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Electrical Characteristic of AlGaN/GaN HEMTS with AlN Spacer Layer

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Abstract - Two-dimensional electron gas (2DEG) formed at AlGaN/GaN interface is a critical part to tune the characteristic of AlGaN/GaN HEMT devices. In this work, AlN spacer layer is used between AlGaN and GaN layer to improve 2DEG density, mobility, and drain current. Modeling and simulation of AlGaN/AlN/GaN is successfully performed to explore transport properties. The carrier's mobility attains a maximum at the 0.5-nm-thick AlN spacer thickness. Current and transconductance increases with the thickness of AlN spacer and reaches a maximum at a critical thickness. Beyond the critical thickness, the current and transconductance decrease due to degradation of ohmic contact. The critical thicknesses for the drain current and transconductance are 1.5 nm and 1.2 nm respectively.

I. INTRODUCTION

GaN-based high electron mobility transistor (HEMT) has been the subject of many recent investigations. A combination of the wide band gap which leads to high breakdown field (1-3x10^6 V/cm), strong polarization field which leads to produce high sheet charge densities (1x10^{13}cm^{-2}) [1-3], high saturation velocity (1.5x10^7cm/sec) of electrons promises for use in high-temperature, high-power devices. In order to increase the power density, product of carrier concentration (ns) and electron mobility must be maximize. Carrier concentration can be increased by increasing Al mole fraction. Unfortunately, the mobility is dropped owing to low surface quality of crystal and alloy scattering [4]. However, the existence of different types of scattering mechanism such as acoustic and optical phonons, ionized impurity, interface roughness, dislocation and alloy disorder play important role to limit the mobility of 2DEG in AlGaN/GaN HEMT [5]. An additional thin AlN spacer between AlGaN and GaN improves the mobility at low temperatures [6]. An insertion of AlN in AlGaN/GaN interface causes the reduction of alloy scattering which plays a dominant role in mobility [7]. The thickness of AlN is important factor for the mobility in AlN/GaN heterostructures [8-10].

In this study, the electron transport characteristics of AlGaN/GaN HEMTs are numerically studied by inserting the AlN spacer layer, where the effect of the spacer thickness is also considered. The results of this study indicate the best thickness of spacer layer.

II. SIMULATION AND RESULT DISCUSSION

For device simulation, explored device has been modeled as shown in Figs. 1(a) and (b), where the adopted parameters are listed in Table 1. Simulation is performed for devices, without AlN spacer layer (conventional HEMTs) and with AlN spacer layer (the explored one in this work). For simulated device, AlGaN and GaN epilayer are 25 nm and 2 μm thick and Al composition in AlGaN layer is 30%. Gate length, source-gate separation, gate drain separation and gate width are 1.0, 1.5, 3.5, and 15 μm respectively. To simulate the device with AlN spacer layer, AlN spacer layer with different thickness between AlGaN/GaN layers is inserted (0.3, 0.5, 1, 1.2, 1.4, 1.5, and 2.0 nm). Notably, the total thickness of AlGaN and AlN layer is 25 nm. The device characteristic is simulated by solving a set of quantum mechanically corrected transport equations. High and low field models along with concentration and temperature dependent analytic model are used to calculate mobility in high and low electric fields. Polarization is crucial properties in III-Nitride devices. Therefore, polarization model has been used for including the effect of polarization in AlGaN/GaN HEMTs.

The carrier's mobility and carrier concentrations are first calculated for both the conventional HEMT and the explored new HEMT which is with the AlN spacer layer between the layers AlGaN and GaN. The thickness of AlN spacer layer affects the electron concentration in the device channel. Fig. 2 shows the relationship between the electron concentration and the thickness of AlN spacer layer. AlN thickness affects the total polarization thus contributing significantly in increase of electron concentration. Fig. 3 shows that the quantum well depth increases with increasing the spacer layer's thickness. This increase in the quantum well depth and barrier directly helps to better confinement of electron concentration. Due to the increase in the quantum well depth, the carrier-carrier scattering is lowered. Alloy scattering is lowered because binary compound such as AlN has less alloy scattering in comparison to ternary compound [7]. As a result, the mobility is increased. The significantly improvement of mobility with insertion layer is shown in Fig. 4. The simulation result, as shown in Fig. 4, exhibits that variation of mobility is not similar as that of electron concentration and quantum well depth. On insertion of AlN between GaN and AlGaN, the carrier's mobility increases because of reduction of alloy and other type of scattering. The mobility attains its maximum, when the thickness is equal to 0.5 nm; it decreases with further increase of thickness. This is owing to the Coulomb scattering between the 2DEG carriers after critical thickness. As the drain current is result of the combine effect of mobility and electron concentration, current also vary with the spacer layer and corresponding thickness. As shown in Fig. 5, current increase on insertion of spacer layer and on increasing the thickness. After the critical thickness, there is degradation of ohmic contact and hard to measure the drain current. Fig. 5 shows that drain current can be measured without any difficulties up to 1.5 nm thick AlN spacer layer. Figs. 6 and 7 show the variation of trans-conductance with thickness of AlN spacer layer. The trans-conductance increases on the insertion of AlN layer between AlGaN and GaN; and its increase is proportional to the thickness. Our simulation result indicates that the critical thickness for the trans-conductance is 1.2 nm.

III. CONCLUSIONS

In this work, modeling of GaN HEMT with AlN spacer layer was successfully done. Effect of AlN spacer layer and its thickness on the transport properties in 2DEG of HEMT has successfully been studied. The key findings of the different thickness of AlN spacer layer conclude that the electron concentration significantly increases on the insertion of AlN spacer layer and its value increases for the thicker AlN spacer layer. The carrier's mobility increases as the thickness of the spacer layer up to certain critical value. The critical thickness is 0.5 nm, beyond this thickness, the mobility decreases. Besides these transport parameters, the drain current increases with the thickness but as the spacer layer is thick enough ohmic contacts degraded and the drain current decreases. This simulation shows that beyond 1.5 nm thick AlN ohmic resistance incrase highly and drains current decrease. Finally, the thickness of spacer layer varies the transconductance, where an optimal thickness is at 1.2 nm.

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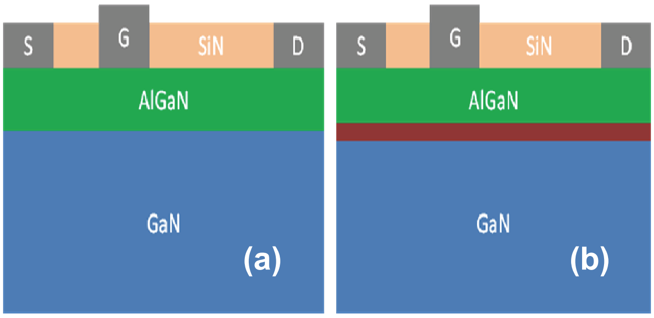

Fig. 1. The structure of HEMTs. (a) Conventional device which is without AlN spacer layer and (b) the explored device which is with AlN spacer layer (the red layer).

Table 1. The adopted physical parameters of the HEMT devices.

Parameters	Values
Gate length	1.0 µm
Gate width	15 µm
Source-gate separation	1.5 µm
Gate-drain separation	3.5 µm
GaN thickness	2 µm
Al fraction in AlGaN	30%
AlGaN thickness	25 nm
AlN thickness	0.5, 1, 1.2, 1.4, 2 nm (Note that the total AlGaN/AlN thickness is kept at 25 nm)

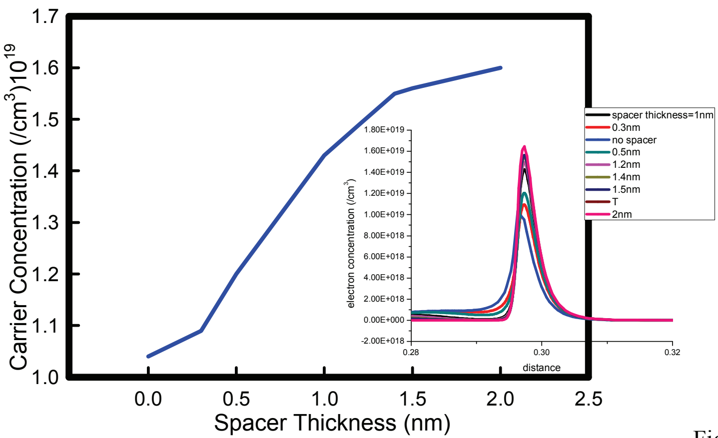

Fig. 2. The electron concentration for the device with respect to the different thickness of AlN spacer layer.

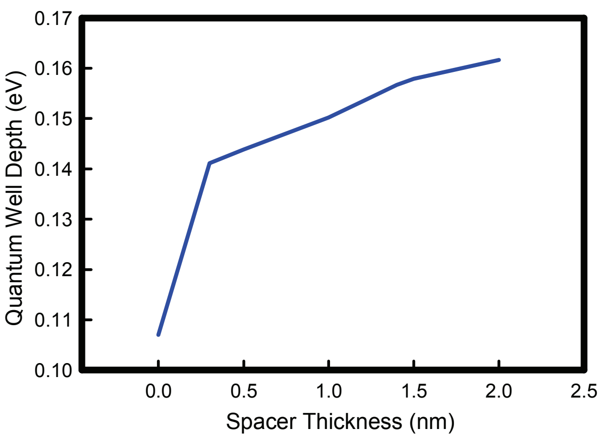

Fig. 3. Plot of the quantum well depth versus the thickness.

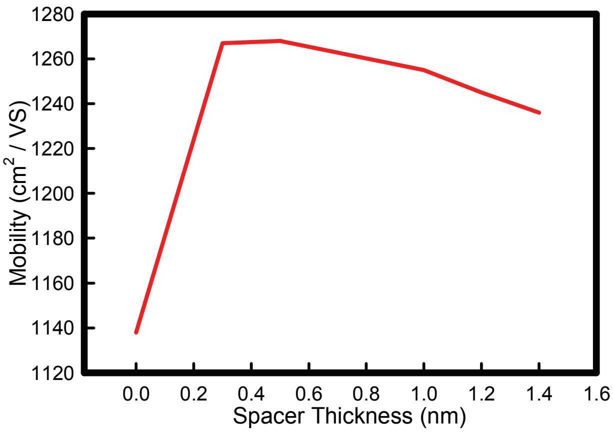

Fig. 4. The carrier's mobility versus the thickness.

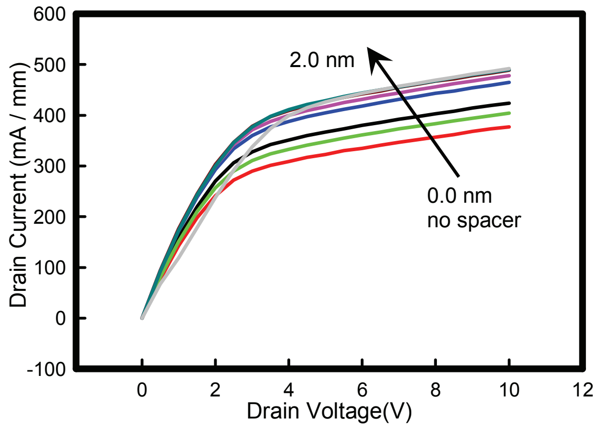

Fig. 5. The drain current versus the drain voltage with respect to the different thickness of spacer layer which is varying from 0.0, 0.3, 0.5, 1.0, 1.2, 1.4, 1.5, and 2.0 nm, respectively. Notably the critical thickness for the maximal drain current is at 1.5 (gray line).

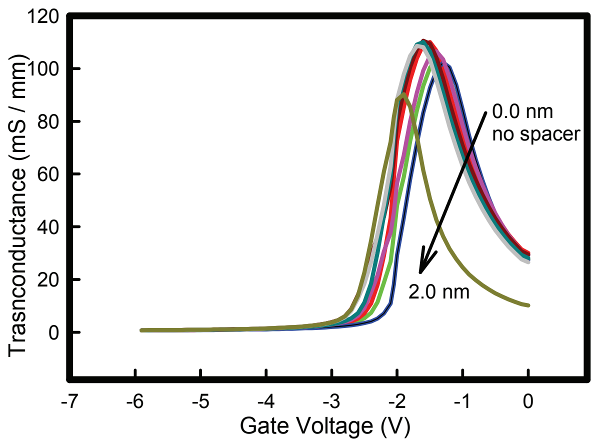

Fig. 6. Plot of the transconductance for the thickness of AlN spacer layer varying from 0 to 2 nm according to the steps in Fig. 5.

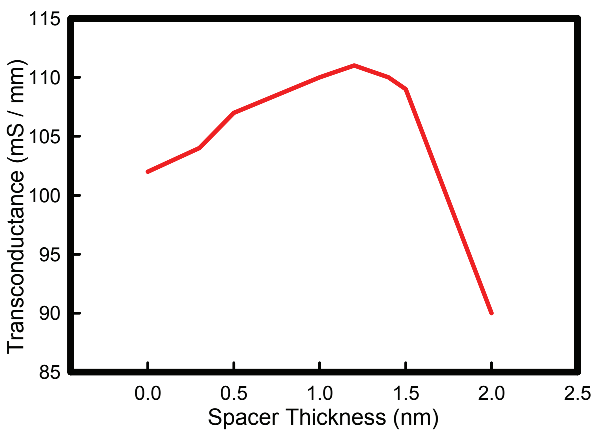

Fig. 7. Plot of the variation of transconductance with respect to the thickness of AlN spacer layer. The maximum occurs at 1.2 nm.