Effect of Surface Passivation on the Electrical Characteristics of Nanoscale AlGaN/GaN HEMT

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Abstract: In this paper, we present the effect of passivation layer on the electrical characteristics of AlGaN/GaN HEMT. The energy band diagram, drain current voltage characteristics, transconductance and cut off frequency was calculated for both long channel and short channel devices. It was found that the electrical characteristics of the device improve with the introduction of high K dielectric in the passivation layer. The results obtained agree well with the data available in literature.

Keywords: AlGaN/GaN HEMT, passivation, electrical characteristics.

1. INTRODUCTION

Because of presence of spontaneous and piezoelectric polarization effect between AlGaN and GaN, formation of 2DEG channel takes place. The impurities do not suffer from impurity scattering and so they have high mobility and high concentration which makes HEMT suitable for high power and high frequency operation [1-5]. At high frequency there are chances of current collapse which mainly occurs due to defects present in the device.

Normally crystalline defects are present in GaN buffer and AlGaN barrier layer. AlGaN also suffers from surface defects. So, better crystalline structure and passivation techniques are researched for reducing the defects. Many models are proposed in literature for study of the device for current-voltage characteristics, breakdown voltages, effects due to traps etc. When HEMT is biased in an OFF state, a negative voltage provides a large supply of electrons, which can be driven out to surface states in the presence of high electric field [6-10]. Once electrons are trapped in surface states, the fixed negative charge remains until an opposite polarity field drives back the electrons to the gate electrode or in the absence of electric field the slow process of surface diffusion allows the electrons to disperse.

With charge recovery time constants ranging from milliseconds to seconds the effective gate voltage is determined by the amount of trapped negative charge during that period not the gate electrode potential. To reduce the effect of surface states new device geometries are researched or proper dielectric passivation layers are used to reduce the effect of surface states. Many dielectric materials are used as passivation layers like SiO, SiO2, Si3N4, AlN, MgO [11-15] and so on. All of them have shown improvement in one or the other parameters. In this paper we
show the effect of passivation layers on the electrical characteristics of nanoscale AlGaN/GaN HEMTs.

TCAD simulations have been performed for two devices with a gate length of 2μm and 18nm. The electrical parameters like current voltage characteristics, Transconductance, Voltage characteristics, drain conductance and cut-off frequency has been calculated for different passivation layers. The obtained results agree well with the data available in literature.

2. DEVICE STRUCTURE

The AlGaN/GaN High Electron Mobility Transistor layered structure is shown in figure 1(a) and is made on a Sapphire Substrate. The device is composed of three GaN and AlGaN layers. First layer the buffer layer is of 1.75 μm thickness. Second GaN layer, the channel layer is of 0.005 μm thickness. Channel formation take place in this layer. After this three AlGaN layers are built on it. First is interlayer of thickness 0.002 μm, second is barrier layer of thickness 0.016 μm and last is cap layer of thickness 0.002 μm. The Al content in all the AlGaN layers is 26%. The Interlayer is doped with Si material with concentration 1×10¹⁹ cm⁻³. The device is passivated with a layer of Si3N4 with a dielectric constant of 7.6. Also, the device was tested with different passivation layers like SiO₂, Al₂O₃, HfO₂.

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Figure1: Structure of the Device (a) general structure (b) Simulated structure with gate length 2 μm

In the second device Simulation model shown in Figure. 2, the first GaN layer, the nucleation layer is of 0.01 μm thickness. Second GaN layer, the buffer layer is of 2 μm thickness. Channel formation take place in this layer. After this three AlGaN layers are built on it. First is interlayer of thickness 0.003 μm, second is barrier layer of thickness 0.015 μm and last is cap layer of thickness 0.002 μm. The Al content in all the AlGaN layers is 25%. The Barrier layer is doped with Si material with concentration 2×10¹⁸ cm⁻³. The interface between AlGaN interlayer and GaN buffer layer is n-type doped with concentration 1×10¹⁹ cm⁻³. The device is passivated with a layer of Si3N4 with a dielectric constant of 7.5. Also different devices were tested with different passivation layers like SiO₂, Al₂O₃, AlN, MgO and ZnO are used in analysis.
3. SIMULATION MODELS

SILVACO TCAD which is standard software for device simulation has been used for simulation of the device. Three main models have been employed for analysis: CONMOB (Concentration Dependent Model), FLDMOB (Field Dependent Mobility) and SRH (Shockley-Read-Hall Recombination). Caughey and Thomas model is used for field dependent mobility model, SRH model is used to figure out the statistics of production of holes and electrons and their recombination through the phenomenon of trapping.

4. RESULTS AND DISCUSSIONS

Surface passivation has been done with different materials like SiO2, Si3N4, AlN, Al2O3, MgO and ZnO with different dielectric constants. It was found that the characteristics (electrical) of the device vary largely with the change in passivation layer. These electrical characteristics of the device are understood from obtaining the following parameters:

The potential distribution inside the device and the energy band diagram of AlGaN/GaN HEMT is shown in Figure 3(a) and 3(b) respectively. The formation of triangular potential well is the characteristics of HEMT devices.
Figure 3(a): Potential distribution inside the device

Figure 3(b): Energy band diagram of AlGaN/GaN HEMT

Figure 4 shows the drain current-drain voltage characteristics of the device.

Figure 4(a): Drain current-drain voltage characteristics of 2 μm gate length device

Figure 4(b): Transfer characteristics of the device showing the effect of different passivation layers

Figure 4(a) shows the usual trend of drain current voltage characteristics and figure 4(b) shows the effect of passivation layers on the transfer characteristics. As can be observed from the figure 4(b), that HfO2 which has the highest dielectric constant of 25 out of the other three and
shows highest current. It can also be observed that at lower gate voltages the difference in drain current is quite lower and only at higher gate voltages also drain voltages this difference is notable. Passivation with high-k reduces the surface effects which in turn increases the number of carriers in the channel that increases the drain current.

Figure 5 shows the effect of different passivation layer on transconductance of the device. It is observed that for high K passivation layer the transconductance improves. Another device under test was an 18nm AlGaN/GaN HEMT device. This nanoscale device was also under consideration to see the effects of different passivation layers. Figure 6 (a) shows the Id-Vg characteristics for three different layers: SiO2 with 3.9, Si3N4 with 7.5 and Al2O3 with 9 as dielectric constant has been plotted. There were minute differences in the drain current and hence the main section of the on-current part of the device from Vg = 4V to 6V is shown. It is clearly seen from the graph the Al2O3 shows higher current as compared to the other two materials. Id-Vd characteristics was also obtained for two different gate voltages for different passivation layers as shown in Figure 6(b).
Figure 7 shows the variation of drain current with gate length. Drain current increases with the decrease in gate length.

![Figure 7: Variation of drain current with gate length](image)

Cut off frequency was calculated for all the passivation layers for 18nm AlGaN/GaN HEMT used and the values obtained are shown in Table 1.

**Table 1: Cut-off frequency for different passivation layer**

| Passivation Layer | Cut-off Frequency |
|-------------------|-------------------|
| SiO$_2$           | 153               |
| Si$_3$N$_4$       | 149               |
| AlN               | 138               |
| Al$_2$O$_3$       | 138               |
| MgO               | 137               |
| ZnO               | 99                |

5. CONCLUSIONS

Surface passivation plays an important role in the electrical characteristics of AlGaN/GaN HEMT. In this paper, we analyzed the effect of different passivation layers on the electrical characteristics of the device. Drain current increases for high K passivation layers. It is proposed that new materials compatible with the AlGaN/GaN material system with high dielectric constant can be used to obtain very high currents and can be used for the designing of high power amplifiers.
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