectric demonstrated higher performance when compared to standard dielectric materials and HfO_2. This finding demonstrates the high research value and application potential of HZO grid dielectric.

Previous studies have compared i-v characters among HfO_2 HEMT and HZO HEMT and conventional unpassivated HEMTs (traditional HEMT) [25].

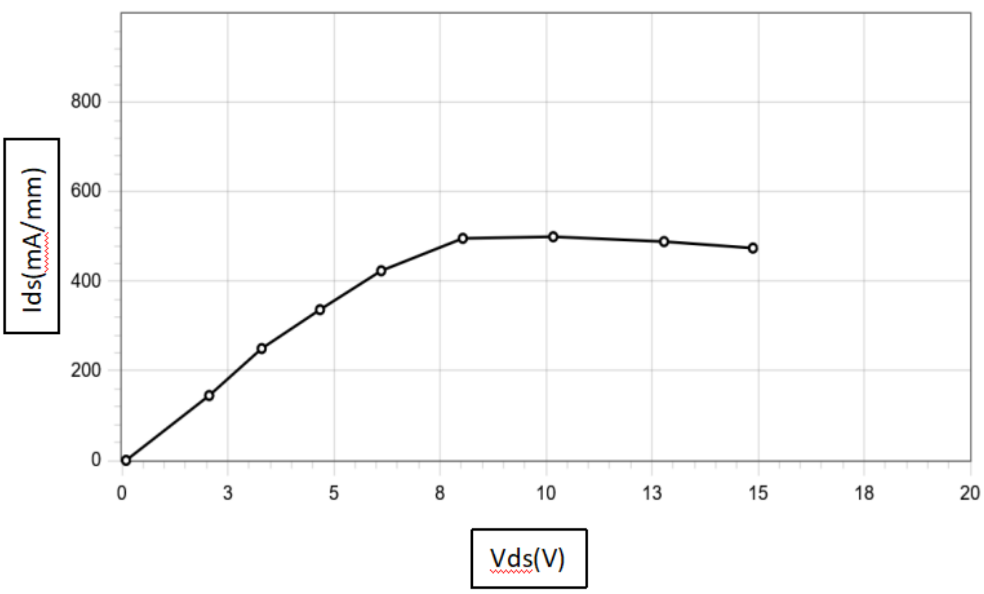

Figure 3. The DC output performances of the traditional HEMTs where the gate voltage is +1 V.

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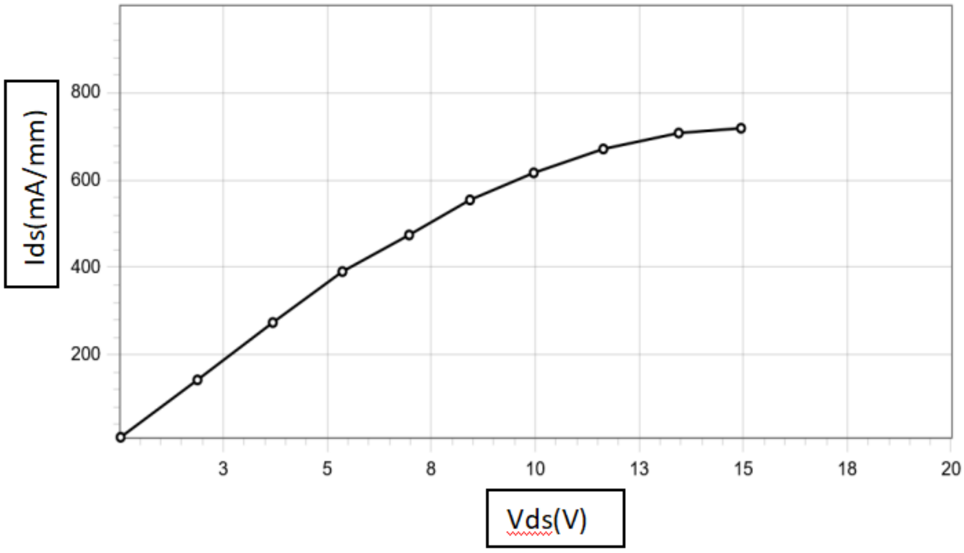

Figure 4. The DC output performances of the HfO_2 HEMTs where the gate voltage is +4 V.

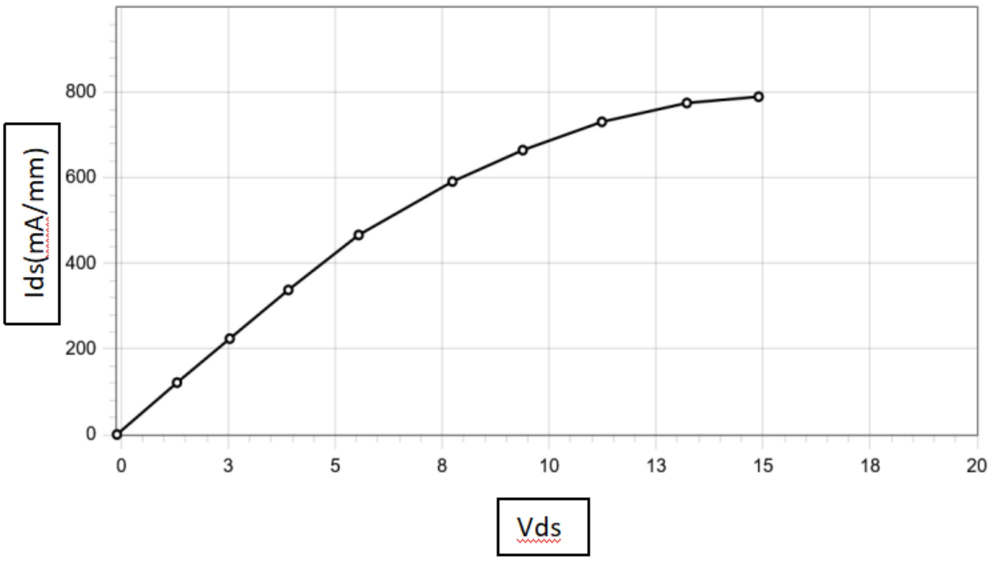

Figure 5. The DC output performances of the HZO HEMTs where the gate voltage is +6 V.

Figure 3, Figure 4, Figure 5 are respective DC output performances (Ids–Vds) of the HEMTs with traditional dielectric, HEMTs with HfO_2 dielectric and HEMTs with HZO dielectric. Gate-width per millimeter has previously been created using the practically current data. [26] Traditional HEMTs can only be biased that low because of the high leakage current, but now with high k, they can withstand very high voltages. Therefore, the maximum grid voltage applied to conventional HEMTs is +1V, for HfO_2 HEMTs is +4V and for HZO HEMTs can reach +6V. Higher gate voltage bias indicates a better stability at higher positive voltages. At the same time, when using the HfO_2 or HZO dielectric the current collapse is facilitated significantly [13].

4. Comparison of low-K dielectric used for reducing current collapse

Electrons leaking from the grid prefertively accumulate at traps on the device surface, forming virtual grids. On this principle, electron traps are often considered to be one cause of the current collapse, while ionization of water produces water and water molecules converge on the surface of HEMTs, which may result in electron traps [27], especially under special conditions. For example, in millimeter-wave MMIC, the shorter the gate length, the more severe the current collapse. To optimize device performance, the researchers introduced a low dielectric constant material grid medium, such as benzocyclobutene (BCB), to millimeter-wave MMIC [28-32]. However, the dampness removal ability of BCB is not qualified since this material has a low film density [33]. So AlGaN/GaN HEMTs may suffer the current collapse as a result of water molecules adhering to their surface if low-k films' ability to resist moisture is insufficient. Moister is also a key factor affecting the collapse current of HEMT devicesmethyl silsesquioxane (MSQ)-based low-k films are of great potential to reduce current collapses by promoting the moisture resistance [34]. As is mentioned, moisture led to electron trap, which caused the current to collapse, less the humidification, less the current collapse. So, we can demonstrate the current collapse by comparing water absorption(humidification).

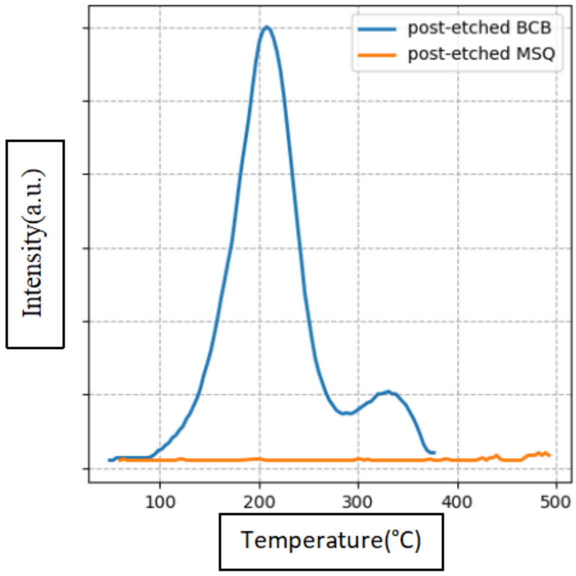

Figure 6. Thermal desorption spectrum of absorbed water in BCB and MSQ after an hour's wetting.

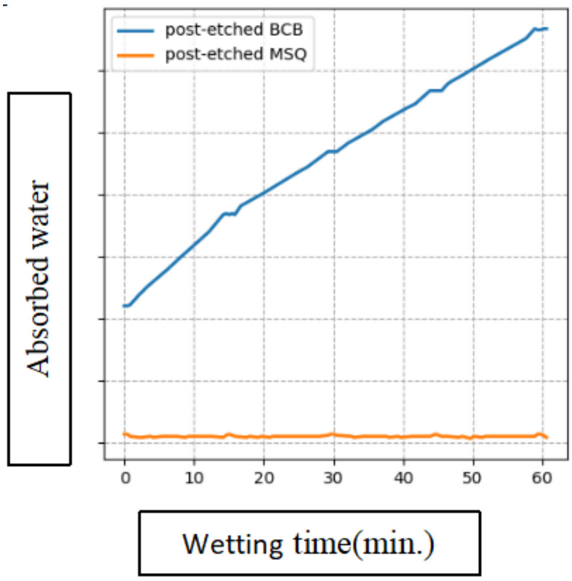

Figure 7. The change of absorbed water with wetting time, the amount of water is caculated by peak area of thermal desorption spectrum.

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From Figure 6 and Figure 7, yet, despite the humidification, the absorbed water was not found in the MSQ sample. It can be clearly seen that MSQ's water absorbency significantly decreased in comparison to BCB. It also means fewer electron traps and current collapses

To sum up, using the low ‘k’ humidification resisted material MSQ can successfully reduce the current collapse of HEMT.

5. Conclusion

Through the above analysis and comparison, the appropriate use of high dielectric materials and low dielectric materials can reduce the current collapse in their own way. The greater dielectric can be used to create a gate modulation that is more efficient, and concentrate the interface trap, reduce the internal fixed oxide defects, and obtain the ideal interface which improves the thermal stability of the HEMTs. At the same time, low dielectric constant layer materials by resisting moisture. Through these comparisons, we can see that there are many ways to reduce current collapse and optimize device performance, and there is a lot of potential worth exploring.

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