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On the Operation Mechanism and Device Modeling of AlGaN/GaN High Electron Mobility Transistors (HEMTs)

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***Abstract*—**In this work, the physical based device model of AlGaN/GaN high electron mobility transistors (HEMTs) has been established and the corresponding device operation behavior has been investigated also by using Sentaurus TCAD from Synopsys. Advanced AlGaN/GaN hetero-structures with GaN cap layer and AlN spacer have been considered and the GaN cap layer and AlN spacer are found taking important roles on the gate leakage blocking and off-state breakdown voltage enhancement.

***Keywords*—**AlGaN/GaN, HEMT, Physical mechanism, TCAD simulation

I. Introduction

THREE-nitride wide-bandgap materials, e.g. GaN, AlN attract a lot of attentions owing to their material advantages. Especially, AlGaN/GaN hetero-junction based high electron mobility transistors (HEMTs) can provide both low on-resistance and high off-state breakdown voltage simultaneously, possessing unique device characteristics for power electronics applications.

Tremendous progress has been made in AlGaN/GaN HEMT technology [1-3], however, a complete physical based device model of AlGaN/GaN HEMTs is still highly desired, which can be used to reveal the transistors' unique physical mechanisms and predict the device operation behavior.

In this work, a physical based device simulation of AlGaN/GaN HEMTs has been carried out by using Sentaurus TCAD from Synopsys. Pivotal physical mechanisms, such as gate Schottky tunneling, surface cap layer leakage, avalanche breakdown and GaN buffer leakage can be revealed. According to device simulation, the switching on/off behavior, on-state output characteristics and off-state breakdown of AlGaN/GaN HEMTs can be modeled. GaN cap layer and AlN spacer are suggested to be implemented into the standard AlGaN/GaN hetero-structure to suppress the gate leakage and to enhance both the off-state breakdown voltage and on-state current driving capability.

II. Device Structure and Modeling Setup

For the device simulation, the standard AlGaN/GaN HEMTs on high resistivity Si wafer have been modeled as shown in Fig. 1. From top to bottom, the hetero-structure consists of an $Al_{0.24}Ga_{0.76}N$ barrier layer (20 nm), a GaN buffer layer (3 µm), an AlGaN/AlN transition/nucleation layer (1 µm) and the Si substrate (1 µm).

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The unintentional background n-type doping in AlGaN and GaN layer is set to be 10^{16} cm^{-3} [4], and the Fe compensation doping (2×10^{17} cm^{-3}) in GaN buffer [5] is also considered. High density donor-like traps are added in the AlGaN/AlN transition/nucleation layer to model the lattice dislocations. The Si layer here is un-doped to model the high-resistivity substrate.

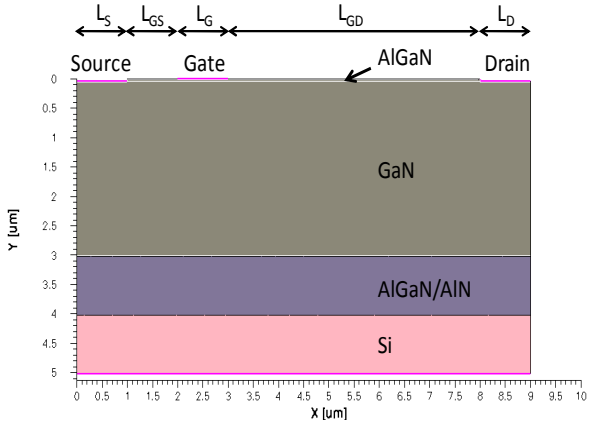


Fig. 1 The cross-section view of AlGaN/GaN HEMT device model structure

Three different barrier structures on top of the GaN buffer have been modeled in our work, (a) the standard AlGaN barrier, (b) the AlGaN barrier with 2 nm GaN cap layer and (c) the AlGaN barrier with 2 nm GaN cap layer and 1 nm AlN spacer.

Same device geometries with Ni gate length of 1 µm, source/drain ohmic contact length of 1 µm, L_{GS} of 1 µm and L_{GD} of 5 µm are used in our simulation.

In our device simulation, the Sentaurus TCAD v2010.03 software is used. The simulated conduction band diagram of AlGaN/GaN hetero-junction is shown in Fig. 2. With the lattice stress relax of 10%, the spontaneous and piezoelectric polarization of the AlGaN/GaN hetero-junction are 0.78×10^{13} cm^{-2} and 0.51×10^{13} cm^{-2}, respectively.

On the surface of AlGaN barrier, there are donor-like surface states of ~10^{13} cm^{-2} arising from the Ga adatom dangling bonds [6]. In our simulation, the AlGaN surface trap state is set to be located at 3.2 eV above the valance band. The distribution of electron carriers within the AlGaN/GaN hetero-junction is shown in Fig. 3.

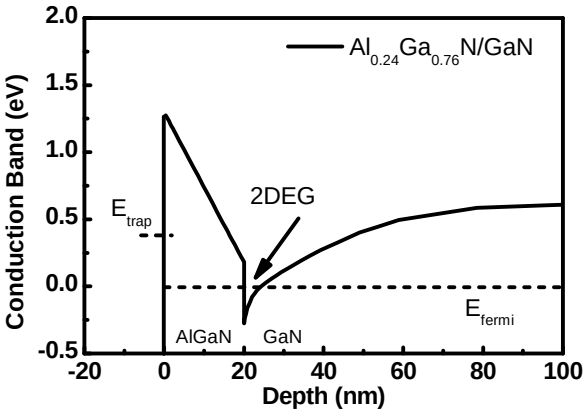


Fig. 2 The conduction band diagram of AlGaN/GaN hetero-junction

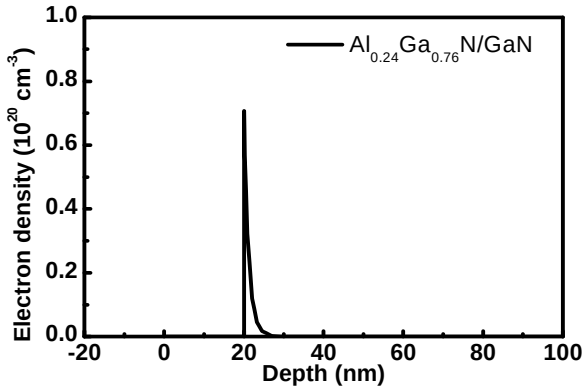


Fig. 3 The electron carrier distribution profile within the AlGaN/GaN hetero-junction

The conduction band structures of AlGaN/GaN hetero-junction under Ni gate Schottky contact are calculated and shown in Fig. 4. The influence of GaN cap layer and AlN spacer are also taken into account. As we can see, the conduction band of GaN cap layer is lower than AlGaN barrier, due to the material properties. In addition, with the polarization effect between AlGaN and GaN, both two dimensional electron gas (2DEG) and two dimensional hole gas (2DHG) will be formed. The AlN spacer can provide an additional energy barrier between AlGaN/GaN and enhance both the electron carrier mobility and concentration [8].

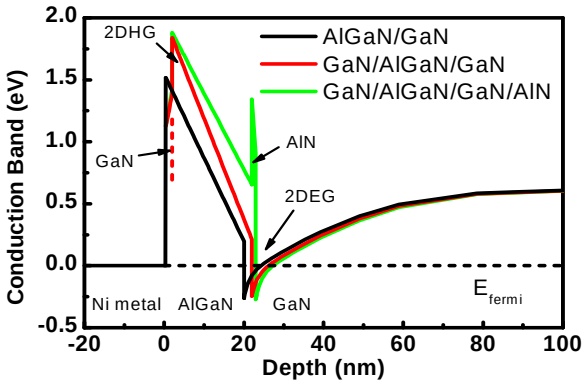


Fig. 4 The conduction band diagram of AlGaN/GaN hetero-junction with GaN cap layer and AlN spacer under the Ni gate metal contact

III. Results and Discussions

The transfer I_{DS}-V_{GS} characteristics of standard AlGaN/GaN HEMT, HEMT with GaN cap layer and HEMT with GaN cap and AlN spacer are shown in Figs. 5 and 6. As we can see, the standard HEMT suffers both higher gate and drain off-state leakage current compared to the HEMT with GaN cap layer. The current density distribution profiles of standard AlGaN/GaN HEMT at V_{GS} = -6 V and V_{DS} = 10 V are plotted in Figs. 7 and 8, indicating the domination of the leakage behavior of standard AlGaN/GaN HEMT by the gate leakage current, especially at the drain side gate edge.

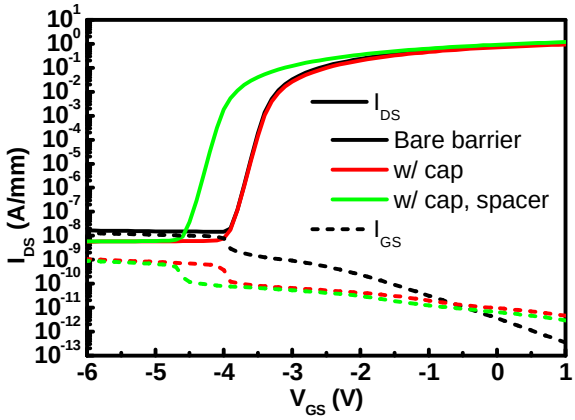


Fig. 5 The simulated I_{DS}-V_{GS} transfer characteristics of standard AlGaN/GaN HEMT, HEMT with GaN cap layer and HEMT with GaN cap and AlN spacer in log scale

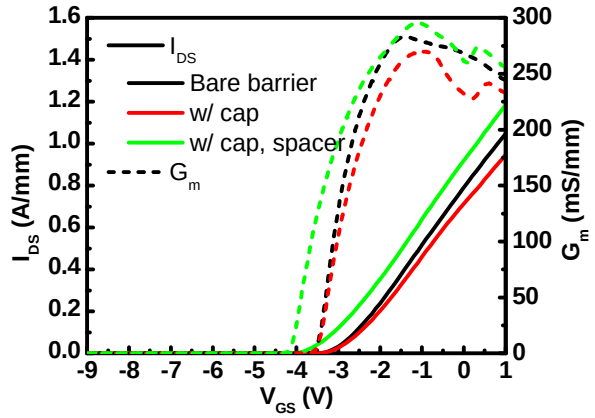


Fig. 6 The simulated I_{DS}-V_{GS} and G_m-V_{GS} transfer characteristics of standard AlGaN/GaN HEMT, HEMT with GaN cap layer and HEMT with GaN cap and AlN spacer in linear scale

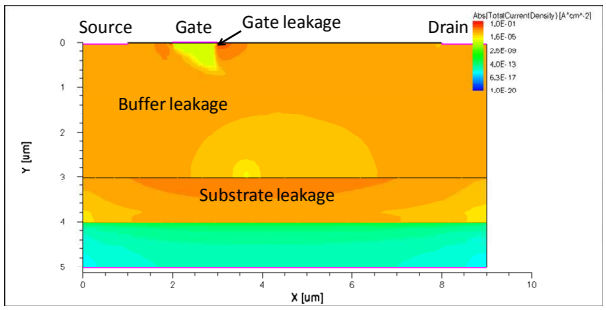


Fig. 7 The current density distribution profile of AlGaN/GaN HEMT at V_{GS} = -6 V and V_{DS} = 10 V

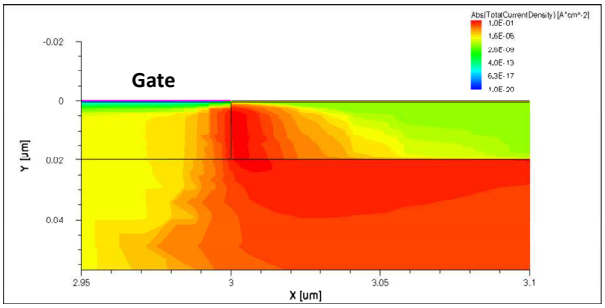


Fig. 8 The zoom-in current density distribution profile of AlGaN/GaN HEMT at V_{GS} = -6 V and V_{DS} = 10 V

In the off-state, the gate Schottky contact is reverse biased, thus the gate current will be compose of the gate tunneling and thermionic emission current. The distribution of gate tunneling rate is plotted in Fig. 9, which shows a strong electron tunneling close to the drain side gate edge and is consistent with the gate leakage current distribution shown in Fig. 8. Fig. 10 shows the conduction band energy level distribution in standard AlGaN/GaN HEMT at V_{GS} = -6 V and V_{GS} = 10 V. As we can see, the positively biased drain electrode can pull down the conduction band level between gate and drain, thus at the drain side gate edge, the voltage drop between the gate contact and the 2DEG channel will be higher than the one under the gate electrode and far from the drain, therefore the strongest electron carrier tunneling will occur at the drain side gate edge.

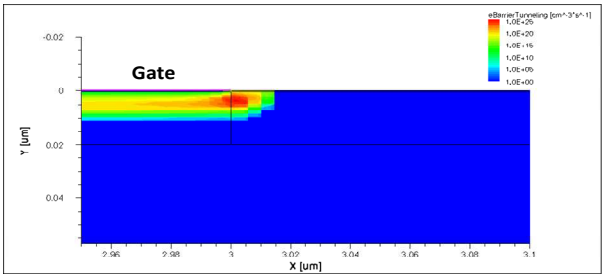


Fig. 9 The zoom-in gate electron tunneling distribution profile of AlGaN/GaN HEMT at V_{GS} = -6 V and V_{DS} = 10 V

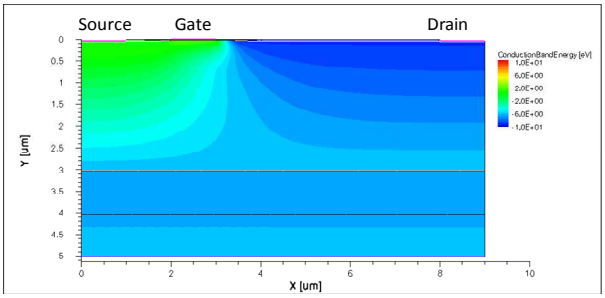


Fig. 10 The conduction band distribution profile of AlGaN/GaN HEMT at V_{GS} = -6 V and V_{DS} = 10 V

When AlGaN/GaN HEMT is capped by the GaN layer, the gate tunneling current can be suppressed, due to the virtual gate screen effect [9, 10] induced by the surface leakage current along the GaN cap layer, as shown in Fig. 11.

The AlGaN/GaN HEMT with GaN spacer and AlN spacer delivers higher current driving capability and more negative threshold voltage compared to the standard AlGaN/GaN HEMT, owing to the higher 2DEG channel mobility and carrier concentration. The output characteristics of standard AlGaN/GaN HEMT, HEMT with GaN cap layer and HEMT with GaN cap and AlN spacer are plotted in Fig. 12.

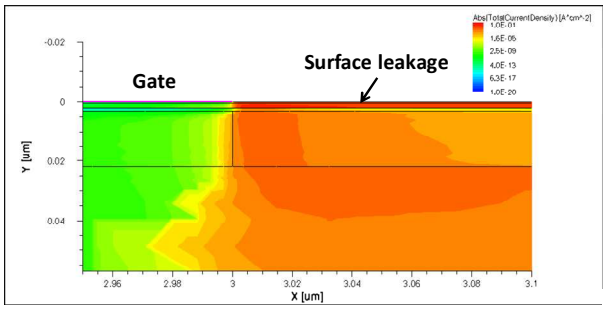


Fig. 11 The zoom-in current density distribution profile of AlGaN/GaN HEMT with GaN cap layer at V_{GS} = -6 V and V_{DS} = 10 V

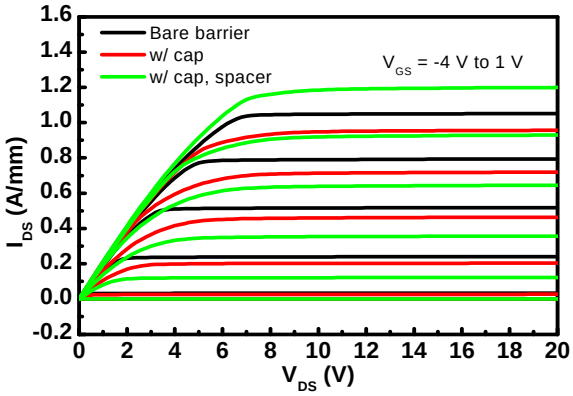


Fig. 12 The simulated I_{DS}-V_{DS} output characteristics of standard AlGaN/GaN HEMT, HEMT with GaN cap layer and HEMT with GaN cap and AlN spacer. V_{GS} sweeps from -4 V to 1 V at a step of 1 V

The off-state I_{DS}-V_{DS} characteristics of standard AlGaN/GaN HEMT, HEMT with GaN cap layer and HEMT with GaN cap and AlN spacer are illustrated in Fig. 13. As we can see, the breakdown voltages of three kinds of devices are extracted as 268 V, 705 V and 630 V, respectively. As discussed above, with the assistant of the GaN cap layer, impact of the drain voltage on the potential distribution between gate and drain can partially be screened by the virtual gate effect. As a result, not only the gate leakage will be suppressed but also the electrical field distribution can be uniformed (Fig. 14), compared to the standard AlGaN/GaN HEMT. Therefore, HEMTs with GaN cap layer can deliver higher breakdown voltage. In addition, the breakdown voltage of AlGaN/GaN HEMT with AlN spacer will be slightly lower than GaN capped HEMT without AlN spacer, due to the higher 2DEG carrier concentration and corresponding shorter depletion length. The off-state conduction band distribution profile of standard AlGaN/GaN HEMT and HEMT with GaN cap and AlN spacer are compared in Fig. 15.

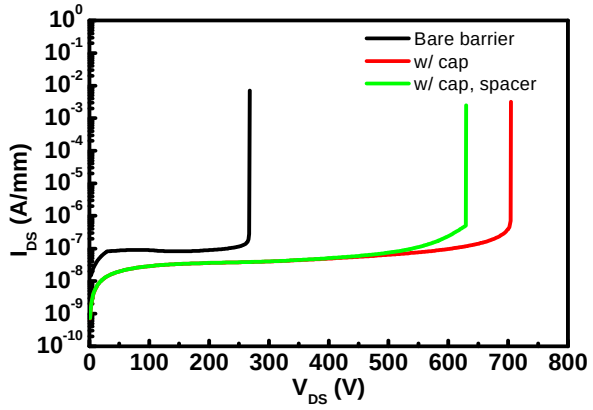


Fig. 13 The simulated I_{DS}-V_{DS} output characteristics of standard AlGaN/GaN HEMT, HEMT with GaN cap layer and HEMT with GaN cap and AlN spacer at V_{GS} = -5.5 V

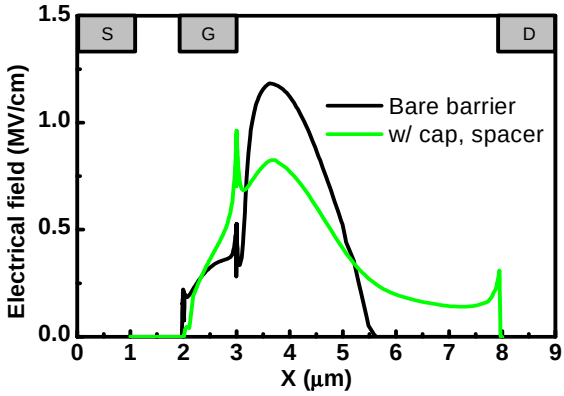
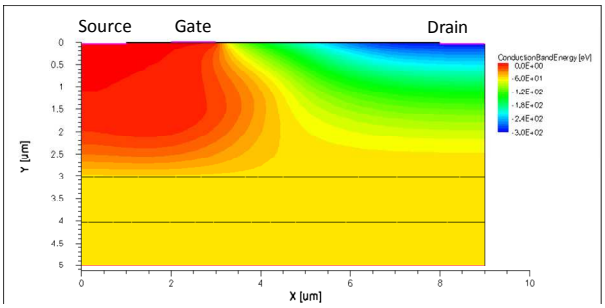
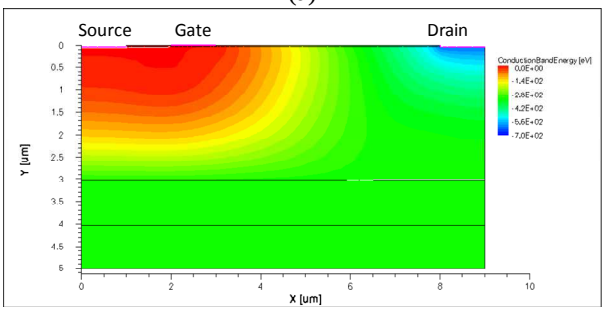


Fig. 14 The electrical field distribution profile in the 2DEG channel of standard AlGaN/GaN HEMT and HEMT with GaN cap and AlN spacer at V_{GS} = -5.5 V and V_{DS} = 200 V



(a)



(b)

Fig. 15 The conduction band distribution profile of (a) standard AlGaN/GaN HEMT at V_{GS} = -5.5 V and V_{DS} = 268 V (b) AlGaN/GaN HEMT with GaN cap and AlN spacer at V_{GS} = -5.5 V and V_{DS} = 630 V

IV. Conclusion

The device models of AlGaN/GaN HEMTs have been built and the corresponding device simulations have been carried out by using Sentaurus TCAD tools. It has been found the gate tunneling at the drain side gate edge dominates the off-state leakage current of AlGaN/GaN HEMTs. With the GaN cap layer, in AlGaN/GaN HEMTs both the off-state leakage current and peak electrical field strength can be reduced owing to the virtual gate screen effect induced by the surface current in the GaN cap layer, thus higher breakdown voltage can be achieved. Thanks to the higher 2DEG channel carrier mobility and concentration, the AlGaN/GaN HEMTs with GaN cap and AlN spacer can deliver both better on-state current driving capability and off-state breakdown voltage compared to the standard HEMTs.

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