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Impact of fluorine plasma treatment on AlGaN/GaN high electronic mobility transistors by simulated and experimental results

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ABSTRACT

This paper demonstrates the effect of fluorine plasma treatment on the performance of AlGaN/GaN high electronic mobility transistors. The impact of ion implantation depth on threshold voltage is simulated using the Silvaco software. The simulated results declare that fluorine ions neutralize the positive polarization charge at AlGaN/GaN interface and weaken the polarization electric field. Experimental results confirm that a larger shift of threshold voltage will be achieved at a higher induced fluorine plasma bias voltage, due to the increasing depth of ion implantation. The fluorine plasma treatment is also found to be effective in lowering the gate reverse leakage current and enhance the Schottky barrier height of the metal gate. The influence of fluorine ions on the Schottky barrier height only counts for a small portion of the large shift in threshold voltage.

1. Introduction

Wide bandgap AlGaN/GaN high electron mobility transistors(HEMTs) are emerging as excellent candidates for RF/microwave power amplifiers (PAs) and high-voltage switches, because of their high power handling capabilities [1,2]. Enhancement mode (E-mode) device is highly desirable not only for simplifying the circuit design but also for implementing E/D mode logic [3,4]. A conventional AlGaN/GaN HEMT is commonly operated in depletion mode (D-mode) owing to its high two-dimensional electron gas (2DEG) density induced by inherent polarization effect. However, it is difficult to fabricate enhancement mode AlGaN/GaN HEMTs due to large polarization charges at the heterointerface. A variety of methods have been investigated to enable enhancement mode operation in III-nitride transistors, including recessed-gate structures [5], fluorine-based plasma treatment in the gate region [6,7], and P-type gate injection designs [8]. Fluorine (F) plasma ion implantation is a robust approach to achieving post-epitaxy threshold voltage modulation in AlGaN/GaN high electron mobility transistors [9]. Although it is believed that the incorporated fluorine ions from the plasma play a role in affecting the device performances by modifying band bending, the exact reasons have not yet been completely understood. Grasping exact reasons would likely provide helpful information on the optimization of the process parameters such as the plasma power, plasma treatment time and annealing temperature.

In this paper, a physically-based TCAD simulation tool from Silvaco called ATLAS is used to conduct simulation of fluorine plasma ion implantation in AlGaN layer. The effect of the implantation depth in AlGaN layer on threshold voltage is discussed. We report our study on the carrier transport properties of AlGaN/GaN HEMTs treated with different induced fluorine plasma bias voltages, which has a relationship to fluorine plasma ion implantation power. Schottky contact characteristics of fluorine plasma treatment HEMTs are also investigated.

2. Simulation

The substrate structure under simulation is schematically shown in Fig. 1. The layer sequence is, from top to bottom, metal/n-AlGaN /n-GaN with a 2-DEG formed at the AlGaN/GaN interface. The thickness of the AlGaN and GaN layer are 23 nm and 3 μm, respectively. The background doping for all materials is 1×10^{15} cm^{-3}. These two polarization effects are quite important in nitride-based HEMTs. The difference in piezoelectric and spontaneous polarization between AlGaN and GaN layer determines a fixed 2-D charge density at the interface between the two materials. Polarization difference induces a positive charge at the AlGaN and GaN interface. Electrons are attracted by this positive charge. The electrons accumulate at the interface and form a conductive channel. To simulate the polarization field in the AlGaN layer, a positive charge layer at the two layers interface and an equal amount of negative charge on the surface of the AlGaN layer are used. The density of areal polarization charge in the AlGaN layer is as high as 1.51×10^{13} cm^{-2}. We propose surface donor-like traps are the source of the electrons in the channel, and the electrons are driven into the channel by the strong polarization field [10]. This charge distribution model is used in our simulations along with single-level surface traps.

Most fluorine ions are incorporated into the sample surface and AlGaN barrier layer. The plasma treatment can effectively implant F

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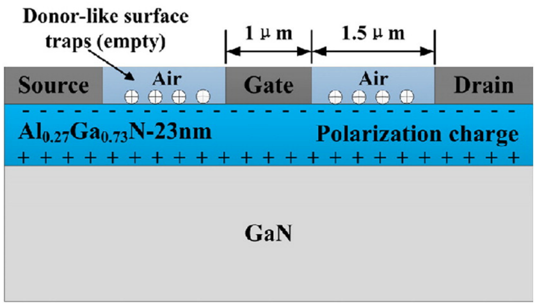

Fig. 1. Cross-sections of AlGaN/GaN HEMT with some physical and geometrical parameters used in simulation.

ions into the AlGaN barrier layer and deplete the electrons in the 2DEG channel, which leads to a change in the threshold voltage of the HEMT. The fluorine ions have a strong electronegativity and are negatively charged. To simulate the effect of the implanted Fluorine ions, negative charge was added inside the AlGaN layer [11]. So the strategy is as following: three structures are simulated, one with negative charges introduced at the AlGaN surface, in the AlGaN barrier layer and another with negative charges at the AlGaN and GaN layers interface. A uniform negative charge concentration (yielding a sheet density of $7 \times 10^{12}/cm^2$) in all structures is used in the simulation for the purpose of simple illustration.

The three simulated devices, shown in Fig. 2, share the same structure, physical parameters and concentration of fluorine ions except for the location of fluorine ions. Fig. 3 shows the DC current–voltage (I–V) transfer characteristics of the conventional normally-on HEMT and

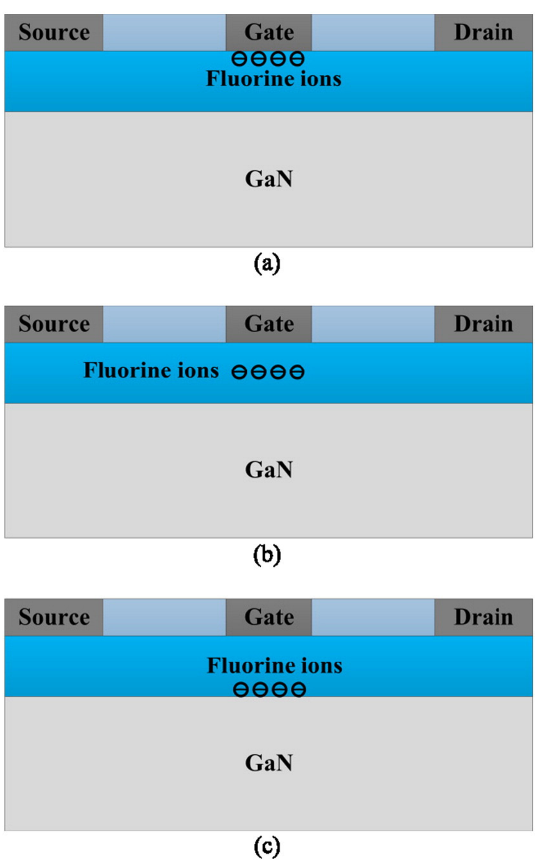

Fig. 2. Simulated schematic cross-sections of AlGaN/GaN HEMT with fluorine ions incorporated directly under the gate: (a) HEMT with fluorine ions at AlGaN surface (b) HEMT with fluorine ions in AlGaN barrier layer (c) HEMT with fluorine ions at AlGaN/GaN interface.

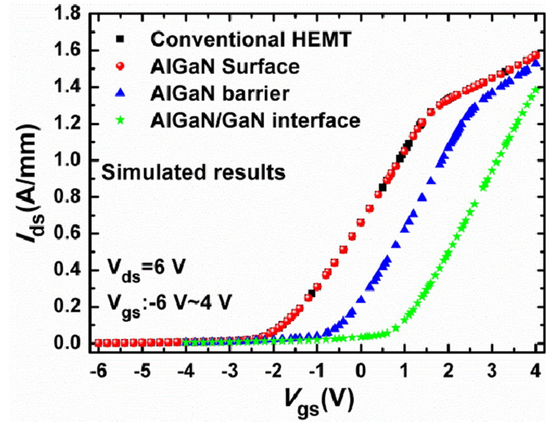

Fig. 3. The simulated transfer characteristics (I_{ds} versus V_{gs}) of the conventional HEMT and HEMT with fluorine ions at different position in AlGaN layer.

fluorine implanted HEMT in AlGaN with fluorine ions at different positions. It is obvious that fluorine ions at AlGaN surface have little effect on threshold voltage. What is more, the closer the fluorine ions are to the AlGaN/GaN interface, the larger is the shift in threshold voltage.

Fig. 3 suggests that these fluorine ions with strong electronegativity act as immobile negative charges neutralize the positive polarization charge at AlGaN/GaN interface. These fluoride ions decrease the concentration of polarization charge, which weakens the electric field induced by the interface charge. We also simulate the conduction-band profiles of AlGaN/GaN HEMT structures with and without fluorine plasma treatment at zero bias, shown in Fig. 4. The fluorine ions cause upward conduction band bending in AlGaN barrier layer due to electrostatic induction effect.

3. Experiment

The AlGaN/GaN HEMT structure used in this paper was grown on a (0001) sapphire substrate by metal–organic chemical vapor deposition (MOCVD). The AlGaN/GaN heterojunction consists of an AlN nuclear layer, a 1.3-μm-thick unintentionally doped GaN buffer layer, and a 23-nm-thick undoped $Al_{0.3}Ga_{0.7}N$ barrier layer, with a 1-nm-thick in-situ growth GaN cap layer. Ohmic contacts consisting of Ti/Al/Ni/Au (20 nm/150 nm/55 nm/45 nm) were annealed in ambient nitrogen at 850 °C for 30 s, with a contact resistance about 0.9 Ω·mm and followed by mesa isolation. Then, surface passivation was carried out by depositing about 60-nm Si_3N_4 through the plasma enhanced chemical vapor deposition (PECVD). After 1-μm-long gate windows were opened by stepper photolithography, the samples were treated by CHF_3 plasma

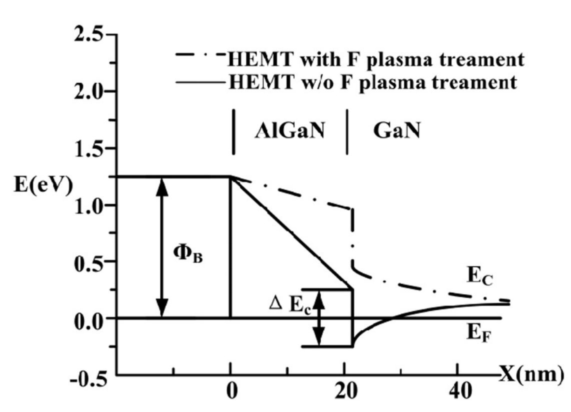

Fig. 4. Simulated conduction-band diagrams of AlGaN/GaN HEMT with and without Fluorine plasma treatment.