Comparing Buffer Leakage in PolarMOSH on SiC and Free-Standing GaN Substrates

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***Abstract*—GaN MOSHEMT or MOSFET on top of conducting (drift layer and drain electrode) layers is a building block for vertical GaN VDMOS power transistors. GaN MOSHEMTs incorporating a polarization-doped p-AlGaN layer as the back barrier on top of conducting layers is named as PolarMOSH. In this work, we present a comparative study of PolarMOSH fabricated on SiC and free-standing GaN substrates. PolarMOSH wafers epitaxially grown on SiC substrates are found to suffer from large leakage currents, with or without Mg doping in the back barrier. Much lower leakage currents are achieved when PolarMOSH wafers are grown on free-standing GaN substrates. The large reduction of buffer leakage current is attributed to the much reduced dislocation density brought by free-standing GaN substrates. The PolarMOSH fabricated on free-standing GaN substrates has a current On/Off ratio $> 10^{10}$ thanks to the low leakage current.**

I. Introduction

Free-standing GaN substrates with continuously improved quality and lowered cost have paved the way for realizing vertical GaN power devices, promising high conduction current but low on-resistance, high blocking voltage and fast switching speed. GaN Metal-Oxide-Semiconductor High Electron Mobility Transistor (MOSHEMT) or MOSFET on top of conducting (drift and drain electrode) layers is an essential element for vertical GaN VDMOS power transistors. GaN MOSHEMTs with a polarization-doped p-AlGaN back barrier on top of conducting layers is named as PolarMOSH. It is a building block for the novel vertical GaN device PolarMOS [1], which takes advantage of the unique polarization properties of GaN for power applications. The cross section schematics of both PolarMOS and PolarMOSH are illustrated in Fig. 1.

Experimental realization of HEMTs with a p-type back barrier grown on unintentionally-doped (UID) GaN or n-GaN has been challenging due to the high buffer leakage as well as difficulty in junction placement due to Mg. In metal-organic chemical vapor deposition (MOCVD) growth, Mg tends to incorporate in subsequently grown layer [2], [3], resulting in compensation effects that prevent formation of two dimensional electron gas (2DEG). Chowdhury *et al.* [4] showed that the Mg diffusion could be suppressed through insertion of an AlN layer or a C doped GaN layer. However,

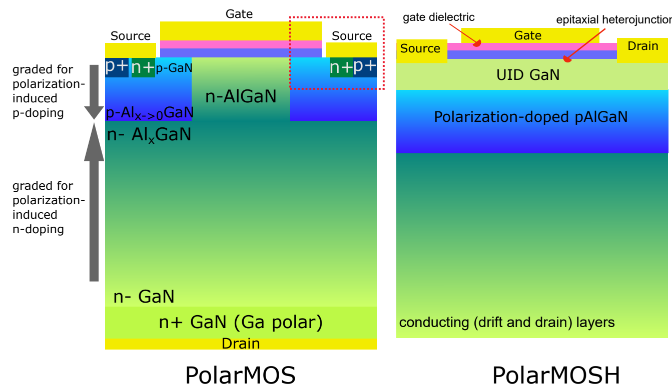

Fig. 1. Cross section schematics of PolarMOS (left) and PolarMOSH (right). PolarMOS is a novel vertical GaN power transistor [1]. PolarMOSH is a GaN MOSHEMT with a polarization-doped p-AlGaN back barrier on top of conducting layers. It is a building block for PolarMOS, as illustrated by the red rectangle in the left figure.

in their experiments, Mg doping is carried out through ion implantation and the subsequent layers were regrown using molecular beam epitaxy. The regrowth interface often has high densities of impurities due to exposure to the atmosphere, which leads to high leakage current [5].

Here we present the first realization of PolarMOSHs, on free-standing GaN substrates and illustrate the adverse effect of dislocations on buffer leakage by comparing PolarMOSHs grown on SiC and GaN substrates. The experiments started with PolarMOSH epitaxial structures grown on SiC substrates, which show a persistently large buffer leakage current since the p-$Al_xGa_{1-x}N$ barrier does not effectively block leakage current between 2DEG channel and the underlying layers due to excessive amount of dislocations ($\sim 10^9$ cm^{-2}). The involvement of Mg doping is found to prevent the formation of 2DEG channel as well as alloyed ohmic contacts. Then the PolarMOSH epitaxial structure was carefully improved to reduce the effects of Mg doping on the 2DEG channel and grown on free-standing GaN substrates. The fabricated PolarMOSHs on free-standing GaN substrates show a high current On/Off ratio of $> 10^{10}$ and a low drain leakage current

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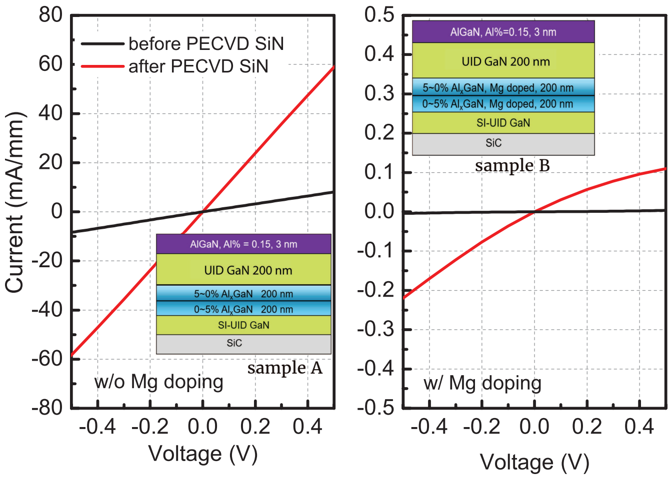

Fig. 2. Comparison of *I-V* characteristics of a pair of ohmic contacts (2 μm separation) before and after 20 nm PECVD SiNx deposition on (left) sample without Mg doping and (right) sample with Mg doping. Mg doping causes large decrease in measured currents.

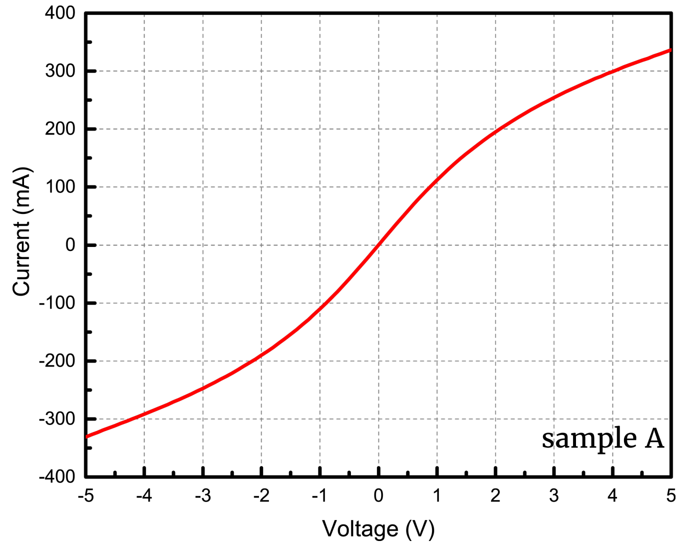

Fig. 3. *I-V* characteristics of a pair of ohmic contacts (2 μm separation) after 20 nm PECVD SiNx deposition on sample without Mg doping. I > 300 mA/mm at 5 V bias.

of $<$ 1 pA/mm .

II. Experiments and Discussions

Two epitaxial structures were first designed to study the effects of graded $Al_xGa_{1-x}N$ and Mg doping. Both structures were grown on SiC substrates by MOCVD, consisting of a high-resistivity UID GaN layer, 0$\sim$5% graded $Al_xGa_{1-x}N$, 5%$\sim$0 graded $Al_xGa_{1-x}N$ (with or without Mg), 200 nm UID-GaN, 3 nm $Al_{0.15}Ga_{0.85}N$, while the only difference between the two device structures is the Mg doping in the back barrier. The epitaxial structures were designed for enhancement-mode (E-mode); 20 nm plasma-enhanced chemical vapor deposition (PECVD) SiNx, which is found to increase the 2DEG concentration thus reduce sheet resistance [6], was deposited after Ohmic contacts formation (alloyed Ti/Al/Ni/Au). Figure 2 shows the comparison of *I-V* characteristics of ohmic contacts before and after SiNx deposition on both samples. As can be seen from both plots in Fig. 2, 20 nm PECVD SiNx is effective in increasing measured current density for both epitaxial structures. However, the measured current density values are quite different. While the current through a pair of ohmic contacts separated by 2 μm could reach 60 mA/mm at 0.5 V bias on the sample without Mg doping, it barely exceeds $\sim$ 0.2 mA/mm on the sample with Mg doping.

Fig. 3 shows the *I-V* characteristics a pair of ohmic contacts separated by 2 μm on the sample without Mg doping, showing a conduction current $>$ 300 mA/mm at 5 V bias. This $I-V$ behavior indicates that the channel 2DEG is compensated by Mg in the sample with Mg-doped back barriers, which is similar to Fe-doped or C-doped back barriers. Secondary ion mass spectrometry (SIMS) measurements (not shown here) show a residue Mg level of 1×10^{17} cm^{-3} near the 2DEG channel region.

Figure 4 shows the comparison of buffer leakage currents, with an excessive leakage current observed on both samples at 20 V bias. Device isolation on both samples are realized through 100 nm Cl_2 based dry etching using reactive ion etching (RIE). The buffer leakage test structure includes a pair of mesa isolated ohmic contacts separated by 10 μm. Although the Mg doping reduces the buffer leakage current at low bias voltage range, the leakage currents are within the same order of magnitude at 20 V. The large dislocation density in GaN grown on SiC substrates have most likely resulted in the buffer leakage current increase as the bias voltage increases. To identify whether the leakage current flows through the buffer layer below the $Al_xGa_{1-x}N$ back barrier, additional etching of 700 nm on the PolarMOSH sample is carried out after PolarMOSH fabrication. The leakage current after 100 nm and 800 nm mesa etching is plotted in comparison in Fig. 5. Also plotted in Fig. 5 is the leakage current on a GaN-on-Si HEMT [7], [8]. A 10^5X reduction in leakage current is observed when the etch depth is increased from 100 nm to 800 nm, suggesting that the $Al_xGa_{1-x}N$ layer and the UID GaN layer above contributes to most of the leakage current. However a further study is required to find out the exact amount of leakage current for each leakage path denoted in the upper inset plot in Fig. 5. The leakage current after 800 nm deep etching is still orders of magnitude larger than the GaN-on-Si HEMT, which has an impurity-doped semi-insulating GaN buffer layer. This indicates that the leakage path through the $Al_xGa_{1-x}N$ to the underlying SI-UID layer (as illustrated in the lower inset plot in Fig. 5), is due to the excessive amount of dislocations.

Following the mesa etch of 100 nm by RIE, the subsequent PolarMOSH fabrication process includes: gate lithography and RIE etching of PECVD SiNx, 20 nm Al_2O_3 deposition by atomic layer deposition (ALD) and gate metal deposition. The

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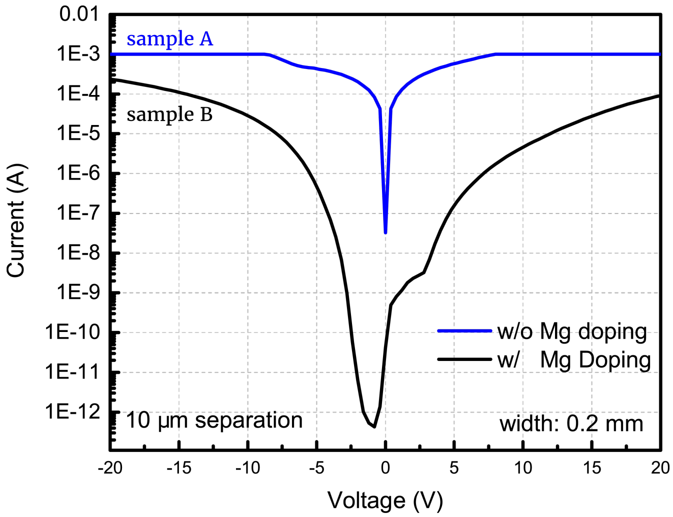

Fig. 4. Buffer leakage current comparison between sample A (without Mg doping) and sample B (with Mg doping). Although Mg doping reduces leakage current at low voltage bias, both samples show large leakage current at 20 V.

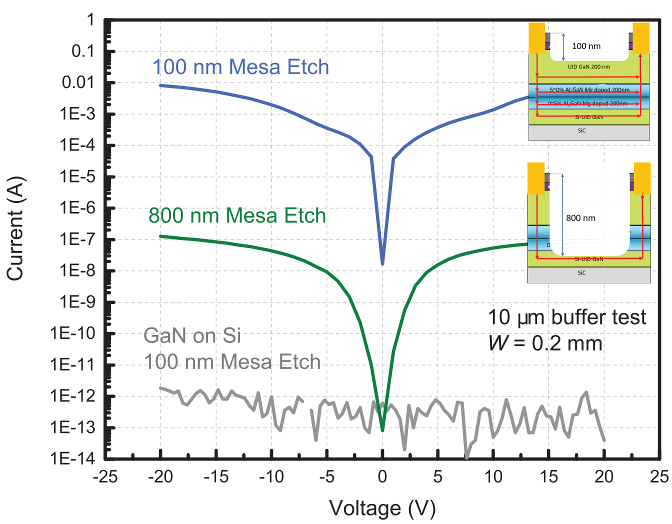

Fig. 5. Leakage current comparison between sample A with 100 nm and 800 nm mesa etching. Also plotted is the leakage current on a GaN-on-Si HEMT [7], [8]. A large leakage current reduction is observed after deep etching, although the reduced leakage current is still orders of magnitude larger than that on the GaN-on-Si sample. The possible leakage path after 100 and 800 nm etching are denoted as red arrow lines in the inset plots.

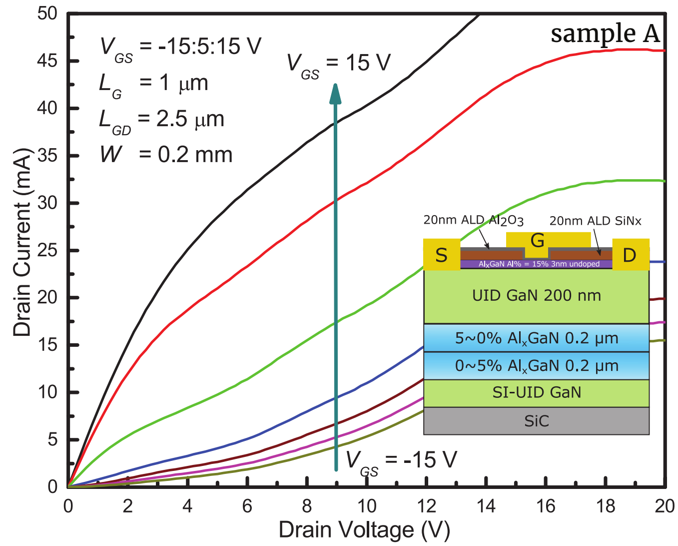

Fig. 6. $I_D - V_D$ characteristics of MOSHEMT fabricated with sample A (No Mg doping). Clear gate modulation of drain current is shown. Large leakage current inhibits complete turn-off of drain current.

I_D-V_D characteristics of the PolarMOSH fabricated on the sample without Mg doping is shown in Fig. 6 along with its cross-section schematic. Although a clear gate modulation of drain current is seen from the plot, indicating the presence of electron channel, the excessive buffer leakage current prevents a complete turn-off of the drain current.

We have recently successfully demonstrated a series of GaN-on-GaN p-n diodes, which show unity ideality factor, avalanche breakdown and a record-setting figure-of-merit BV^2/Ron of $>$ 16 GW/cm^2 [9]–[11]. This indicates that growing the PolarMOSH device structure on bulk GaN substrates (dislocation density $\sim 10^6$ cm^{-2}) is attractive in solving the buffer leakage issue. As illustrated in Fig. 7 (a), the epitaxial structure, starting from the GaN substrate, includes: 7 μm Si doped n type GaN, 1 μm graded $Al_xGa_{1-x}N$ with polarization induced doping, 400 nm Mg doped graded $Al_xGa_{1-x}N$, 400 nm UID GaN, 20 nm $Al_{0.15}Ga_{0.85}N$ and 2 nm GaN cap. This epitaxial structure is designed for depletion mode thus a quicker evaluation of the 2DEG channel is possible; the top AlGaN barrier thickness can be reduced for E-mode devices. The PolarMOSH fabrication process is similar to that carried out on SiC substrate, except that the D-Mode epitaxy design eliminated the need of PECVD SiNx to form ohmic contacts. The fabrication process flow includes: ohmic contacts through Ti/Al/Ni/Au deposition and rapid thermal annealing, mesa isolation by dry etching, Al_2O_3 deposition by ALD and gate metal deposition.

The I_D-V_G characteristics of the fabricated PolarMOSH on free-standing GaN substrates is plotted in Fig. 7 (b), with the inset figure showing the cross section schematic. It is seen that an On/Off ratio $> 10^{10}$ and a drain off-current $<$ 1 pA/mm are achieved. The large On/Off ratio, enabled by the low leakage current through the Mg doped graded $Al_xGa_{1-x}N$ layer as well as gate oxide, shows that the current blocking capability of Mg doped graded $Al_xGa_{1-x}N$ is vastly improved when grown on free-standing GaN substrates. This improvement in leakage current could be attributed to the much lower dislocation density in GaN grown on GaN substrates compared to GaN grown on SiC substrates [12], 1×10^6 cm^{-2} versus 1×10^9 cm^{-2}. As dislocations provide a vertical leakage path between the 2DEG above the p-layer and the conducting layer below the p-layer, reduction in dislocation density results in a reduction in measured buffer leakage current. The sharp turn-on behavior of drain current at $V_G \sim 5\ V$ also shows that the compensation effects by Mg is limited.

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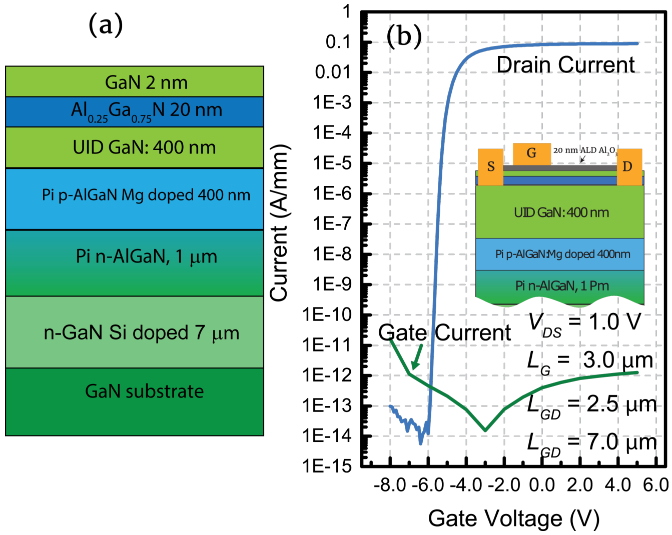

Fig. 7. (a) Epitaxial structure of PolarMOSH on free-standing GaN substrates. (b) The $I_D - V_G$ characteristics of the fabricated PolarMOSH. The inset figure in (b) shows the cross section schematic of the fabricated PolarMOSH.

III. Conclusion

In conclusion, we compare the leakage current behavior of PolarMOSH fabricated on SiC and free-standing GaN substrates. It is found out that the PolarMOSH fabricated on SiC substrates suffers from a large buffer leakage current. Though Mg doping in the graded $Al_xGa_{1-x}N$ back barrier reduces the leakage current, the channel residue Mg concentration is too high to form a 2DEG after depositing SiNx. The PolarMOSH fabricated on free-standing GaN substrates, shows a low drain leakage current of < 1 pA/mm and a high On/Off ratio of $> 10^{10}$. The much improved leakage characteristics could be attributed to the lower dislocation density of GaN grown on free-standing substrates than on SiC substrates. The device performance improvement shows the benefits of the superior quality of free-standing GaN substrates.

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