Ultra-thin double barrier AlGaN/GaN high threshold voltage HEMT with graded AlGaN/Si3N4 gate and p-type buffer layer

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Research Article

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Ultra-thin double barrier AlGaN/GaN high threshold voltage HEMT with graded AlGaN/Si_3N_4 gate and p-type buffer layer

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Abstract

An ultra-thin double barrier enhancement mode (E-mode) AlGaN/GaN high electron mobility transistor (HEMT) with p-type buffer layer and Si_3N_4/graded p-AlGaN gate is proposed and investigated by Silvaco TCAD. The simulation results show that the designed HEMT can obtain a high threshold voltage over 5.0 V and large gate swing. The maximum gate leakage current is 3.11×10^{-4} A/mm at 30 V gate voltage, which decreases four orders of magnitude compared to the conventional double barrier HEMTs. Due to the p-type buffer layer, the cut-off frequency for the proposed HEMT is raised over three-times compared to the conventional double barrier structure HEMT with n-type buffer layer. Meanwhile the designed HEMT exhibits high breakdown voltage and large current-gain. Moreover, the impacts of Si_3N_4 layer thickness under gate and GaN channel layer thickness are analyzed. Both layers play significantly roles in obtaining high threshold voltage for the device by adjusting the conduction band energy of AlGaN/GaN interface quantum well.

Keywords: E-mode, HEMT, thin barrier, p-type buffer

1. Introduction

Because of the excellent properties for (Al)GaN based Ⅲ-nitride semiconductor materials such as wide band energy, high-electron saturation velocity, large mobility, high breakdown electric field and better thermal stability, which have been widely used in opto-electronic devices, high temperature high power devices and high frequency microwave devices [1,2]. In the last few decades, GaN-based high electron mobility transistors (HEMTs) have attracted more and more attention thanks to their outstanding advantages [3-6]. As a result of spontaneous and piezoelectric polarization effects, a high density two-dimensional electron gas (2DEG) about $10^{13}/cm^2$ is formed at the interface of AlGaN/GaN hetero-junction. Therefore, GaN HEMTs are intrinsic normally-on devices. However, for fail-safe operation in power electronic applications, the enhancement-mode (E-mode) GaN-base HEMTs with large positive threshold voltage (>3 V) and large gate swing (>10 V) are desirable [7].

So far, the mainly strategies have been proposed to realize the enhancement mode GaN-based HEMTs including thin barrier [8], gate recess [9], the injection of fluorine ion under gate [10], p-GaN/AlGaN gate [11,12], and metal-insulator-semiconductor gate etc [13]. GaN-base E-mode HEMTs with thin barrier suffer from the low 2DEG in source-gate area [8]. p-GaN cap layer technology faces the challenge of the

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effective p-type doping. The gate recess structures have the difficulty to accurately control the remaining barrier layer thickness, and bring serious material damage. The charge formed by fluorine ion injection has the poor thermal stability [14]. Hence, the E-mode GaN-base HEMTs with high threshold voltage V_T (>5 V), large gate swing, low device leakage current, high saturation drain current, high breakdown voltage and cut-off frequency still need to be further investigated [15].

In this work, we designed an ultra-thin double barrier E-mode HEMT with polarization-induced p-doping in p-AlGaN gate. As we know, the polarization doping is often used in high Al content AlGaN avalanche photodiodes [16, 17]. Meanwhile, the buffer layer with p-type doping is also used in this structure to improve the threshold voltage and cut-off frequency. The characteristics containing the threshold voltage, gate swing, gate leak current, drain current, breakdown-voltage and cut-off frequency etc. are analyzed by Silvaco Atlas.

2. Structure, parameters and physical models

The schematic of the ultra-thin double barrier E-mode HEMT with polarization-induced p-type doping gate is shown in Fig. 1(a). It consists of a 2-μm p-type $Al_{0.05}Ga_{0.95}N$ buffer layer on the silicon substrate, a 5-nm GaN channel layer, a $Al_{0.2}Ga_{0.8}N$ (5-nm)/$Al_{0.3}Ga_{0.7}N$ (5-nm) double barrier layer and a stack polarization-doped $Al_xGa_{1-x}N$ (60-nm)/Si_3N_4 (20-nm) gate structure along the device grown direction. The Al content in graded $Al_xGa_{1-x}N$ layer changes from 0.2 to 0 with the highest Al content at the $Al_{0.3}Ga_{0.7}N$ barrier layer and graded $Al_xGa_{1-x}N$ layer interface. The hole-doping density in the p-type buffer layer is 1×10^{16} cm^{-3}. The two conventional double barrier HEMTs are used here for comparison as shown in Fig. 1(b) and Fig.1(c). They have the similar structure with the proposed HEMT except the doping concentration in buffer layer and the gate structure. Fig. 1(b) and Fig. 1(c) have 80-nm-thick p-type GaN gate (p = 3×10^{17} cm^{-3}). The doping concentration of buffer layer in Fig. 1(b) is the same as the designed structure. The doping concentration of buffer layer in Fig. 1(c) is unintentionally doped and the background carrier is 1×10^{16} cm^{-3}. The length of gate, the distance from the source to gate, the distance between the gate and drain are 1.4 μm, 1 μm and 18 μm respectively.

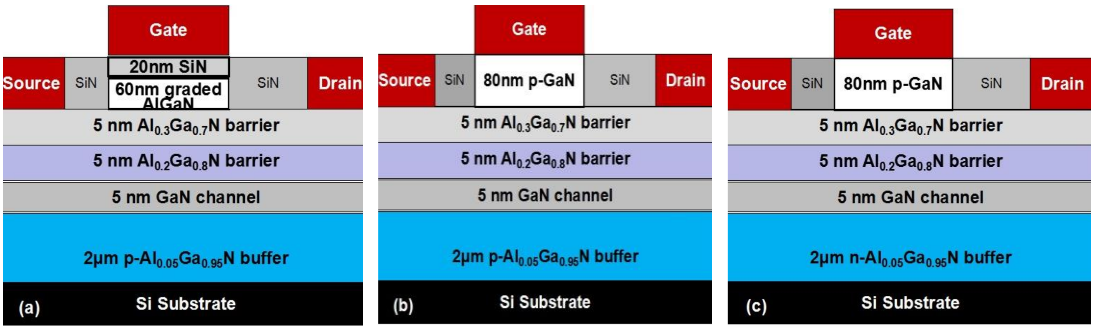


Fig.1 schematic of (a) proposed HEMT (b) conventional double barrier HEMT with p-type buffer layer (c) conventional double barrier HEMT with n-type buffer layer

In simulation, the Shockley-Read-Hall recombination model, the polarization model, the nitride specific high field mobility model, the Albrecht low field mobility mode, the hot carrier injection model and the impact ionization model are adopted. In buffer layer, a donor-like trap with trap energy level of 3.2 eV above valence band and trap density of 1×10^{18} cm^{-3}, as well as an acceptor-type trap with energy level of 0.36 eV below the conduction band and trap density of 7×10^{17} cm^{-3} are taken into account [5]. The impact ionization parameters are same as the reference [5]. The source and drain are ohmic contact. The gate is schottky contact and work function is 5.2 eV.

3. Results and discussion

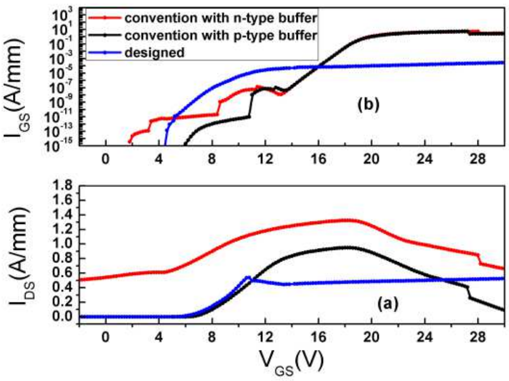
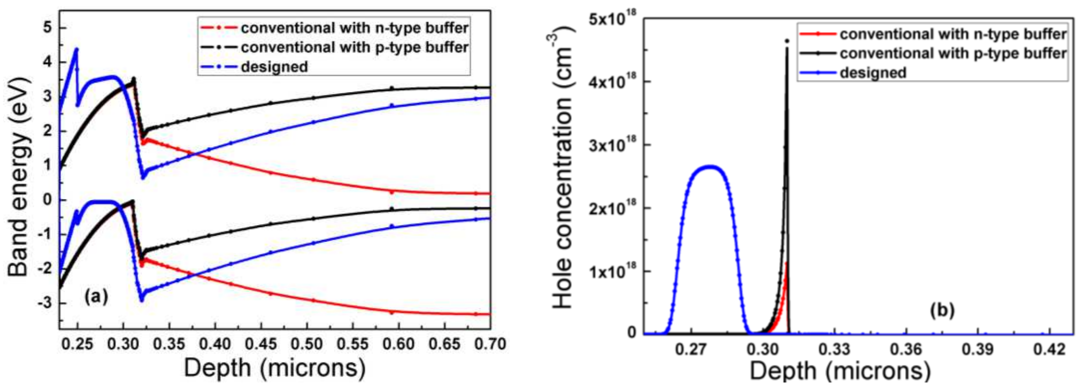


Fig. 2 (a) the drain current (I_{DS}) and (b) the leakage current of the gate (I_{GS}) for three HEMTs at drain voltage (V_{DS}) of 10 V and gate voltage (V_{GS}) from -2 V to 30 V

Fig. 2 shows the transfer characteristics and leakage current characteristics of the gate for three HEMTs at V_{DS}=10V. Form Fig. 2, we can obtain that the threshold voltage (V_{TH}) for conventional HEMT with n-type buffer layer is lower than -2 V, indicating a normally on operation. In contrast, for conventional HEMT with p-type buffer layer and proposed HEMT, E-mode is realized. The threshold voltages for both HEMTs are 4.46 V and 5.02 V respectively. Here, we define the threshold voltage is the gate voltage when the drain current reaches a constant of 10 μA/mm as reference [18]. The drain current at V_{GS}=0V are 8.82×10^{-14}A/mm and 2.54×10^{-13}A/mm correspondingly. With the increase of the gate voltage, the drain currents for both conventional structures enhance to a peak value, then, decline rapidly. While, the drain current for the proposed structure shows a slight upward trend and exceeds that of conventional HEMT with p-type buffer layer when the gate voltage is over 25.2 V, showing a better gate swing. The maximum drain current for proposed HEMT is 0.52816 A/mm at 30 V gate voltage. The maximum gate leakage current for proposed HEMT is 3.11×10^{-4} A/mm, which is four orders of magnitude lower than that of both conventional structure. Moreover, the proposed structure also exhibits a large on/off current ratio of 10^8 and steep sub-threshold slope of 71.1mV/dec.



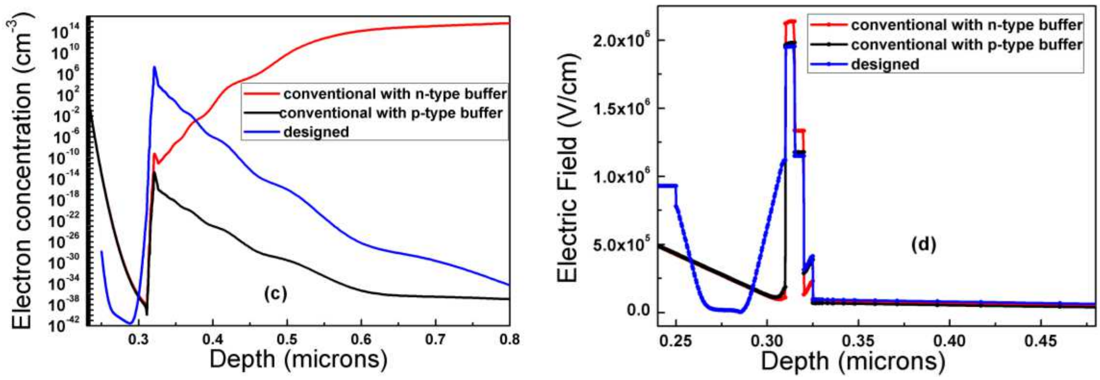


Fig.3 (a) the band energy (b) the hole concentration (c) the electron concentration (d) the electric field distribution for three HEMTs under gate at V_{DS}=0V and V_{GS}=0V

In order to analyze the electric characteristics in Fig. 2, we calculated the band energy, the electron concentration, the hole concentration, and electric field distribution for three HEMTs under gate along the vertical channel direction as shown in Fig. 3. For proposed structure, a high bulk hole concentration near 2.65×10^{18} cm^{-3} caused by polarization-induced effect can be seen form Fig. 3 (b), which obviously increases the build-in electric field in graded p-AlGaN layer and enhances the barrier height for electron transmission from GaN channel layer to gate as displayed in Fig.3 (d) and Fig. 3(a). The enhanced barrier results in a very small gate leakage current as observed in Fig. 2(b) even at large gate voltage. We also find that there is a small quantum well at the interface of AlGaN barrier layer/GaN channel layer for three structures, and the conduction band diagrams in the quantum well are all above the Fermi level, which produce the maximum electron density less than 8×10^{6} cm^{-3} at the interface (Fig.3(c)). Hence, the three structures should be the E-mode HEMTs in theory. However, the conventional HEMT with n-type buffer layer is a depletion-mode (D-mode), which may be caused by the thinner GaN channel layer and high n-type doping in buffer layer. An additional quantum well can be noticed at Si_3N_4/graded p-AlGaN interface in proposed HEMT. With the increased forward gate voltage, the electron will inject from AlGaN/GaN interface quantum well into this additional quantum well. The electron in additional quantum well has no contribution to drain current. Meanwhile, the conduction band energy of AlGaN/GaN interface quantum well drops very slow thanks to the small forward voltage applied at this area, because this quantum well is connected in series with a large resistor Si_3N_4 layer. Thus, a higher threshold voltage is needed to collect the electron in AlGaN/GaN interface quantum well and turn on the HEMT [19].

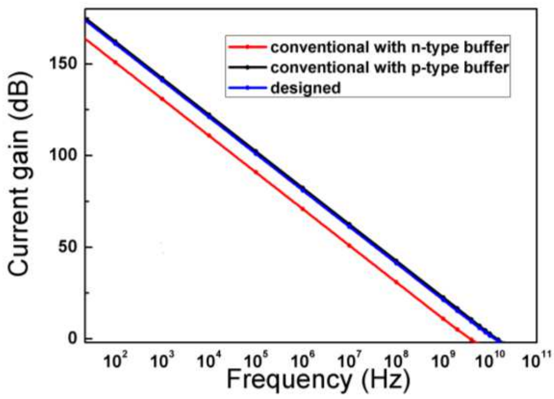


Fig.4 current gains of frequency dependence for three HEMTS at V_{DS}=10 V

The current gains of frequency dependence for three HEMTs at V_{DS}=10 V are studied by the AC small-signal analysis as shown in Fig.4. The cut-off frequencies for proposed HEMT and conventional HEMT with p-type buffer layer are 12.7 GHz and 14.2 GHz. These two structures raise the cut-off frequency over three-times compared to the conventional structure with n-type buffer layer (3.84 GHz) at V_{DS}=10 V. The large cut-off frequencies for both HEMTs may be attributed to the p-type doping in buffer layer, which can enhance the conduction band energy, decreases the electron concentration and increase the electric field strength in AlGaN/GaN interface potential well. Hence, the electron velocity in the well is improved.

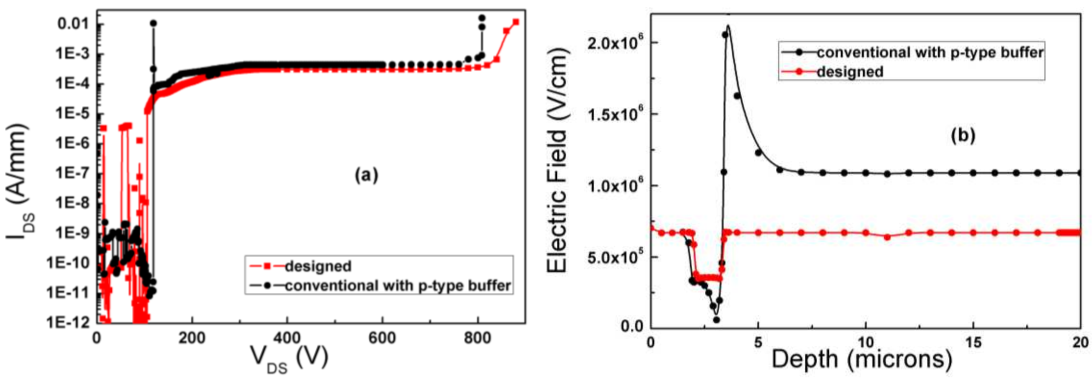


Fig. 5 (a) the breakdown characteristic and (b) the electric field distribution along the channel at V_{DS}=100 V for designed HEMT and conventional HEMT with p-type buffer layer

Fig. 5(a) presents the drain current-voltage curves for proposed HEMT and conventional HEMT with p-type buffer at V_{GS}=0 V. From Fig. 5 (a), it can be found that the breakdown voltage for proposed HEMT is 860 V, exhibiting a large improvement as compared with the conventional HEMT with p-type buffer (808 V). The improvement of breakdown voltage for proposed HEMT is ascribed to the insertion of Si_3N_4 layer between gate and graded p-AlGaN layer, which evidently reduces the electric field strength in the region from gate to drain, and makes the electric field distribution more uniform along the channel as shown in Fig. 5 (b).

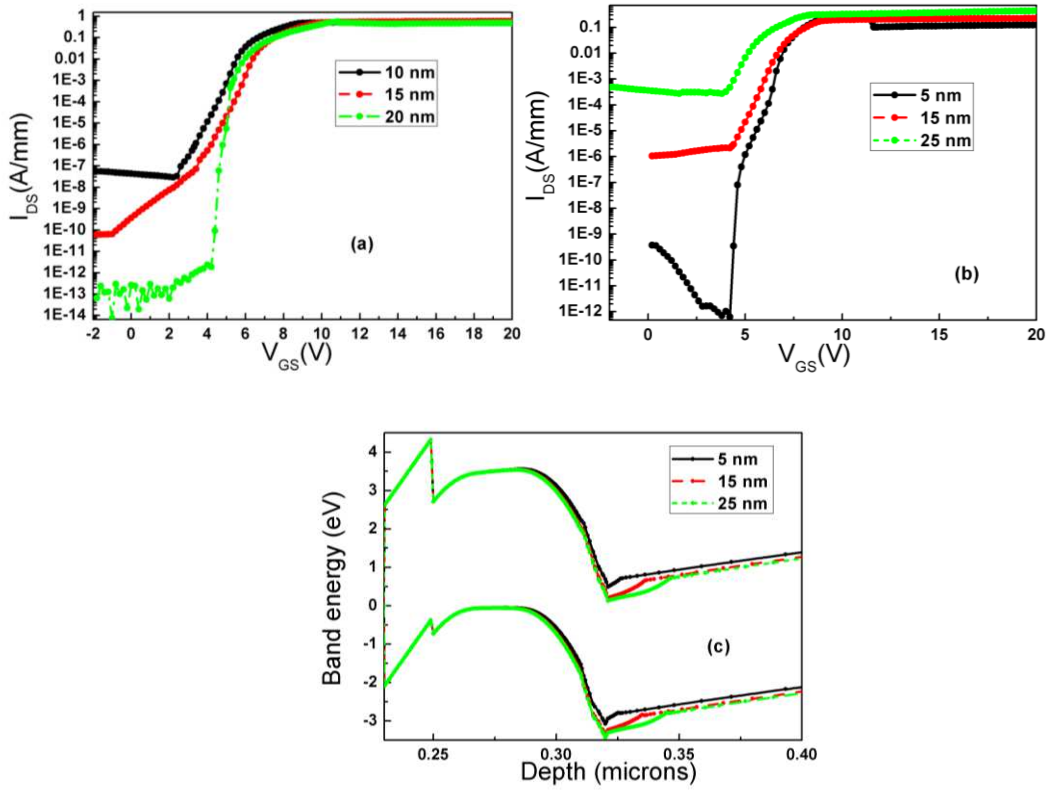


Fig.6 (a) I_{DS}-V_{GS} curves at different Si_3N_4 layer thicknesses under the gate (b) I_{DS}-V_{GS} curves and (c) the band energy diagram at different GaN channel layer thicknesses for proposed HEMT

Fig.6 (a) and Fig.6 (b) are the I_{DS}-V_{GS} curves for designed HEMT as a function of Si_3N_4 layer thicknesses under gate and GaN channel layer thicknesses respectively, where the drain voltage is 10 V. From Fig. 6 (a), it is observed that the threshold voltages are 3.94V, 4.79 V and 5.02V as the Si_3N_4 thicknesses are 10 nm, 15 nm and 20 nm. The threshold voltages emerge an ascent trend with the increasing Si_3N_4 thicknesses. The influence of GaN channel layer thickness on the threshold voltage is illustrated in Fig. 6 (b). When GaN channel layer thickness varies from 5nm to 15nm, the threshold voltage decreases form 5.02 V to 4.25 V. As the GaN layer thickness further increases to 25 nm, the threshold voltage is less than 0V. The device degenerates into the depletion mode. This can be interpreted by the band energy diagram at V_{GS}=0 V and V_{DS}=0 V as shown in Fig.6(c). The conduction band energy of AlGaN/GaN interface quantum well is closer to Fermi level with increased channel layer thickness, which makes the more electrons accumulate in the channel layer and causes the HEMT to lose its E-mode.

4. Conclusion

In conclusion, for fail-safe operation in power electronic applications, a high threshold voltage ultra-thin double barrier AlGaN/GaN HEMT with bulk polarization-induced doping p-AlGaN /Si_3N_4 gate has been presented. Meanwhile, the p-type buffer layer was also considered in this structure. In this work, two conventional double barrier HEMTs with n-type buffer and p-type buffer layer are investigated as comparison. The device performance including threshold voltage, gate leakage current, on/off current ratio, sub-threshold slope, cut-off frequency and breakdown voltage show obviously improved, thanks to the high p-type doping density in graded p-AlGaN gate caused by polarization effect, as well as p-type buffer layer and Si_3N_4 layer under gate. Moreover, the influence of Si_3N_4 dielectric layer and GaN channel layer thickness on device performance has also been simulated. With the increased Si_3N_4 thickness, the threshold voltage enhances apparently. In contrast, a drastic decreasing threshold voltage is observed with increased channel layer thickness. The reason is that the conduction band diagram of AlGaN/GaN interface quantum well is closer to Fermi level with increased channel layer thickness. Hence, the more electrons accumulate in the channel layer, leading to a small open voltage.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request..

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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