

Design and Demonstration of High Breakdown Voltage GaN High Electron Mobility Transistor (HEMT) Using Field Plate Structure for Power Electronics Applications

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AlGaN/GaN power high electron mobility transistors (HEMTs) with a breakdown voltage of 600 V are fabricated and demonstrated as switching power devices for motor drive and power supply applications. A high breakdown voltage was realized in the fabricated power-HEMT by the field plate technique and an ultra low on-state resistance of $3.3 \text{ m}\Omega\cdot\text{cm}^2$, which is 20 times lower than the silicon limit, due to the high critical field of the GaN material and the high mobility in a two-dimensional electron gas channel. A device with the double-field plate structure was also designed using two-dimensional device simulation to increase the breakdown voltage without any increase of the GaN layer thickness.

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KEYWORDS: GaN, HEMT, power semiconductor device, high voltage device, field plate

1. Introduction

Power semiconductor switching devices with breakdown voltage of 600 V-class have been studied with a view to reducing the power loss for switching mode power supplies and inverter systems.¹⁾ In the Si power metal-oxide-semiconductor field effect transistor (MOSFET), which is the most popular power-switching device, the on-resistance of 110% of the Si-limit has been realized.²⁾ In addition, superjunction MOSFETs have broken through the Si-limit and achieved the on-resistance of $35 \text{ m}\Omega\cdot\text{cm}^2$ for 600 V class devices.³⁾

For a more significant reduction of the on-resistance, AlGaN/GaN heterostructure devices are attractive due to their high carrier mobility in a two-dimensional electron gas (2DEG) channel and large critical electric field.^{4–6)} Recently, high breakdown voltage AlGaN/GaN devices have been demonstrated and they exhibited an ultra low on-resistance below the Si-limit.^{7–10)}

The relationship between the specific on-resistance and the breakdown voltage becomes the trade-off characteristics. Therefore, the application of the optimized design for high breakdown voltage is highly effective in reducing the on-resistance. In the previous work, high voltage GaN devices were designed with only a minor change of radio frequency HEMT (RF-HEMT)^{7,9)} and thus they were not optimized as high-voltage switching devices.

The field plate (FP) structure is effective for the high breakdown voltage AlGaN/GaN HEMT design because of the following points. 1) No additional doping is required, 2) the fabrication process is compatible with the conventional HEMT process, 3) its effectiveness has been proved using a silicon device and 4) current collapse does not occur.¹¹⁾

In this study, 600 V AlGaN/GaN HEMTs are experimentally demonstrated using the FP structure and the results reveal a sufficient breakdown voltage and an ultra low on-state resistance. A device with the double FP structure was also designed using two-dimensional device simulation to increase the breakdown voltage.

2. Device Structure and Experimental Results

The source FP structure shown in Fig. 1 was employed for high breakdown voltage AlGaN/GaN HEMTs. The field plate is placed over the gate electrode and the edge of the field plate should be closer to the drain than to the gate electrode edge so that the electric field concentration near the gate edge is efficiently eased and the electric field is distributed uniformly between the gate electrode and drain electrode.^{8,11)} In the same figure, the electric field at the interface of AlGaN and GaN layers is compared. In the figure, the electric field is maximum and is the sum of transverse and vertical fields. The electric field with a field plate is distributed between the drain and gate while the electric field without a field plate concentrates near the gate

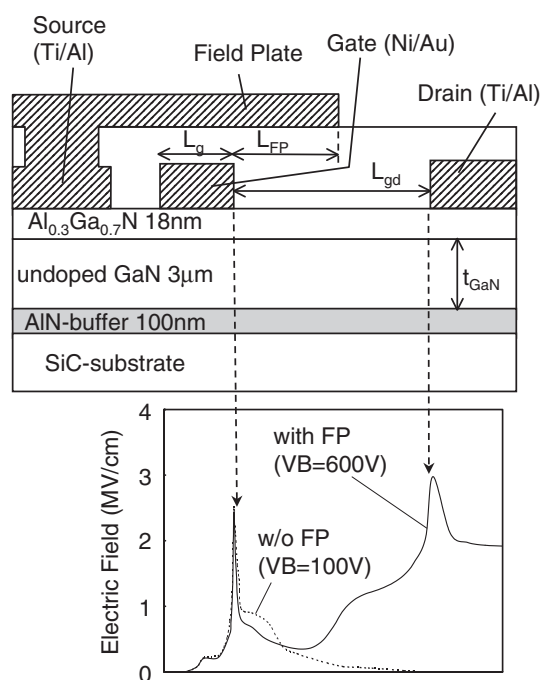


Fig. 1. Cross-sectional structures of fabricated AlGaN/GaN HEMT with field plate structure (FP-HEMT) and electric field distribution along the interface of the AlGaN layer with field plate (solid line) and without field plate (broken line).

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electrode edge.

The AlGaIn/GaN heterostructure was grown on a highly resistive n-type (0001) 4H-SiC substrate by metalorganic chemical vapor deposition (MOCVD). The material growth began with the growth of a 100-nm-thick AlN buffer layer, followed by that of a 3- μm -thick undoped GaN layer as a channel layer. Finally, a 3-nm-thick undoped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ spacer, a 10-nm-thick Si doped ($5 \times 10^{18} \text{ cm}^{-3}$) $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ carrier supply and a 5-nm-thick undoped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ barrier layer were grown.

The device processing consisted of conventional HEMT fabrication steps. After mesa etching by electron cyclotron resonance reactive ion beam etching (ECR-RIBE), a Ti/Al was evaporated and lifted off for source and drain ohmic contacts. The gate electrode was formed with Ni/Au. As passivation films, 360-nm-thick SiN and 600-nm-thick SiO_2 were deposited by CVD. The field plate electrode connected to the source electrode was formed on the SiO_2 passivation layer. The gate length L_g and width W_g were 1.5 μm and 200 μm , respectively. The gate-source length was 1.5 μm . The gate-drain offset length L_{gd} was 5 or 10 μm . The active device areas for $L_{gd} = 5$ and 10 μm devices were 6.93×10^{-5} and $8.27 \times 10^{-5} \text{ cm}^2$, respectively. The active device area does not include the pad area.

The breakdown voltage markedly improved on using the field plate structure. In this case, the breakdown voltage was defined as the drain-source voltage at the drain current of 5 mA/mm. The breakdown voltage was clearly indicated by the hard breakdown I - V curve, which showed the avalanche breakdown. FP-HEMTs with $L_{gd} = 5 \mu\text{m}$ and $L_{FP} = 1.6 \mu\text{m}$ showed the breakdown voltage of 350 V, which is threefold that of the HEMT without the field plate, as shown in Fig. 2. The breakdown voltage was improved to 600 V, as L_{gd} and L_{FP} increased to 10 μm and 5 μm , respectively. The threshold gate voltage was -6 V . The breakdown voltage and the on-resistance were measured at $V_{gs} = -8$ and 0 V, respectively. The substrate was connected to the source during the measurements. The specific on-resistances $R_{ON}A$ of fabricated devices with the breakdown voltages of 350 V and 600 V were 1.9 and 3.3 $\text{m}\Omega\text{cm}^2$, respectively. The trade-off characteristics between the breakdown voltage and the on-resistance were improved by the field plate technique due to increase of the breakdown voltage as shown in Fig. 3. The

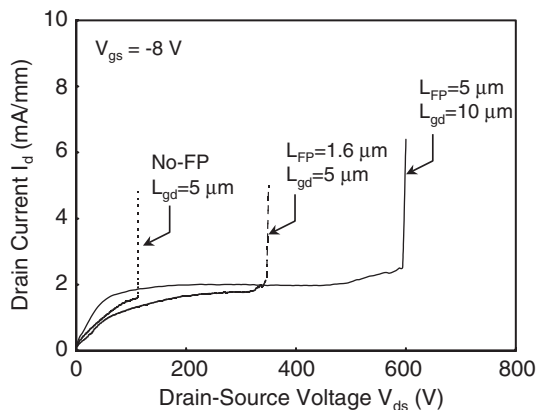


Fig. 2. Off-state I_D - V_{DS} characteristics of AlGaIn/GaN HEMT with field plate structure (FP-HEMT).

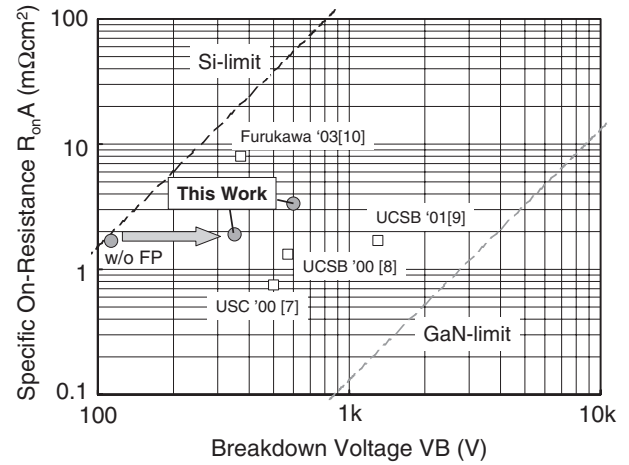


Fig. 3. Trade-off characteristics between specific on-resistance and breakdown voltage of AlGaIn/GaN devices and theoretical Si- and GaN-limits.

on-resistance for the 600 V device is 20 times lower than the silicon limit.

3. Optimized Design of Field Plate Structure

The breakdown voltage can be further improved by the design optimization. The device characteristics were calculated using the device simulator *ISE-DeSSis*.¹²⁾ The avalanche breakdown parameter from ref. 13 was used in the simulation, and the Schottky barrier tunneling was considered for the gate leakage current calculation.

The breakdown voltage can be increased by relaxation of the electric field at the drain electrode, because the breakdown voltage for the FP-HEMT depends on not only the electric field peak at the gate edge but also on the electric field peak under the drain electrode as shown in Fig. 1. The GaN layer thickness t_{GaN} is a very important parameter for the electric field under the drain electrode, since the SiC substrate has the same voltage as the source electrode, and thus the vertical electric field beneath the drain electrode depends on the GaN layer thickness. Figure 4 shows the relationship between the breakdown voltage and the GaN layer thickness t_{GaN} . Up to 6 μm , the breakdown voltage increases with t_{GaN} . This is simply because the SiC substrate is electrically grounded and thus the applied voltage is vertically sustained across the undoped GaN layer between

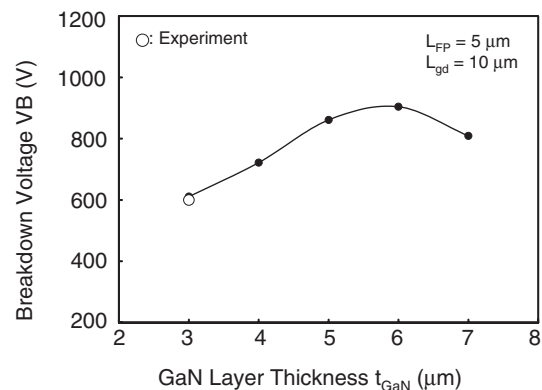


Fig. 4. Simulation results for the relationship between GaN layer thickness and breakdown voltage.

the drain electrode and the SiC substrate. Therefore, the increase of t_{GaN} relaxes the vertical electric field beneath the drain electrode. In the case of an undoped GaN layer thickness of over $6\mu\text{m}$, however, the breakdown voltage decreases, because an increase of the undoped GaN layer thickness decreases the shielding effect of the substrate and thus the breakdown occurs at the gate edge.

These results imply that the optimum undoped GaN layer thickness is approximately equal to the field plate length for both lower and higher voltage device design because the electric potential distribution in the device follows the scaling law on the device dimensions, i.e., the electric field strength does not change with the scaling up or down of device dimensions in proportion to the device blocking voltage.

Although the breakdown voltage can be increased with the GaN layer thickness due to the reduction of the vertical drain electric field, it is difficult to grow a thick GaN layer without cracks and bowing due to the strain between the GaN layer and the substrate. The double field plate (DFP) structure shown in Fig. 5 is very attractive for increasing the breakdown voltage without any increase of the GaN layer thickness. The drain FP is connected to the drain electrode and is placed over the drain electrode, and the edge of the field plate should be closer to the gate than to the drain electrode edge. The drain FP relaxes the electric field at the drain electrode edge, similar to the source FP.

The DFP structure can realize a high breakdown voltage without any of increase of the GaN layer thickness. Figure 6 shows the relationship between the insulator thickness and the breakdown voltage, which was calculated using device

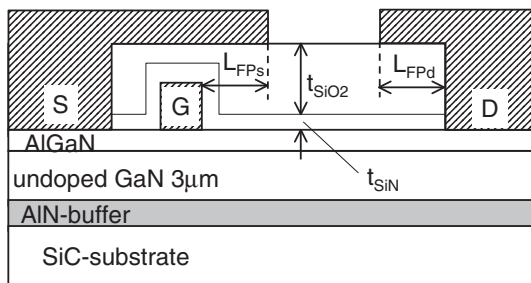


Fig. 5. Cross-sectional structure of double field plate (DFP) AlGaIn/GaN HEMT.

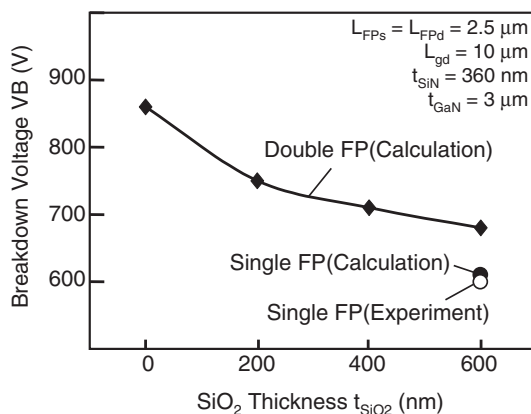


Fig. 6. Simulation results for relationship between SiO_2 thickness and breakdown voltage for DFP-HEMT.

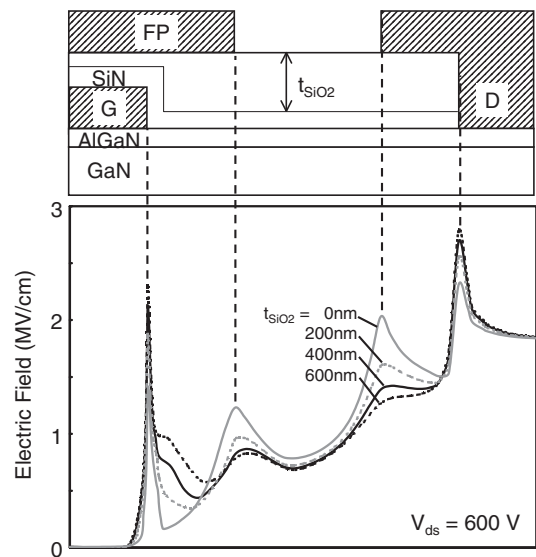


Fig. 7. Electric field distribution between gate and drain electrodes for DFP-HEMT as a function of SiO_2 thickness.

simulator ISE-DESSIS. In the calculation, the drain FP length L_{FPd} is $2.5\mu\text{m}$, which is equal to the source FP length L_{FPs} . This is because the optimized FP length is almost the same as the GaN layer thickness as shown in Fig. 4. The breakdown voltage for DFP-HEMT is 13% (680 V) higher than that of the fabricated single FP-HEMT as shown in Fig. 1, even with the same GaN layer thickness ($t_{\text{GaN}} = 3\mu\text{m}$). In addition, the breakdown voltage increases with decreasing SiO_2 thickness t_{SiO_2} , because the drain electric field peak is weakened with a decrease of the SiO_2 thickness. The breakdown voltage at $t_{\text{SiO}_2} = 0$ is almost the same as the breakdown voltage for the single FP device with a $6\mu\text{m}$ -thick GaN layer. The DFP structure increases the breakdown voltage while maintaining the GaN layer thickness.

The relationship between the breakdown voltage and the SiO_2 thickness is explained in terms of the electric field distribution between the gate and the drain. Figure 7 shows electric field distribution as a function of t_{SiO_2} at $V_{\text{DS}} = 600\text{ V}$. In the figure, the electric field is maximum and is the sum of transverse and vertical fields. The electric field peak at the drain electrode edge relaxed with decreasing SiO_2 thickness, and the electric field peak under the drain FP edge increased due to the spreading of the electric field peak by the drain FP. Since the electric distribution becomes uniform with decreasing SiO_2 thickness, the breakdown voltage is improved.

4. Conclusions

A high breakdown voltage AlGaIn/GaN HEMT with the field plate structure (FP-HEMT) was fabricated. The specific on-resistance was $3.3\text{ m}\Omega\cdot\text{cm}^2$ for the 600 V breakdown voltage FP-HEMT with $L_{\text{FP}} = 5\mu\text{m}$ and $L_{\text{gd}} = 10\mu\text{m}$. It was also found by two-dimensional device simulation that the breakdown voltage can be further increased by the optimization of the undoped GaN layer thickness and the double field plate structure due to relaxation of the electric field at the drain edge. The double field plate structure is highly attractive for increasing the breakdown voltage without any increase of the GaN layer thickness.

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