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Improved breakdown voltage of AlGaN/GaN HEMTs grown on Si substrates using partially Mg-doped GaN buffer layer by MOCVD

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AlGaN/GaN high electron mobility transistors (HEMTs) were grown on Si substrates by MOCVD. In the HEMT structure, a 1 μm GaN buffer layer was partially doped with Mg in an attempt to increase the resistivity and minimize the buffer leakage. The AlGaN/GaN HEMTs grown on undoped and partially Mg-doped GaN buffer layers were processed and the DC characteristics of the devices were characterized for comparing the effect of Mg doping. For the device with the partially Mg-doped GaN buffer layer, a lower drain leakage current density of 55.8 nA/mm, a lower gate leakage current density of 2.73 μA/mm, and a higher off-state breakdown voltage of 104 V were achieved with device dimensions $L_g/W_g/L_{gs}/L_{gd}$=1/10/1/1 μm, better than the device with the undoped GaN buffer layer, which has a higher drain leakage current density of 9.2 μA/mm, a higher gate leakage current density of 91.8 μA/mm, and a lower off-state breakdown voltage of 87 V with the same device dimensions.

AlGaN/GaN HEMT, Si substrate, MOCVD, breakdown voltage, Mg-doped

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1 Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) grown on Si substrates are very promising in commercial applications of RF power devices and high-breakdown switchers [1,2], with the combined advantages of high breakdown field of the GaN-based materials, and high thermal conductivity and potential low manufacturing cost of the Si substrates. Compared with those on SiC or sapphire substrates, the AlGaN/GaN HEMTs grown on Si substrates suffer from poorer crystalline quality, smaller critical-layer thickness and higher buffer leakage current density, which limit their applications.

In order to improve breakdown voltage of the HEMT devices, low background electron concentration and high resistivity in the buffer layer are needed for HEMT growth. High resistivity in the GaN buffer layer can prevent the parallel conductivity, reduce the buffer leakage current, improve the breakdown voltage, and lower the parasitic loss at high frequencies and cross-talk between adjacent devices.

The high-resistivity GaN buffer layer grown on sapphire substrate has been achieved by compensating the donors with acceptor states [3–6]. However, GaN grown on the Si substrate will inevitably generate a large diffusion of silicon directly from the substrate into the GaN buffer layer. As a result, the unintentionally doped continuous GaN buffer layer grown on the Si substrate shows much lower resistivity than on the sapphire substrate. Up to date, the approach on increasing the resistivity of GaN grown on the Si substrate has rarely been reported.

In this work, a 1 μm GaN buffer layer with partially Mg-doped was calibrated to increase the resistivity of the GaN buffer layer. For the 1 μm GaN buffer layer, the bot-

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*Corresponding author (email: eeywang@gmail.com) tom 125 nm layer was Mg-doped to compensate the residual donors, and the top 875 nm layer was unintentionally doped to decrease the scattering from the Mg dopant. The AlGaN/GaN HEMTs were grown on the undoped and partially Mg-doped GaN buffer layers and the HEMT devices were processed and characterized for comparing the effect of Mg doping.

2 Experiment

The AlGaN/GaN HEMTs were grown on Si (111) substrates by low-pressure MOCVD in an Aixtron 2000HT system. Trimethylgallium (TMGa), trimethylaluminum (TMAl), trimethylindim (TMIn) and ammonia (NH_3) were used as the Ga, Al, In and N precursors, respectively. Biscyclopentadienyl magnesium (Cp_2Mg) and silane (SiH_4) were used as the p- and n-type doping sources. H_2 or N_2 serves as the carrier gas.

The 2-inch Si (111) substrates with high resistivity of more than 3000 Ω-cm and thickness of 280 μm were chosen. Before the Si substrates were loaded into the growth chamber of the MOCVD system, they were cleaned by the standard cleaning process of Radio Corporation of America (RCA).

Prior to growth, the substrates were heated up to 1190°C for 10 min under the H_2 ambience to remove the native oxide on the surfaces of the Si substrates. Then about 40 nm AlN nucleation layer was grown at 1150°C for initiation of the GaN growth on the Si (111) substrates, followed by a SiN_X mask layer grown at 1160°C on top of the AlN nucleation layer. Then a 0.8 μm undoped GaN transition layer was grown at 1170°C by vertical growth on the exposed AlN nucleation layer and by lateral overgrowth on the SiN_X mask layer. Afterwards, a stacked AlGaN/AlN interlayer was grown on the 0.8 μm GaN transition layer to further reduce the tensile stress, with a growth temperature of 950°C for AlN and 1150°C for AlGaN. Subsequently, a continuous 1 μm GaN buffer layer was grown at 1170°C on the AlGaN/AlN interlayer. Finally the HEMT structure was grown on top of the continuous 1 μm GaN buffer layer. The whole structure of the AlGaN/GaN HEMT on Si (111) substrate is shown in Figure 1.

3 Results and discussion

Figure 2(a) and (b) show the AFM images of the AlGaN/GaN HEMT (a) with and (b) without partially Mg-doped. According to the AFM images, the surface RMS roughness of Samples (a) and (b) is 1.1 nm and 1.2 nm, respectively. The smaller RMS of Sample (a) than that of Sample (b) indicates that the GaN buffer layer with partially Mg-doped may help to improve the sample surface morphology.

The mercury-probe capacitance-voltage system was employed to characterize the properties of 2DEG in the AlGaN/GaN HEMTs. The profiles of capacitance versus voltage (*C*-*V*) and concentration versus thickness (*n*-*d*) are shown in Figures 3 and 4. According to the *C*-*V* measure-

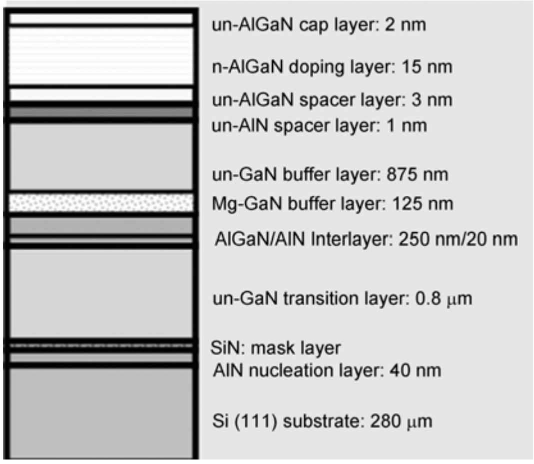

Figure 1 Whole structure of AlGaN/GaN HEMT on Si (111) substrate.

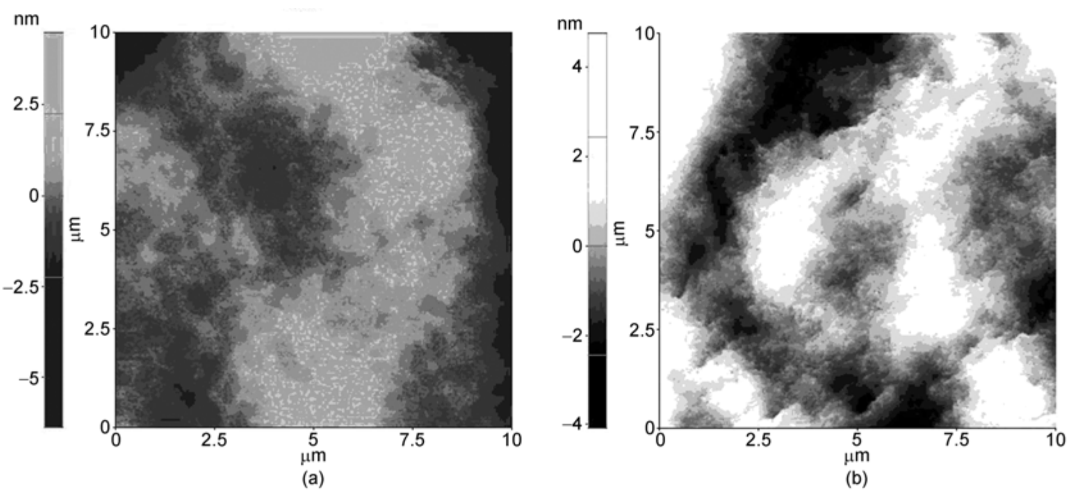

Figure 2 AFM images of Samples (a) and (b). (a) With partially Mg-doped: RMS=1.1 nm; (b) without Mg-doped: RMS=1.2 nm.

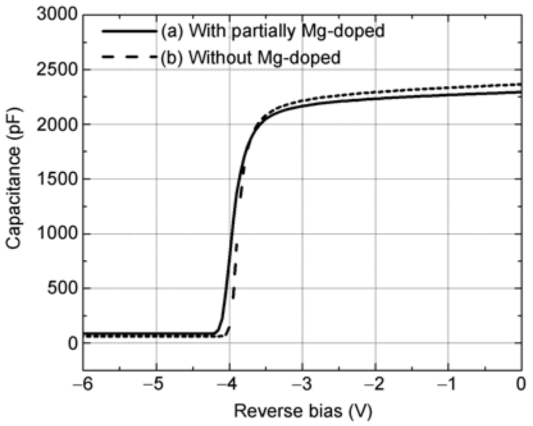

Figure 3 Mercury-probe *C-V* profiles of Sample (a) and (b).

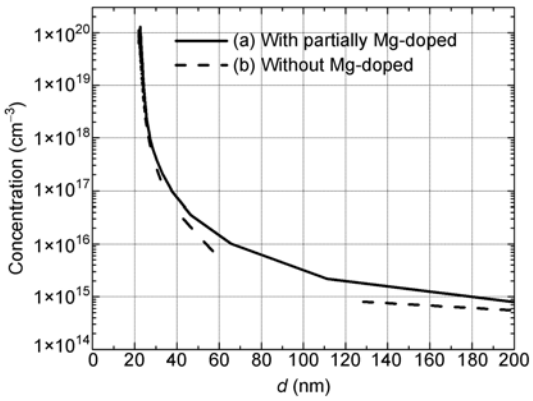

Figure 4 2DEG profiles of Sample (a) and (b).

ment, the pinch-off voltages are −4.0 V and −3.9 V, and the 2DEG concentration peaks are located at 22.5 nm and 21.8 nm for Samples (a) and (b), respectively. It indicates that basically a same HEMT structure for Samples (a) and (b) is achieved, so that both Samples (a) and (b) have the same 2DEG concentration, about 8×10^{19} cm^{-3}.

The 2DEG density and mobility of the AlGaN/GaN sample (7 mm×7 mm) were characterized at room temperature (RT) by the van der Pauw Hall measurement. The ohmic contact was prepared using the e-beam evaporated Ti/Al/Ni/Au, followed by annealing at 850°C for 30 s under N_2 ambient. Table 1 shows the comparison of RT Hall results between Samples (a) with and (b) without partially Mg-doped. According to the Hall results, Sample (a) with partially Mg-doped shows a little lower mobility and higher R_s than Sample (b) without Mg-doped, which indicates that Mg doping in the GaN buffer layer inevitably introduces impurity scattering and therefore reduces the mobility in the 2DEG.

Table 1 Comparison of RT Hall results of Samples (a) and (b)

Samples	R_s (ohm/sq)	M_{ob} (cm^2/V s)	N_s ($\times10^{13}$ cm^{-2})
(a) With partially Mg-doped	298	1230	−1.71
(b) Without Mg-doped	280	1260	−1.77

The AlGaN/GaN HEMT devices with (a) and without (b) partially Mg-doped were fabricated. The source and drain ohmic contacts were prepared by evaporating Ti/Al/Ni/Au (20 nm/150 nm/50 nm/80 nm) multi-layer metals in the e-beam evaporator, followed by a rapid thermal annealing (RTA) at 850°C for 30 s in the N_2 ambient. The gate was defined by contact photolithography, and formed by evaporating Ni/Au (50 nm/300 nm) metals for Schottky contacts.

The DC output and transfer characteristics of the AlGaN/GaN HEMTs with device dimensions of $L_g/W_g/L_{gs}/L_{gd}$= 1/10/1/1 μm were measured by using an HP4156A precision semiconductor parameter analyzer. Figures 5–8 show the DC current-voltage (I_{ds}–V_{ds}) characteristics, transfer (I_{ds}–V_{gs}) characteristics, gate leakage currents, and off-state breakdown voltages of the devices with (a) and without (b) partially Mg-doped. The detailed DC output and transfer characteristics of Devices (a) and (b) are shown in Table 2 for comparing the effect of Mg doping.

According to Table 2, Device (a) has a higher maximum drain current density (I_{dss}) than Device (b), which is caused by good surface morphology achieved in Sample (a) with partially Mg-doped. Additionally, Device (a) has much lower drain leakage current density (I_{ds}) and lower gate leakage current density (I_{gs}) than Device (b), which is caused by high resistance in the GaN buffer layer with partially Mg-doped for Sample (a). Furthermore, Device (a) achieves a higher off-state breakdown voltage (V_{BR}) than Device (b), resulting from high resistance in GaN buffer layer with partially Mg-doped. So the off-state breakdown voltage of 104 V was achieved with device dimensions $L_g/W_g/L_{gs}/L_{gd}$= 1/10/1/1 μm by using partially Mg-doped GaN buffer layer, which is the best result so far for the same device dimensions [7–9].

Table 2 Comparison of the DC transfer characteristics of Devices (a) and (b)

Devices	I_{dss} (mA/mm) @ V_{gs} = 2.0 V, @ V_{ds} = 10 V	G_m			V_{th} (V)	I_{ds} (μA/mm) @ V_{gs} = −8 V, @ V_{ds} = 6 V	I_{gs} (μA/mm) @V_{gs} = −35 V	V_{BR} (V) @ I_{ds}=1 mA/mm
		G_m (mS/mm)	@V_{gs} (V)	@V_{ds} (V)				
(a)	732	175	−1	6	−2.3	0.0558	2.7	104
(b)	705	179	−0.8	6	−2.7	9.2	91.8	87

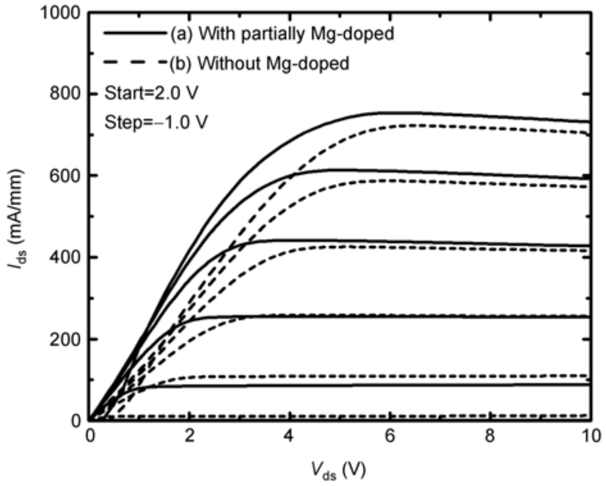

Figure 5 DC I_{ds}–V_{ds} characteristics of Devices (a) and (b).

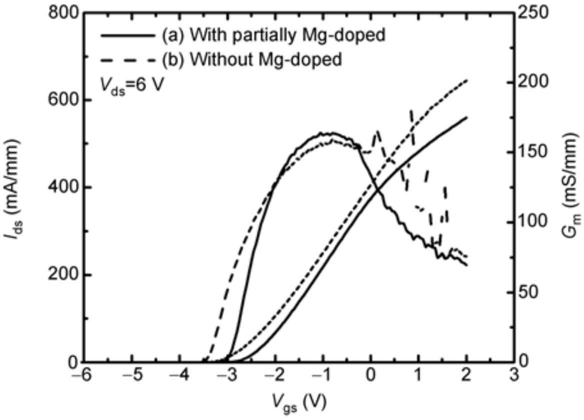

Figure 6 DC transfer (I_{ds}–V_{gs}) characteristic of Devices (a) and (b).

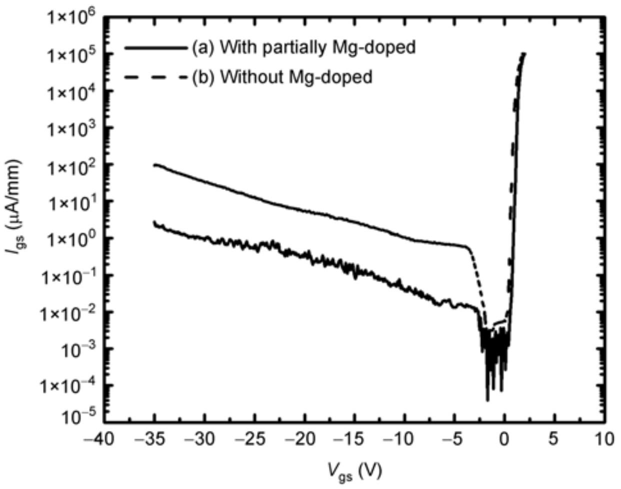

Figure 7 Gate leakage currents of Devices (a) and (b).

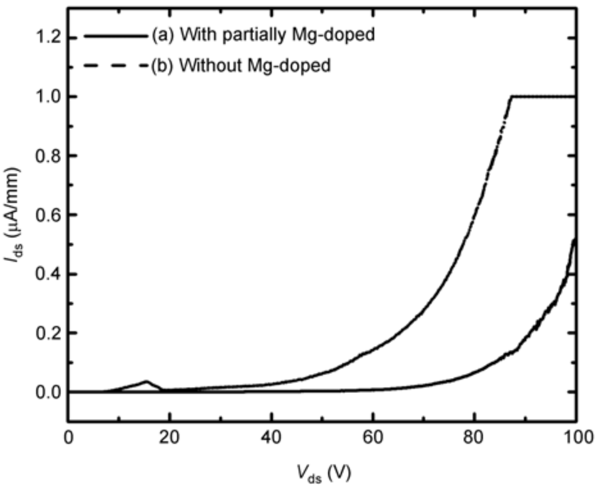

Figure 8 Off-state breakdown voltages of Devices (a) and (b).

4 Conclusion

Devices of AlGaN/GaN HEMTs grown on undoped and partially Mg-doped GaN buffer layers were processed and characterized for comparing the effect of Mg doping. For the DC characteristics, a low drain leakage current density of 55.8 nA/mm, a low gate leakage current density of 2.73 μA/mm and a high off-state breakdown voltage of 104 V were achieved with $L_g/W_g/L_{gs}/L_{gd}$ = 1/10/1/1 μm by using partially Mg-doped GaN buffer layer.

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