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Design and simulation of reverse-blocking Schottky-drain AlN/AlGaN HEMTs with drain field plate

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Abstract In this paper, Schottky-drain reverse-blocking AlN/AlGaN HEMTs with drain field plate (FP) have been investigated by Silvaco-ATLAS tools. For HEMTs without FP, with the increase of Al mole fraction in AlGaN channel from 0 to 0.5, the reverse-blocking voltage increases from −158 V to −720 V. By using the drain field plate technique, a second electric field peak is introduced and the reverse-blocking voltage can be improved. Combined with the optimization of the SiN passivation thickness, optimal electric field management can be achieved to obtain the highest reverse-blocking voltage devices. Since HEMTs with different Al mole fractions possess different critical electric field values, the optimal SiN thickness are varied. With the increase of the Al mole fraction from 0 to 0.5, the reverse-blocking voltage increases from −510 V to −4500 V for HEMTs using drain FP and optimal SiN passivation thickness, and a high power figure-of-merit of 1.171 GW/cm^2 is achieved. AlGaN channel HEMTs with Al mole fraction demonstrate great potential for power applications.

Keywords reverse-blocking voltage, AlN/AlGaN HEMTs, Schottky-drain, field plate, optimal passivation thickness

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1 Introduction

AlGaN/GaN HEMTs are considered as promising candidates for power and high frequency applications owing to high critical breakdown electric field, high switching frequency and high saturation velocity [1–3]. Devices with reverse-blocking capability are essential for many power applications [4]. In order to obtain reverse-blocking capability, Schottky-drain technique is used by integrating a Schottky barrier diode into the drain [4, 5]. Bahat-Treidel et al. [6] first presented an AlGaN/GaN HEMT with a recessed Schottky-drainprotection diode and achieved a reverse-blocking voltage (V_{RB}) of more than −110 V. For future power applications, we need to further improve the forward and reverse-blocking voltage, it has been demonstrated that several approaches are effective, such as using field plate (FP) technique [7–9], using AlGaN channel [10], and doping the buffer [11]. A V_{RB} of −656 V was achieved in a double-channel MOS-HEMT by using Schottky drain combined with drain field plate [12]. Ma et al. [13] reported a MOS-HEMT using a hybrid tri-anode Schottky drain and high V_{RB} of −900 V was obtained. In 2019, an extremely high reverse-blocking voltage of more than −3000 V HEMTs was proposed by using field plate

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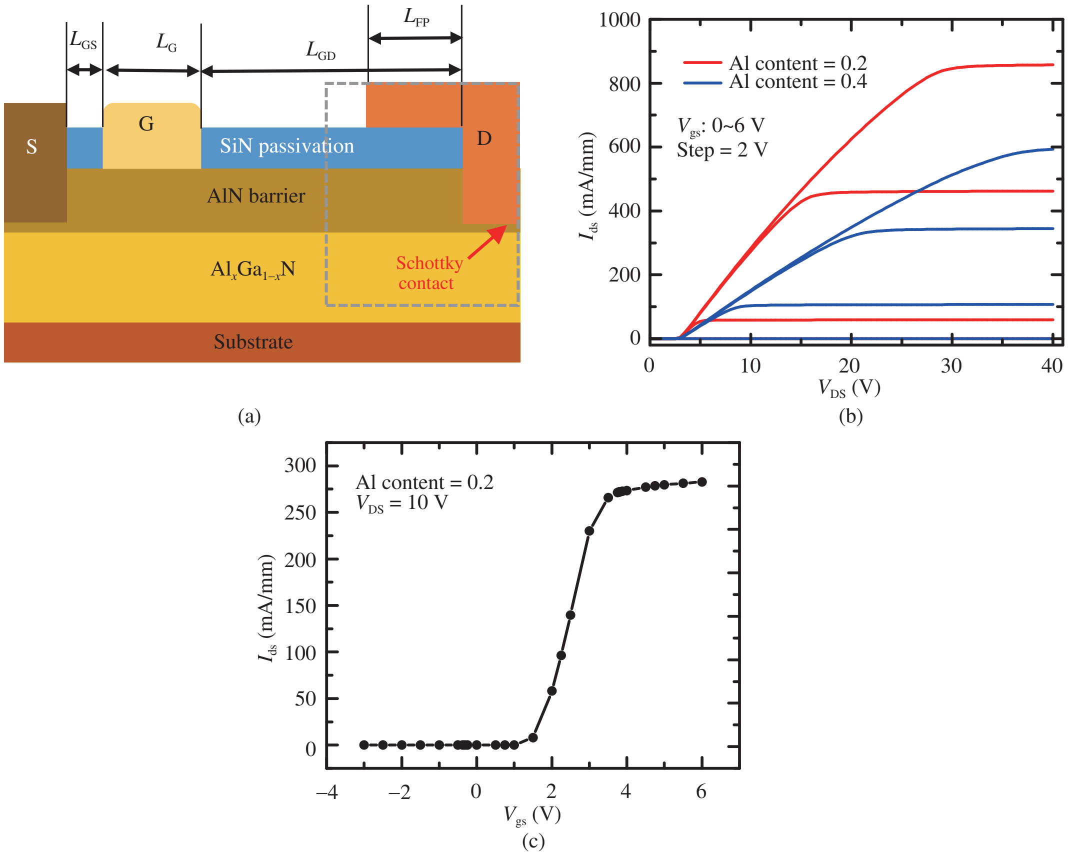


(a)

(b)

(c)

Figure 1 (Color online) (a) Device structure of Schottky-drain AlN/AlGaN HEMT with drain field plate, (b) output characteristics for HEMTs with 0.2 and 0.4 Al mole fractions in AlGaN and (c) transfer characteristics for HEMTs with 0.2 Al mole fraction in AlGaN.

protected Schottky drain and AlGaN channel, and high power figure-of-merit of more than 230 MW/cm^2 was obtained [1].

Wider bandgap materials possess a higher critical electric breakdown field, and the critical electric breakdown field of AlN is about 12 MV/cm, which is much higher than 3.3 MV/cm of GaN materials [10]. Therefore, AlGaN channel with higher Al mole fraction possesses higher electric breakdown field. Previous research of reverse-blocking AlGaN channel devices focused on low Al mole fraction of 10%, and so far reverse-blocking AlGaN channel devices with high Al mole fraction have not been reported. In order to further improve reverse-blocking characteristics, it is essential to carry out research on reverse-blocking AlGaN channel devices with different Al mole fractions.

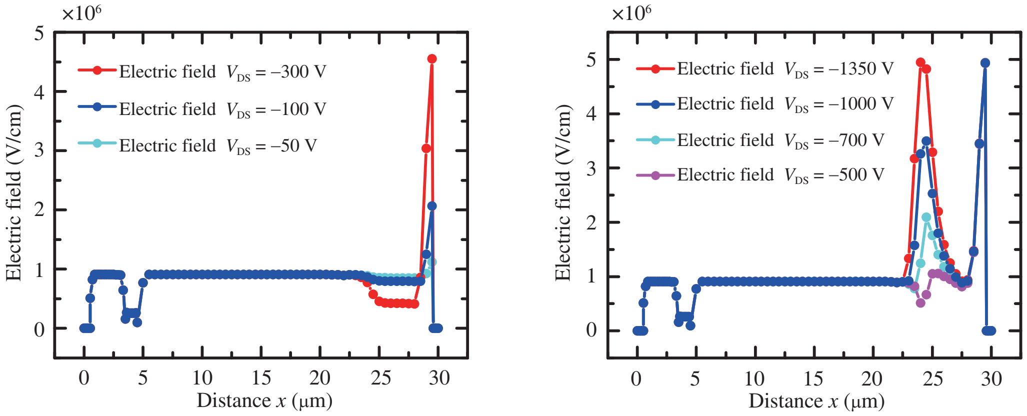
In this work, we propose a Schottky-Drain AlN/AlGaN HEMTs with drain field plate, and extremely high reverse-blocking voltage has been achieved by simulation. The electric field strength at the drain edge is effectively reduced owing to a second electric field peak introduced by drain FP at the drain FP edge [14], leading to higher breakdown voltage. In addition, the influence of passivation thickness on electric field distributions has been investigated. Combined with drain field plate technique and optimal passivation thickness, the high reverse-blocking voltage of -4500 V is achieved for the Al mole fraction of 0.5. For the proposed HEMTs with gate-drain distance of 25 μm, the specific on-resistance Ron is 17.29 m$\Omega \cdot$cm^2 for 0.5 Al mole fraction in AlGaN channel, and super high power figure-of-merit FOM of 1.171 GW/cm^2 is obtained by simulation.

2 Device structure

Figure 1(a) shows the proposed Schottky-drain AlN/AlGaN HEMTs with drain field plate. The devices have a gate length (L_G) of 1 μm, source to gate distance (L_{GS}) of 3 μm, gate to drain distance (L_{GD}) of 25 μm, and drain field plate length (L_{FP}) of 5.5 μm. The thicknesses of AlN barrier and SiN passivation are varied. The drain electrode contacts the AlN barrier, AlGaN channel and the 2DEG to form

Table 1 The thickness of AlN barrier with different Al mole fractions in AlGaN channel

Al mole fraction in AlGaN	AlN barrier thickness (nm)
0	2.5
0.1	3
0.2	3.5
0.3	4.5
0.4	6
0.5	8



(a)

(b)

Figure 2 (Color online) Electric field distributions of Shottky-drain AlN/$Al_{0.2}Ga_{0.8}N$ HEMTs with different drain voltages. (a) Drain voltage below the certain value and (b) drain voltage above the certain value. The certain value is the drain voltage when FP edge electric field peak appears.

Schottky contacts and the equivalent Schottky barrier height for HEMTs with 0.2 Al mole fraction is about 1.6 eV, which is extracted from the output characteristics. Growing AlN layers on low Al mole fraction AlGaN layers is difficult owing to large tensile strain, and the lattice mismatch between GaN and AlN is about 2.4% [15]. Smorchkova et al. [15] reported MBE grown AlN/GaN structures utilizing extremely thin (24Å∼50Å) AlN layers, and achieved high electron sheet densities from 1.51×10^{13} cm^{-2} to 3.65×10^{13} cm^{-2}. Li et al. [16] reported $Al_{0.72}Ga_{0.28}N$/GaN HEMT with a total barrier thickness of 4.5 nm (4 nm AlGaN barrier and 0.5 nm AlN interlayer), and the high mobility has reached up to 1350 cm^2/Vs at room temperature. In addition, they also grow a sample with a barrier thickness of 10 nm, and there were no evident cracks observed. The thickness of the barrier cannot be too thin in order to keep high 2DEG density. According to the analysis above, we set the thickness of AlN barrier as Table 1 shows. Figure 1(b) shows the output characteristics of HEMTs with 0.2 and 0.4 Al mole fractions in AlGaN. The maximum I_{ds} of AlN/AlGaN HEMT with 0.2 Al mole fraction is 462 mA/mm for V_{gs} = 4 V, which is higher than 345 mA/mm of HEMT with 0.4 Al mole fraction, and that may be due to the decrease of 2DEG density. Figure 1(c) shows a normally-on HEMTs for 0.2 Al mole fractions with 1 V threshold voltage (V_{th}, defined at I_{ds} = 0.1 mA/mm), which results from the high work function of the gate metal (5.65 eV, Pt) and thin barrier layer thickness.

The device characteristics are analyzed by Silvaco TCAD tools. Physical models such as Selberherr's Impact Ionization Model, Shockley-Read-Hall, field dependent mobility, spontaneous polarizations and Auger recombination are applied. Owing to the increasing alloy scattering, the 2DEG mobility would decrease with the increase of Al mole fraction in AlGaN channel, and we set the mobility value as in [17]. In addition, deep energy level traps are introduced in the buffer layer, the energy level of the deep acceptor is Ec-0.8 eV (Ec is the conduction band energy level of AlGaN), and the trap destiny is 1×10^{17} cm^{-3}. The energy level of the deep donor is Ec-0.75 eV and the trap destiny is 2×10^{17} cm^{-3}.

3 Simulation results and analysis

The dynamic change process of the electric field peaks is simulated and the electric field value is extracted at 1 nm below the AlN/AlGaN interface. As shown in Figure 2, we can conclude that there is only one

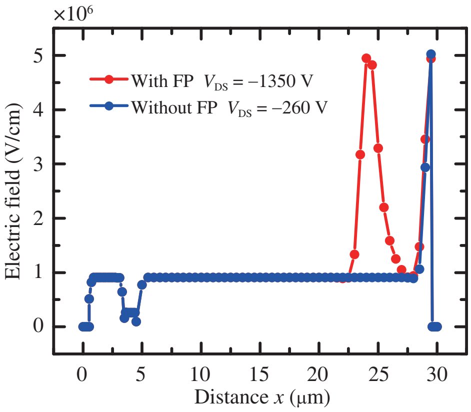


Figure 3 (Color online) Optimal electric field distributions of Schottky-drain AlN/Al$_{0.2}$Ga$_{0.8}$N HEMTs with/without FP.

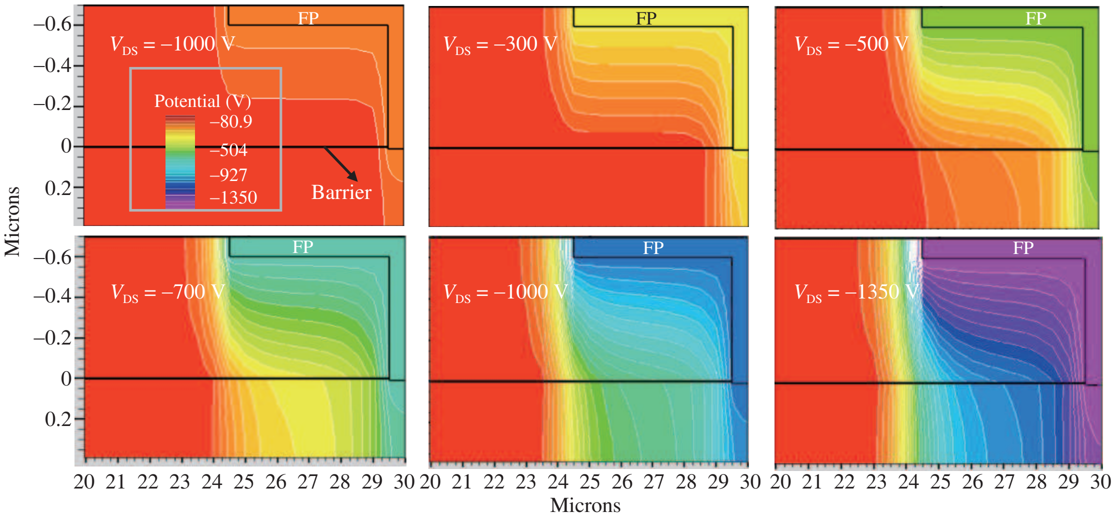


Figure 4 (Color online) Potential line distributions of Schottky-drain AlN/Al$_{0.2}$Ga$_{0.8}$N HEMTs with different drain voltages: (a) $V_{\rm DS} = -100$ V, (b) $V_{\rm DS} = -300$ V, (c) $V_{\rm DS} = -500$ V, (d) $V_{\rm DS} = -700$ V, (e) $V_{\rm DS} = -1000$ V, (f) $V_{\rm DS} = -1350$ V.

electric field peak when the drain voltage is low, and the electric field strength will increase with the increase of the drain voltage. As the drain voltage keeps rising, the second electric field peak appears at the drain FP edge and increases with the increase of the drain voltage. However, the drain edge electric field strength remains unchanged since the second electric field peak appears. When the drain electric field peak and drain FP electric peak reach the critical electric field simultaneously, the reverse-blocking voltage is the highest (the reverse-blocking voltage was defined as the drain voltage at which the electric field peak reaches the critical electric field of AlGaN channel). Figure 3 shows the optimal electric field distributions of AlN/Al$_{0.2}$Ga$_{0.8}$N HEMTs with/without drain FP.

Figure 4 shows the potential line distributions of the device in the dashed-line-square area in Figure 1(a). The potential line is pointing from the positive charge in the depletion region to the drain and FP edge. When the drain voltage becomes more negative, the depletion region will be expanded and some potential lines will start from the expanded area to the FP edge, which introduces a second electric field peak at the FP edge. Meanwhile, the potential line density at the drain edge keeps unchanged after the second electric field peak appears, which confirms the unchanged drain edge electric field strength in Figure 2(b).

Figure 5 shows the electron concentration distributions of Schottky-drain AlN/Al$_{0.2}$Ga$_{0.8}$N HEMTs with/without FP. It can be observed that the drain side depletion region is expanded using drain FP, which can suppress the reverse leakage current and thus leads to improvement of reverse-blocking voltage.

Simulations on potential line distributions have been done to investigate the influence of the passivation thickness on the drain edge electric field. As shown in Figure 6(a) and (b), for a given FP length and drain voltage, more potential lines will concentrate at the FP edge for HEMT with a thinner passivation

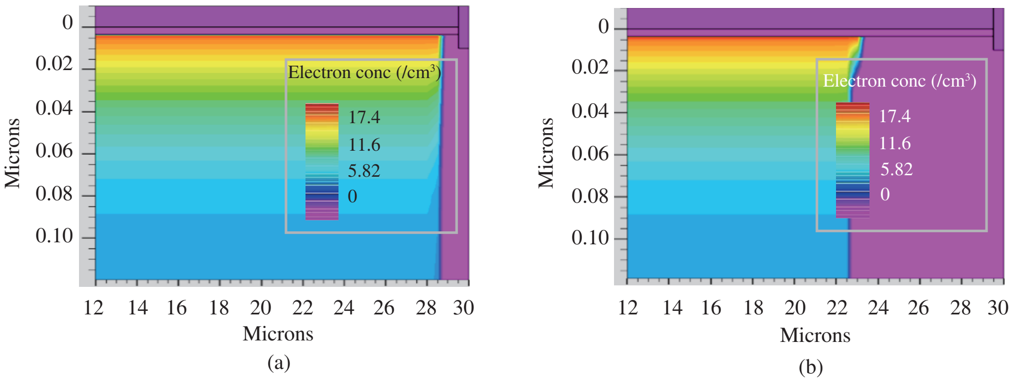


Figure 5 (Color online) Logarithmic electron concentration distributions of Schottky-drain AlN/$Al_{0.2}Ga_{0.8}N$ HEMTs (a) without and (b) with drain FP.

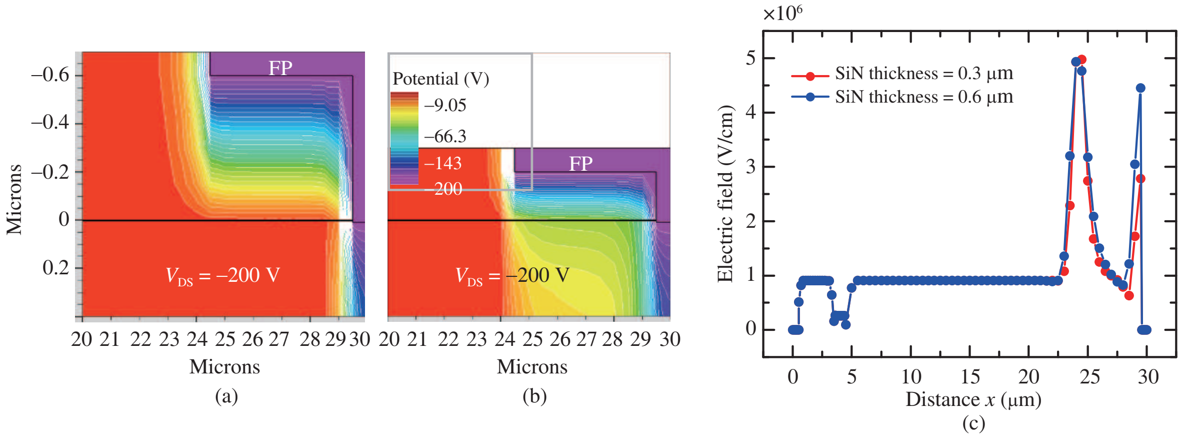


Figure 6 (Color online) Potential line distributions of Schottky-drain AlN/$Al_{0.2}Ga_{0.8}N$ HEMTs with (a) passivation thickness = 0.6 μm and (b) passivation thickness = 0.2 μm at $V_{DS} = -200$ V and (c) electric field distributions when breakdown occurs for 0.2 Al mole fraction in AlGaN with 0.3 μm and 0.6 μm SiN thickness.

thickness, which results in a smaller drain edge electric field. And combined with the phenomenon in Figures 2(b) and 4, we can conclude that there exists a maximum drain edge electric field (E_{dmax}) for a given FP length and passivation thickness, and E_{dmax} will increase with the increase of the passivation thickness. Figure 6(c) shows the electric field distributions of AlN/$Al_{0.2}Ga_{0.8}N$ HEMTs when breakdown occurs for SiN thickness of 0.3 μm and 0.6 μm, which can further verify the rule that E_{dmax} will increase with the increase of the passivation thickness.

The influence of the passivation thickness on E_{dmax} has been shown in Figure 7. E_{dmax} will increase with the increase of the passivation thickness, so there exists a passivation thickness where E_{dmax} can reach the critical value. For a given FP length, the optimal electric field management is the situation where two electric field peaks reach the critical electric field simultaneously. Since FP edge electric field will increase with the increase of the drain voltage, the optimal electric field can be achieved when E_{dmax} reaches the critical value by optimizing the passivation thickness.

With the increase of Al mole fraction in AlGaN, the critical electric field of AlGaN channel HEMT is increased. Accordingly, the optimal passivation thickness will increase so that E_{dmax} can reach the critical electric field. As shown in Figure 8, the optimal SiN thickness varies from 0.24 μm to 1.77 μm while the Al mole fraction increases from 0 to 0.5.

Figure 9 shows the electric field distributions of Schottky-drain AlN/AlGaN HEMTs with optimal SiN thickness and different Al mole fractions. The electric field peaks at the drain and drain field plate edges are equal, resulting in optimal electric field management and the optimized reverse-blocking voltage. The average breakdown electric field strength is calculated and the results are shown in Figure 10. The average electric field of HEMTs with 0.5 Al mole fraction in AlGaN reaches a fairly high value of 1.8 MV/cm.

As shown in Figure 11, for HEMTs without FP, the reverse-blocking voltage increases from −158 V to −720 V with the increase of the Al mole fraction. With the increase of Al mole fraction for HEMTs

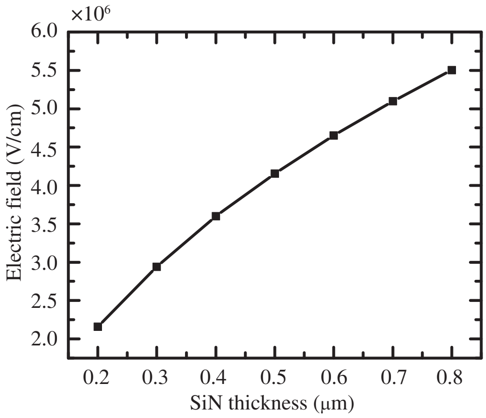


Figure 7 The maximum drain edge electric field with different SiN passivation thickness for 0.2 Al mole fraction in AlGaN.

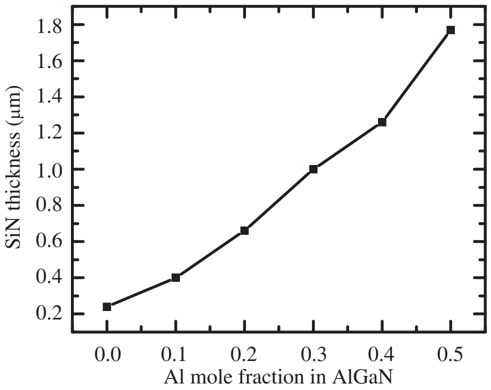


Figure 8 Optimal SiN thickness of Schottky-drain HEMTs with different Al mole fractions in AlGaN.

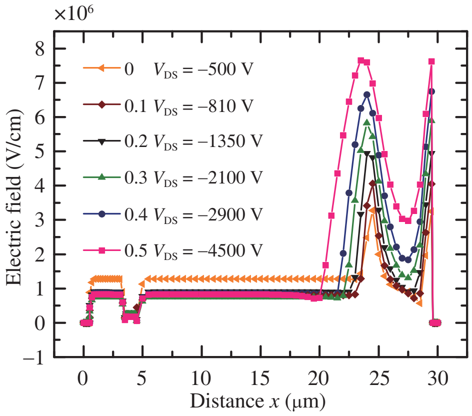


Figure 9 (Color online) Electric field distributions of Schottky-drain AlN/AlGaN HEMTs with optimal SiN thickness and different Al mole fraction.

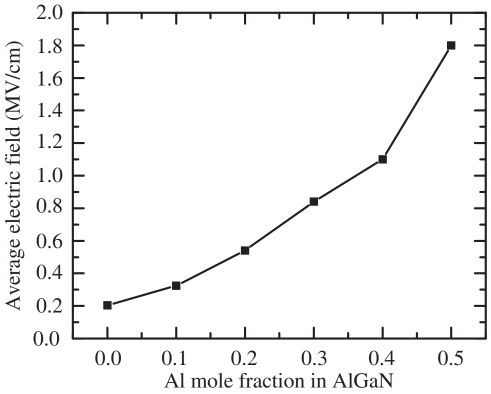


Figure 10 The average electric field strength of HEMTs with different Al mole fractions. L_{GD} = 25 μm.

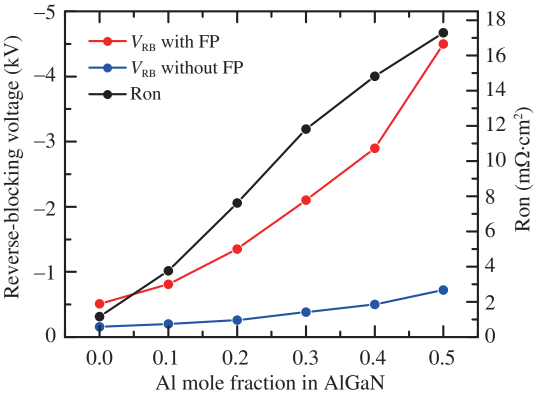


Figure 11 (Color online) Reverse-blocking voltage and Ron of AlN/AlGaN HEMTs with different Al mole fractions.

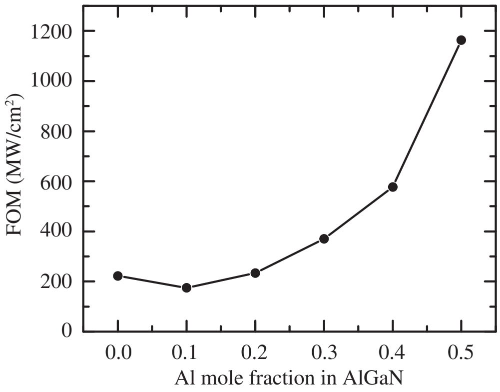


Figure 12 FOM of HEMTs with different Al mole fractions in AlGaN.

with drain FP, the reverse-blocking voltage increases from −510 V to −4500 V, and the specific on-resistance Ron increases from 1.17 to 17.29 $\mathrm{m\Omega \cdot cm^2}$ owing to the reduced electron mobility. Compared to Schottky-drain AlN/GaN HEMTs (0 Al mole fraction in AlGaN), the reverse-blocking voltage improves tremendously for HEMTs with high Al mole fraction in AlGaN channel, especially for HEMTs using FP technique. Power figure-of-merit (FOM) for HEMTs with different Al mole fraction is given in Figure 12, the minimal point appears at 0.1 Al mole fraction owing to the steep decrease of mobility and the slight improvement in breakdown voltage. For HEMTs with 0.5 Al mole fraction in AlGaN, the FOM reaches 1171 MW/cm^2, which is the highest value by simulation. The Al mole fraction can further increase to obtain a higher critical electric field, and much higher breakdown voltage and power FOM can be obtained. In addition, according to the electric field distribution, the area (x: 5–20 μm) with low and unchanged electric field is not well used, which indicates the gate-drain distance can be optimized to reduce specific on-resistance and improve power FOM with the same high reverse-blocking voltage.

4 Conclusion

The influence of Al mole fraction in AlGaN channel and the thickness of SiN passivation under the drain FP on reverse-blocking voltage of Schottky-Drain AlN/AlGaN HEMTs have been investigated. Reverse-blocking capability was obtained by Schottky-drain technique and was further improved by drain FP technique. With the increase of Al mole fraction in AlGaN channel, the critical electric field strength increases, leading to higher breakdown voltage. With the increase of the Al mole fraction from 0 to 0.5, the optimal SiN thickness is increased from 0.24 μm to 1.77 μm, and the reverse-blocking voltage increases from −510 V to −4500 V for Schottky-drain AlN/AlGaN HEMTs with drain FP. Design and simulation results demonstrate that extremely high reverse-blocking voltage can be achieved in high Al mole fraction AlGaN channel HEMTs by using Schottky drain and field plate technology.

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