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Design and Demonstration of High Breakdown Voltage GaN-HEMT using Field Plate Structure for Power Electronics Applications

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1. Introduction

Power semiconductor switching devices with breakdown voltage of several hundred volts have been studied with a view to reducing the power loss for switching mode power supplies and inverter systems [1]. In the Si power MOSFET, which is the most popular power-switching device, the on-resistance of 110% of the Si-limit has been realized [2]. For more drastic reduction of the on-resistance, AlGaN/GaN heterostructure devices are attractive, due to high carrier mobility in 2-dimensional electron gas (2DEG) channel and large critical electric field. Recently, high breakdown voltage AlGaN/GaN devices have been demonstrated and showed the ultra-low on-resistance below the Si-limit [3]-[5]. In the previous work, high voltage GaN devices are designed with only a minor change of RF-HEMT and thus they have not been optimized as high voltage switching devices for power electronics applications.

In this paper, AlGaN/GaN HEMT were experimentally demonstrated for 600V switching power device using single field plate structure. The device with the double field plate structure was also designed using 2D device simulator to increase the breakdown voltage without increase of the GaN layer thickness.

2. Device Structure and Experimental Results

Field plate structure shown in Fig. 1 is employed for high breakdown voltage design for AlGaN/GaN HEMTs. The field plate structure is chosen because of follow reasons. 1) No additional doping is required, 2) fabrication process is compatible to conventional HEMT process, and 3) the effect has been proved by silicon device. The field plate is placed over the gate electrode and the edge of the field plate must be closer to the drain than the gate electrode edge so that the electric field concentration near the gate edge is efficiently eased and the electric field rather uniformly distributes between gate and drain electrodes [4]. The same figure compares the electric field in the interface of AlGaN layer and insulation layer. The electric field with the field plate is distributed between drain and gate while the electric field without field plate concentrates near the gate electrode edge.

The AlGaN/GaN heterostructure was grown on highly resistive n-type (0001) 4H-SiC substrate by MOCVD. The material growth began with a 100 nm-thick AlN buffer layer, followed by 3 μm-thick undoped GaN layer as a channel layer. Finally, a 3 nm-thick undoped $Al_{0.3}Ga_{0.7}N$ spacer, a 10 nm-thick Si doped (5×10^{18} cm^{-3}) $Al_{0.3}Ga_{0.7}N$ carrier supply and a 5 nm-thick undoped $Al_{0.3}Ga_{0.7}N$ barrier layer were grown.

The device processing consisted of conventional HEMT fabrication steps. After mesa etching by ECR-RIBE, a Ti/Al layered metallization was evaporated and lifted off for source and drain ohmic contact. 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 connecting 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 Lgd was 5 or 10 μm. The active device areas for L_{gd} = 5 and 10 μm devices were 6.93×10^{-5} and 8.27×10^{-5} cm^2, respectively.

The breakdown voltage was drastically improved using the field plate structure. FP-HEMTs with L_{gd} = 5 μm and L_{FP} = 1.5 μm showed the breakdown voltage of 350V, which is three times larger than that of the HEMT without the field plate, as shown in Fig. 2. The breakdown voltage

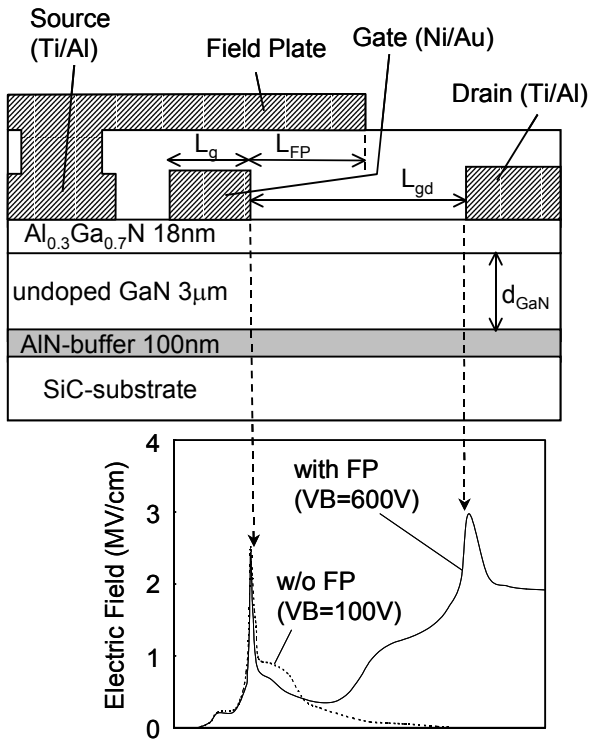

Fig.1 Cross-sectional structures of fabricated AlGaN/GaN HEMT with field plate structure (FP-HEMT) and electric field distribution along the interface of AlGaN layer with field plate (solid line) and without field plate (broken line).

was improved to 600V, 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} of fabricated devices with the breakdown voltage of 350 V and 600 V were 1.9 and 3.3mΩcm^2, respectively. The on-resistance for 600 V device is 20 times smaller than that of conventional Si power MOSFET.

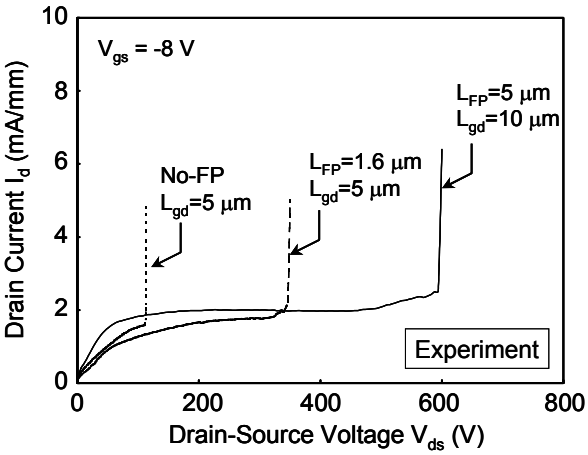

Fig. 2 Off-state I_d-V_{ds} characteristics of AlGaN/GaN HEMT with field plate structure (FP-HEMT).

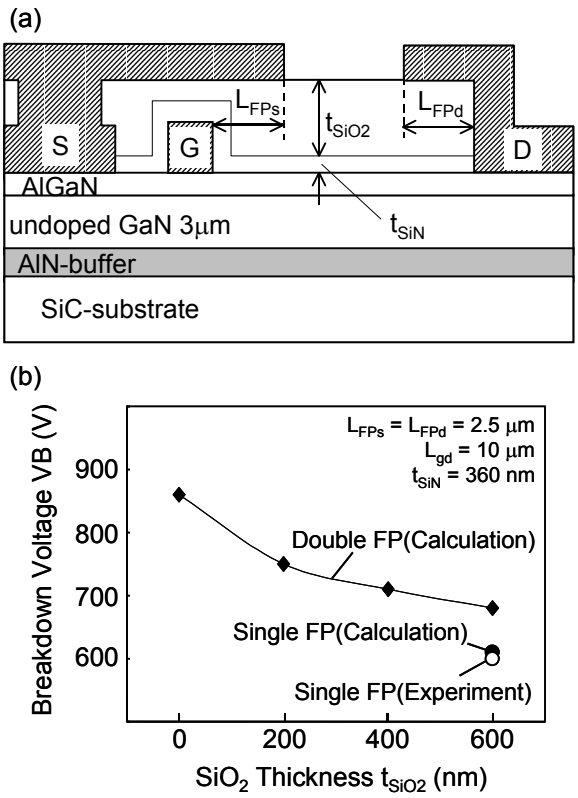

Fig. 3 (a) Cross-sectional structures AlGaN/GaN HEMT with double field plate structure (DFP-HEMT) and (b) calculated relation between SiO_2 thickness and breakdown voltage for DFP-HEMT.

3. Design of Double Field Plate Structure

The double field plate (DFP) structure is very attractive to increase the breakdown voltage. The breakdown voltage strongly depends on the electric filed at the drain electrode edge as shown in Fig.1. Therefore the breakdown voltage increases by relaxation of the drain electric field peak. Although the breakdown voltage is increased by increase of the GaN layer thickness due to reduction of vertical drain electric field, it is difficult to grow thick GaN layer without crack and bowing due to strain between the GaN layer and the substrate.

The DFP structure as shown in Fig. 3(a) can be realized high breakdown voltage without increase of GaN layer thickness. Figure 3(b) shows relation between the insulator thickness and the breakdown voltage, which was calculated using device simulator ISE-Dessis. The breakdown voltage for DFP-HEMT is 13% (680V) higher than that of the fabricated single FP-HEMT even with same GaN layer thickness. In addition, the breakdown voltage increases with decreasing of the SiO_2 thickness due to relaxation of the drain electric field peak. The breakdown voltage at t_{SiO2}=0 is almost same as the breakdown voltage for the device with 6μm-thick GaN layer. The DFP structure can be increased the breakdown voltage maintaining the GaN layer thickness.

4. Conclusions

The high breakdown voltage AlGaN/GaN HEMT with the field plate structure was fabricated. The specific on-resistance was 3.3 mΩcm^2 for the 600V breakdown voltage FP-HEMT with L_{FP} = 5 μm and L_{gd} = 10 μm. It is also found by 2D device simulation that the double field plate structure is very attractive to increase the breakdown voltage without thick GaN layer.

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