Avoiding Plasma Damage: MacEtch enabled β-Ga_2O_3 FinFETs for On-Resistance Reduction and Hysteresis Elimination

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Abstract

Although highly promising, the performance of β-Ga2O3 transistors are far from their theoretical potentials. Structural innovations by adopting the FinFET geometry remains a relatively virgin field for this material. Here we report the results and discuss the prospect of β-Ga_2O_3 FinFETs fabricated by the plasma-free highly anisotropic metal-assisted chemical etching (MacEtch) method. A specific on-resistance ($R_{on,sp}$) of 6.5 mΩ·cm^2 and a 370 V breakdown voltage are achieved. The MacEtch-formed FinFETs demonstrate near-zero (9.7 mV) hysteresis. (Keywords: β-Ga_2O_3, MacEtch and FinFET)

Introduction

The worldwide energy transition to sustainable and renewable energy is placing a growing need for highly efficient power electronics system. Power semiconductor device is the key element that determines the energy conversion efficiency as well as the system size and cost. Over the past decade, Ga_2O_3 related materials and devices have drawn tremendous attention and made rapid strides, because of its ultra-wide band gap of ~ 4.8 eV and the availability of bulk substrates. However, the performance of β-Ga_2O_3 based transistors are still far from their theoretical potentials. Structural innovations such as adopting the FinFET geometry remains a relatively less explored field for this material. It is well known that reactive ion etching produces damage that cannot be easily repaired for compound semiconductors, leading to limited effective channel mobility, high leakage and hysteresis. In contrast, plasma-free metal-assisted chemical etch (MacEtch) can achieve ultrahigh aspect ratios and produce a vast range of 3D semiconductor structures with surfaces that are free of damage.[1]. We herebyreport and review β-Ga_2O_3 FinFETs produced by MacEtch for on-resistance reduction and hysteresis elimination.[2], [3]

Device Fabrication

The fabrication flow is illustrated in Fig. 1. A silicon-doped β-Ga_2O_3 film (~2 μm thick) was homoepitaxially grown by metalorganic chemical vapor deposition(MOCVD). The substrate was (010) semi-insulating Fe-doped β-Ga_2O_3. The source/drain and channel regions were then formed by MacEtch using Pt as the catalyst. The MacEtch solution consists of a mixture of HF and $K_2S_2O_8$,[4] forming fin-shaped channels and source/drain mesas. Pt was removed after MacEtch. Subsequently, Ti/Au film was deposited as S/D contacts. 20 nm of Al_2O_3 was then deposited through the atomic layer deposition (ALD) process followed by 1 min of 490^{o}C rapid thermal annealing (RTA). After the removal of Al_2O_3 on top of the S/D mesa by HF, Ti/Au gold gate electrodes were then deposited to form the gate metal stack.

The MacEtch-formed β-Ga_2O_3 FinFET is shown in Fig. 2 (a). As the n-Ga_2O_3 layer completely etched through, the fin-shaped channel consists of both the n-type epitaxial layer (highlighted in red) and the semi-insulating substrate (highlighted in green). Note that the MacEtch rate of the n-doped channel and the semi-insulating substrate are different, resulting in dramatically different sidewall profiles. The top and bottom width of the active n-channel fin is 142/570 nm, respectively, and the height is around 1.5 μm, corresponding to a 4.2:1 average aspect ratio (Fig. 2(b)). Furthermore, a smoother sidewall morphology than the RIE-produced sidewalls can beobserved on the MacEtch-formed structures. Note that the height of the fin is limited by the thickness of the epitaxial layer.

Result and Discussion

The DC transfer characteristics of the MacEtch-formed β-Ga_2O_3 FinFETs under V_{ds} = 5 V is shown as Fig. 2(a). With gate length (L_G) = 1 μm and top fin width ($W_{fin,top}$) = ~ 630 nm, the drive current reaches 2.7×10^{-5} A at V_{gs} = 4 V. The on/off ratio is ~10^5 with gate leakage current at 100 pA level. Moreover, the transfer characteristic showed almost zero hysteresis which is unprecedented for β-Ga_2O_3 FETs with vertical sidewall structures. The hysteresis is only 9.7 mV clockwise, which is largely reduced when comparing to the 120 – 800 mV hysteresis of previously reported β-Ga_2O_3 FETs.[5]–[7] This almost hysteresis-free characteristic could be attributed to the absence of RIE-induced ion damages and traps due to the MacEtch. The SS is extracted tobe 93.6 mV/dec, which is slightly lower than the typical 150 mV/dec of the RIE-fabricated β-Ga_2O_3 transistors,[7] suggesting the plasma-free MacEtch process might produce fin-shape channel with better interface quality than the RIE process. Fig. 4(a) shows the output characteristics of the β-Ga_2O_3 FinFET and the on resistance (R_{on}) can be extracted from the slope of low V_{ds} region and is estimated to be around 128.8 Ω-mm at V_{gs} = 2V. As a result, the $R_{on,sp}$ is ~6.5 mΩ-cm^2 when normalized to the distance between source and drain (5 μm). If we consider the transfer length (L_T) in source/drain contact as 1μm, the $R_{on,sp} = R_{on} \times$ gate width $\times$ (L_{SD}+2L_T) can be extracted as 9.1 mΩ-cm^2.

Fig. 4(a) shows the SS of MacEtch-formed β-Ga_2O_3 FinFETs as a function of channel orientations. The SS is found to decrease as the channel rotates away from [102] and when θ=90°, it reaches its lowest value of 87.2 mV/dec. This V-shaped distribution of SS implies that the interface trap density (D_{it}) could be the lowest on the MacEtch-formed sidewalls at θ =90°. Note that despite the SS increases as channel rotates away from [102], the SS of the MacEtch-produced FinFET is still much lower than the transistors fabricated by RIE. In addition to SS, the hysteresis of β-Ga_2O_3 FinFETs with different orientations are also extracted. The hysteresis vs θ also shows a similar V-shaped distribution with the lowest hysteresis at θ =90° (Fig. 4(b)). This hysteresis dependence of fin orientation suggests thatsidewalls have the lowest D_{it} when the channel is perpendicular to [102] direction, which is consistent with the trend for SS. Note that for all the channel directions, the hysteresis of the MacEtch-produced FinFET are all lower than the transistors with RIE, which have the hysteresis ranging around 120 – 800 mV.

Fig. 5 shows the offstate voltage characterization of the β-Ga_2O_3 FinFETs. The gate and drain current demonstrate a spike when the breakdown occurs at 370V. Fig. 6 shows the average breakdown voltage of the FinFETs with different channel orientations. The V_{br} are around 365 - 380 V, without strong dependence on θ. This suggests the interface properties do not affect thebreakdown mechanism much. Fig. 7(b) shows the benchmark plot of reported β-Ga_2O_3 transistors in theliterature. Note that to provide better comparison, the $R_{on,sp}$ values obtained from the slope of the output characteristics at low V_{ds} region under V_{ov} = ~ 5V are plotted for all cited works. MacEtch-formed β-Ga_2O_3 FinFET demonstrates reasonable 370 V breakdown voltage and a 9.1 mΩ-cm^2 $R_{on,sp}$, which isrelatively low compared to other reported β-Ga_2O_3 transistors. More remarkably, these devices achieved ultralow hysteresis for channel oriented in all directions, significantly lower than RIE fabricated devices (Fig. 4(b)). We believe this work represents important advancement of the development of β-Ga_2O_3-based power electronics with three-dimensional structure and high quality interface.

Conclusion

We have demonstrated β-Ga_2O_3 FinFETs produced by the plasma-free MacEtch with high aspect ratio channels and smooth sidewalls. As a result of the plasma-free virtue of the MacEtch process, the FinFETs shows near hysteresis-free transfer characteristics with a 6.5 mΩ-cm^2 $R_{on,sp}$ and a 370 V V_{br}. The variation and trend of hysteresis, SS and breakdownvoltages as a function of the fin channel orientation are discussed. The results suggest that although there is not a huge difference if fabricated by MacEtch, when channel is perpendicular to [102] direction, thesidewalls with the lowest interface trap density are formed for device applications.

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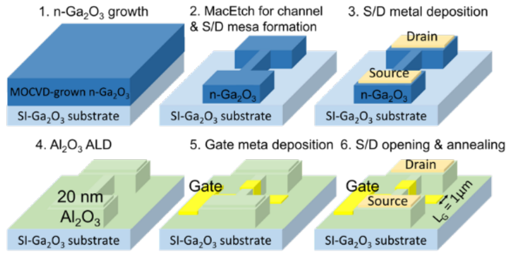

Fig. 1 Illustration of β-Ga_2O_3 FinFET fabrication.

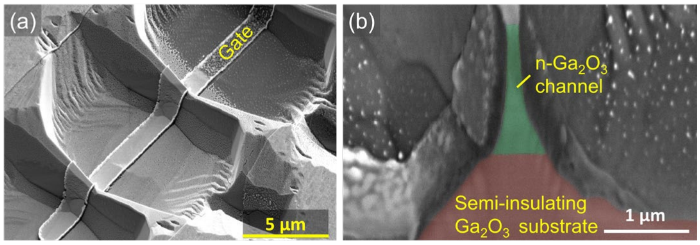

Fig. 2 SEM images of (a) tilted and (b) cross-section of β-Ga_2O_3 FinFETs formed by MacEtch.

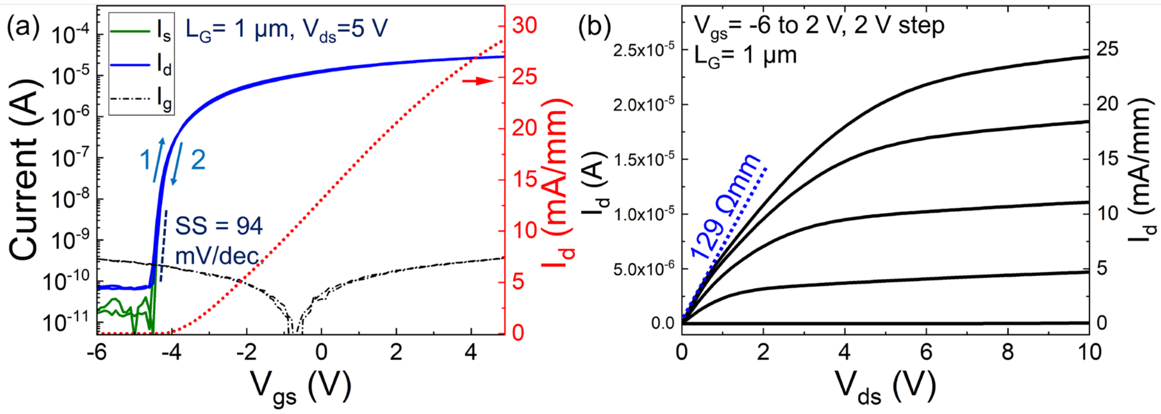

Fig. 3 (a) DC transfer characteristic and (b) output characteristics of β-Ga_2O_3 FinFET , with the channel orientation at 80° from [102] direction and $W_{fin,top}$ = 630 nm.

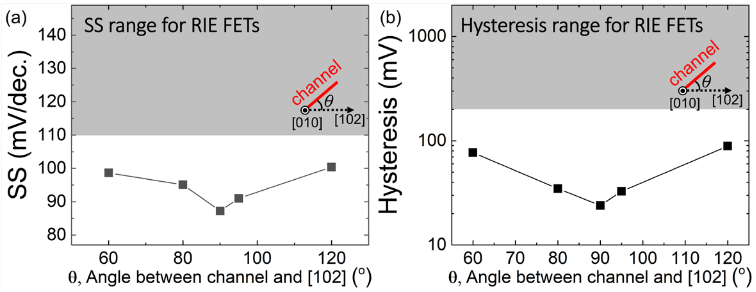

Fig. 4 (a) Subthreshold swings and (b) hysteresis of β-Ga_2O_3 FinFETs vs θ, the angle between channel orientation and [102] direction.

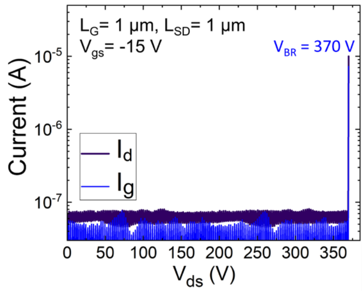

Fig. 5 Three-terminal off-state I_d/I_g-V_{ds} characteristics of β-Ga_2O_3 FinFET, showing a breakdown voltage of 370V.

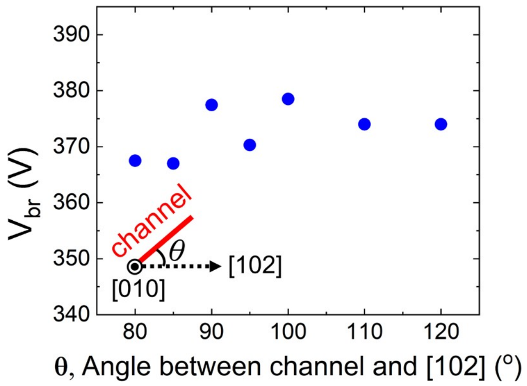

Fig. 6 Breakdown voltages of β-Ga_2O_3 FinFETs vs θ, the angle of the fin channel relative to [102] direction.

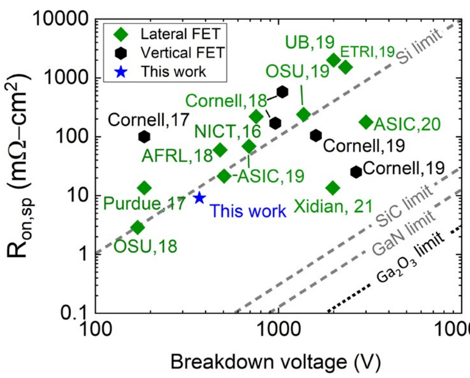

Fig. 7 $R_{on,sp}$ vs V_{br} benchmark plot of β-Ga_2O_3 FETs.