Influence of High-k and Low-k dielectrics on drain current of GaN HEMTs

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Abstract: This paper reports on the influence of high-k and low-k dielectric passivation on the drain current performance of GaN HEMTs. Four different dielectric materials namely SiN_x, Al_2O_3, HfO_2 and SiO_2 were deposited and their effect on drain current was compared. Among all the dielectric materials used, the high-k Al_2O_3 passivation showed the best performance. In this case, the drain current increased by 84%. Even after having the highest k value, HfO_2 did not deliver better results than Al_2O_3 and SiN_x. A comparison of PECVD deposited SiO_2 (low-k) and SiN_x (high-k) showed strong thickness dependent performance.

Keywords: High-k and low-k dielectrics, High Electron Mobility Transistor (HEMT), III-V material, Al_2O_3 and HfO_2.

1 Introduction

AlGaN/GaN HEMTs have shown great performance capabilities in the areas of high power, high voltage, microwave and biosensors due to its properties of large band-gap, high electron mobility, high carrier concentration, high saturation velocity with high electric field value [1-6]. However, performance of these devices is limited by the trapping effects on the surface [7]. Si_3N_4 and SiO_2 had shown to be able to reduce the effects of surface trapping of charges [8-9]. The traps capture electrons and then act as a virtual gate on the surface, which deplete channel electrons and decrease the output current of the device [10]. People are working intensively to reduce this effect on the surface of the device because it is responsible for degrading the output power and overall performance of the device [11]. The surface traps can be suppressed significantly with the help of passivation of dielectric materials [12]. Low-k dielectric materials are used to passivate the HEMTs but now a days people are moving towards high-k dielectric materials because of its superior properties such as better insulating and capacitive property, high thermal stability and sound interface qualities [13].

In this paper, we are reporting on the thickness dependent effect of high-k and low-k dielectrics passivation on drain current performance of GaN HEMTs.

2 Experimental

The AlGaN/GaN based HEMTs were fabricated on sapphire and silicon carbide (SiC) substrates for several experiments. Epitaxial stack consists of 2 nm AlN nucleation layer, followed by a 2.3 μm thick unintentionally doped GaN buffer layer, and finally followed by an 25 nm thick *n*-type $Al_{0.25}Ga_{0.75}N$ layer. These epilayers were grown on the Sapphire and SiC substrate by MOCVD as shown in Fig.1. Device fabrication process consists of five lihography levels as ohmic contact formation, mesa isolation, schottky contact formation, interconnects and passivstion.

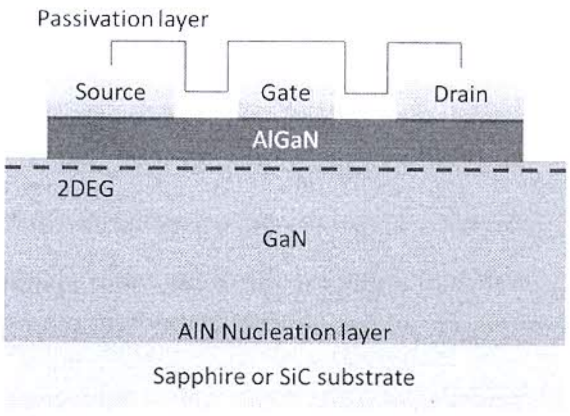

Fig.1 Schematic Cross section of AlGaN/GaN HEMT

Source and drain ohmic contacts were e-beam evaporated of Ti/Al/Ni/Au and then anneled at 830°C in nitrogen environment [14]. Devices were ion implanted using Ar^+ and N^+ for isolation [15]. Then nickel based schottly contacts (gate) were formed. Two different unit gate widths of 2x50 μm and 2x125 μm were designed and fabricated along with a gate length of 2 μm. Gates and source pads were interconnected using Au metal pads for biasing. These devices were characterized and then passivated using SiO_2 as low-k dielectric and SiN_x, Al_2O_3, and HfO_2 as high-k dielectric materials. SiO_2 and SiN_x were deposited using PECVD and Al_2O_3 and HfO_2 were deposited using ALD (Atomic Layer Deposition). Deposited film thicknesses of SiO_2 and SiN_x were 100 nm, 150 nm and 240 nm. The drain current was measured in each case before and after passivation and the effect of thickness variation was checked for a comparison. All the measurements were carried out at zero volt gate bias.

3 Result and Discussion

Fig.2 is showing an effect of thickness variation of SiO_2 on the percentage change in current. The saturated drain current of the device without passivation was 520 mA/mm and increased to 610 mA/mm after passivation of 100 nm thick SiO_2. Therefore, for the thickness of 100 nm the improvement in the current was measured to be 17%. The drain current increased because of increment in charge concentration of 2DEG [16]. SiO_2 passivation layer employing for AlGaN/GaN HEMT seems to suppress the negative virtual gate effect due to increment in drain current [17]. However, as the thickness of SiO_2 layer increased from 100 nm to 150 nm, the betterment in the current reduced. A minor improvement of 1 % was recorded for a thickness of 150 nm. Furthermore, for even thicker layers of 200-240 nm, the output current started decreasing. The reason behind was probably quality and strain issues related to thicker layers of SiO_2. This thickness variation was tested on Sapphire as well as on SiC. Hence for better performance of the device, a thin layer of SiO_2 (100 nm-150 nm) is recommended.

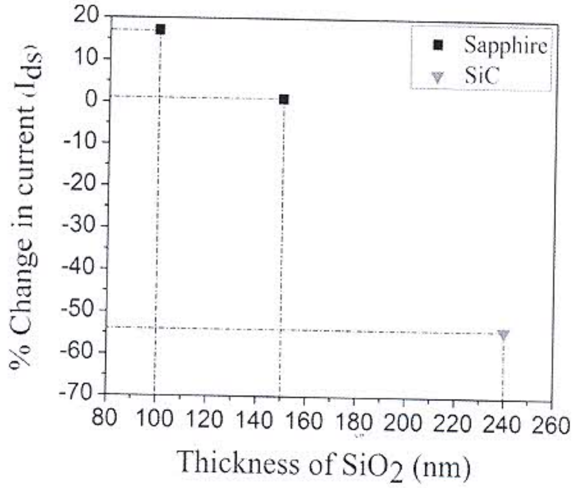

Fig.2 %change in I_{ds} for various thicknesses of SiO_2

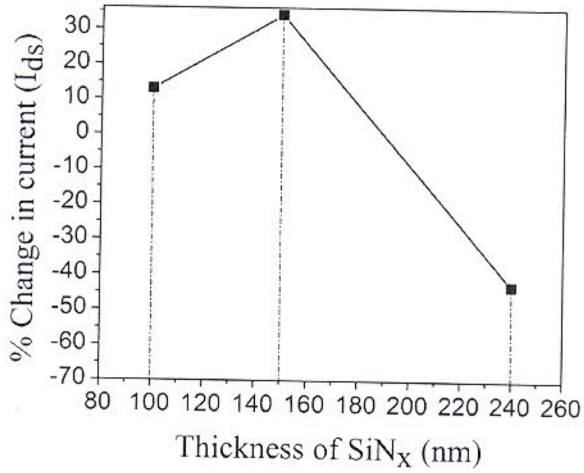

Fig.3 %change in I_{ds} for various thicknesses of SiN_x

In another test of passivation, the high-k dielectric materials namely SiN_x, Al_2O_3 and HfO_2were deposited. Fig.3 shows the effect of thickness of SiN_x on the current change. In this case, as the thickness increased from 100 nm to 150 nm, the current improved. For the thickness of 150 nm the saturated drain current increased from 500 mA/mm to 670 mA/mm indicating a higher sheet carrier concentration in the channel. The reason behind was probably the increase in positive charge at the interface of SiN_x/ AlGaN which neutralized the AlGaN polarization charge thereby mitigating the surface related problems from the channel [18]. However again a threshold value of around 180 nm of SiN_x thickness was recorded beyond which the performance of the device started degrading probably due to the strain generation at the interface of SiN_x/AlGaN for thicker layer of SiN_x. Therefore, 150 nm thickness of SiNx is recommended for the best performance of the device.

In Fig.4, Both traditional high-k (SiN_x) and low-k (SiO_2) dielectric materials are compared for 100 nm and 240 nm thickness. For a thin layer of 100 nm, the SiO_2 proved better due to improvement in the current whereas, for a thick layer of 240 nm SiN_x proved to be more promising. Therefore for proper operation of device, the thickness of the passivation layer must be optimized.

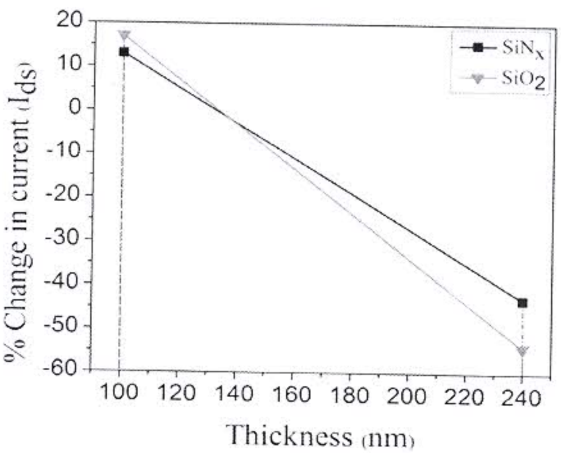

Fig.4 Thickness dependent comparison of SiO_2 and SiN_x

The possible reason behind could be the change in the traps concentrations and strain level with thicknesses in combination to the dielectric constant of material.

Hence, the performance of high-k and low-k dielectric materials deposited using PECVD is strongly thickness dependent.

After studying the effect of traditionally used high-k and low-k dielectric materials, we deposited high-k Al_2O_3 and HfO_2 using Atomic layer deposition (ALD) for betterment in the drain current. Fig.5 compares the current before and after the passivation of Al_2O_3. This figure also shows the negative conductance at large drain to source voltage. This decrease in current at large drain to source voltage is due to the self-heating and especially results in the decrease in mobility. In addition to self-heating, deep traps are also present in the AlGaN/GaN heterostructure and can reduce the performance of the device. [19].

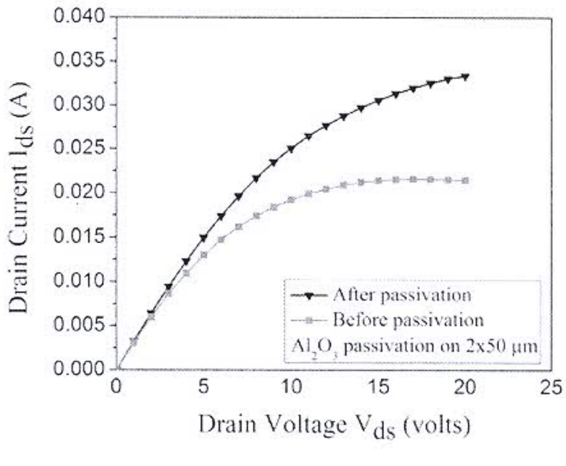

Fig.5 High-k Al_2O_3 effect on drain current

A drastic improvement in the output drain current was observed after the deposition of Al_2O_3. The improvement with increasing thickness saturates at about 30 nm [20]. The percentage improvement in current from its unpassivated value was about +84%. This indicated an effective suppression of surface traps in gate-to-drain/source regions using Al_2O_3 passivation layer. In addition, due to the large difference in the band gap, the chances of traps charging might have reduced due to a possible reduction in the leakage current.

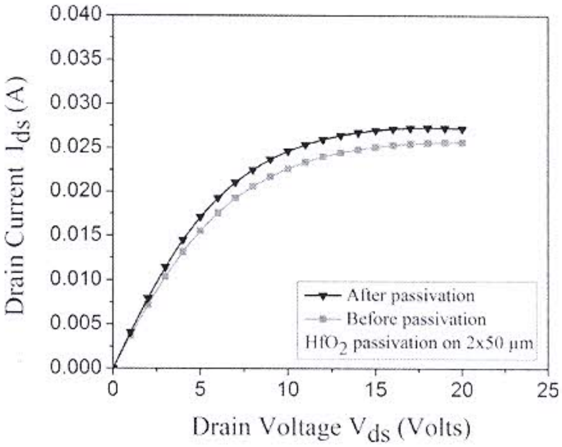

Fig.6 High-k HfO_2 effect on drain current

Similarly, the passivation of HfO_2 also showed an increment in the current from its unpassivated value as shown in Fig.6.

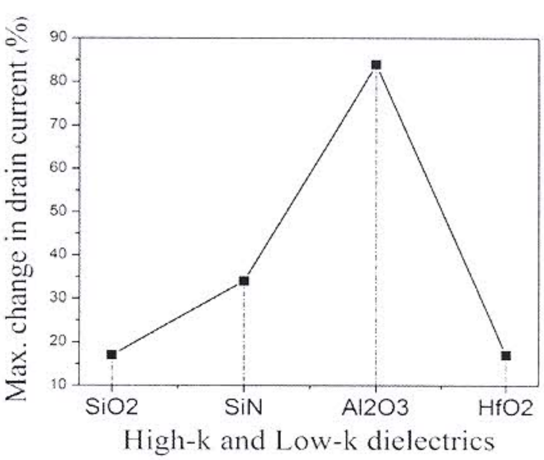

Fig.7 Comparison of high-k and low-k passivation

However, an increment in current value was only 18 % which was less as compared to the case of Al_2O_3. The possible reason behind could be related to the strain development in very high-k dielectric films. The HfO_2 has higher dielectric constant as compared to Al_2O_3 due to which the film could not get relaxed properly on the deposited surface and leads to defects at the interface and in the bulk of materials [13].

Next, we made a comparison of all the four dielectric materials used for the device passivation. Optimized values of thicknesses were used to show the best performance of an individual. Fig.7 clearly shows the best performance of Al_2O_3. When compared to the low-k dielectric material, all the high-k dielectric materials showed better performance in comparison. Passivation by SiN_x proved much more useful as compared to the HfO_2 even though the dielectric constant of nitride is low. One of the possible reasons behind was related to the interface defects of HfO_2 because of its very high dielectric constant and hence the low band gap difference.

4 Conclusion

To passivate GaN HEMTs, four different high-k and low-k dielectric materials were deposited using Atomic Layer Deposition (ALD) method and Plasma Enhanced Chemical Vapor Deposition (PECVD) method. When compared to the low-k dielectric material, all the high-k dielectric materials showed better performance of drain current. The SiNx (high-k) and SiO2 (low-k) were compared for 100 nm and 240 nm thickness. Both of them showed strong thickness dependent performance. For a thin passivation layer of 100 nm, the SiO_2 proved better due to much improvement in the drain current whereas, for a thick passivation layer of 240 nm SiN_x proved to be more promising. A drastic increase in the drain current was observed after the deposition of Al_2O_3. The recorded percentage improvement in current from its unpassivated value was about +84%. Deposition of HfO2 as the highest k dielectric material could not show the best improvement in the drain current as compared to SiNx and Al_2O_3.The reason behind was possibly related to the low band gap difference with AlGaN and hence charging of traps in large volume.

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