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Unpassivated AlGaN/GaN HEMTs with Ideal Sub-threshold Swing (~60mV/decade) on Extremely High Quality Free-standing GaN Substrate

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Abstract

Unpassivated AlGaN/GaN high electron mobility transistors (HEMTs) with a record low or ideal sub-threshold swing *SS* (~60mV/decade) are fabricated on the extremely high quality free-standing (FS) GaN substrate. AlGaN/GaN heterostructure grown on FS-GaN in this work exhibits excellent material properties, such as ultralow FWHM (42.9 and 41.7 arcsec) for (0002) and (10-12) XRD peaks, and ultralow dislocation density (~10^4-10^5 cm^{-2}) measured by cathodoluminescence. Due to these extremely high quality material properties, the fabricated unpassivated AlGaN/GaN HEMTs achieve a record low *SS* (~60 mV/decade), low hysteresis of 54 mV, low on-state resistance of 0.5 mohm.cm^2, I_{on}/I_{off} ratio of ~10^6, and peak μ_{eff} of ~1456 $cm^2V^{-1}s^{-1}$. As compared to the reported oxide passivated GaN-based HEMTs on sapphire or Si, the unpassivated GaN-on-GaN AlGaN/GaN HEMTs in this work have achieved the smallest or lowest *SS*.

Introduction

GaN-based transistors are very promising for future high temperature power electronics, due to its wide bandgap (3.4 eV) and large critical electric field [1]. Over the past two decades, GaN-based devices have been extensively investigated and great improvement has been also achieved [2]. However, these devices have been mostly fabricated on foreign substrates, such as silicon, sapphire, and SiC. The major challenge for GaN-based transistors on foreign substrate is a high density of threading dislocations (10^8-$10^{10}$$cm^{-2}$) originating from the strained heteroepitaxial growth on the foreign substrate, which becomes problematic for devices under high power or high temperature operation. In this work, extremely high quality AlGaN/GaN heterostructure was homoepitaxially grown on the 2 inch FS-GaN substrate, on which unpassivated AlGaN/GaN HEMTs were fabricated, and detailed device electrical characteristics were presented.

Material Characterization

$Al_{0.25}Ga_{0.75}N$(27nm)/GaN(1μm) structure shown in Fig.1 (a) was homoepitaxially grown by MOCVD on 2 inch Fe-doped FS-GaN substrate [3]. Crystal quality of as-grown AlGaN/GaN structure was characterized by XRD rocking curves, shown in Fig.1 (b), in which ultralow FWHM (42.9 and 41.7 arcsec) for (0002) and (10-12) XRD peaks is obtained. With the (0002) reciprocal space map shown in Fig. 1 (c), the lattice constant (c) for GaN and AlGaN is measured to be 0.5184 and 0.5127 nm, respectively, indicating the AlGaN layer is subjected to a tensile strain in the lateral direction and a compressive strain in the vertical direction. High resolution TEM image shown in Fig.1 (d) reveals the perfect lattice structure of AlGaN/GaN layer. The R_{sh} mapping of the as-grown 2 inch AlGaN/GaN HEMT substrate is shown in Fig. 2, in which an average R_{sh} of 445 ohm/square and an average Hall mobility of ~1500 $cm^2V^{-1}s^{-1}$ are obtained. Absence of yellow luminescence (YL) shown in Fig. 3 (a) indicates a low defect density for the as-grown AlGaN/GaN structure, and ultralow dislocation density (~10^4-$10^5$$cm^{-2}$) is measured by cathodoluminescence shown in Fig. 3 (b). The root-mean-square (rms) before and after AlGaN/GaN growth is measured to be 1.1 and 0.3 nm, respectively, by AFM shown in Fig. 3 (c) and (d).

Device Fabrication

Standard fabrication process was used to fabricate GaN-on-GaN AlGaN/GaN HEMTs, and shown in Fig. 4(a). After active region formation using Cl_2-based reactive ion etching, pre-gate cleaning step comprising native oxide removal by HCl was performed. Ti(50nm)/Al(200nm)/Ti(40nm)/ Au(40nm) stack was deposited as source/drain electrode, and formed ohmic contact after 850°C annealing for 3mins. Ni(70nm)/Au(30nm) was deposited as gate electrode. The fabricated AlGaN/GaN HEMTs in this work have no oxide passivation. Fig. 4 (b) and (c) show the cross-sectional TEM image of fabricated device and the gate stack.

Electrical Results and Discussion

The transfer characteristics of AlGaN/GaN HEMTs with a gate length L_G of 3μm is shown in Fig. 5(a), and average *SS* (~65mV/decade) is obtained over the three orders of drain current, in which a minimum *SS* (~54mV/decade) is obtained over one order of drain current, where the threshold voltage V_{th} is ~-3.1V. The inset of Fig. 5(a) shows the top view of an optical image of the fabricated device. Under V_D of 1V, the voltage hysteresis at I_D of 8μA/μm is ~54 mV [Fig. 5(b)]. Fig. 5(c) shows the output characteristics of the fabricated devices, in which the on-state resistance for the active region only is ~0.5mohm.cm^2. As shown in Fig.6, the gate leakage current starts to rapidly increase at V_G of 1V. Fig.7 and Fig. 8 show the *SS* and I_{on}/I_{off} ratio versus gate leakage I_G, respectively. I_{on} and I_{off} is defined as the drain current at V_D of 1V under gate voltage of V_{th}+3V and V_{th}-2V, respectively. I_G is defined as the gate leakage under V_D of 1V and V_{th}-2V. The I_D-V_G curves under various high temperatures from 300K-420K is shown in Fig. 9. According to the plot of Ln(J_G) versus 1/E_{ox} shown in Fig. 10, the dominant gate leakage mechanism is electron surface hopping with an activation energy of 0.02 eV. The field effect mobility μ_{eff} with a peak value of ~1456 $cm^2V^{-1}s^{-1}$ is extracted using the *C-V* method, and the μ_{eff} as a function of carrier density N_s is shown in Fig. 10. A benchmarking of *SS* for GaN-on-GaN and oxide passivated GaN-on-Si (or Al_2O_3) AlGaN/GaN HEMTs is shown in Fig.11, a record low or an ideal *SS* (~60mV/decade) is obtained for GaN-on-GaN AlGaN/GaN HEMTs in this work.

Conclusion

AlGaN/GaN HEMTs with an ideal sub-threshold swing *SS* (~60mV/decade) are fabricated on the extremely high quality free-standing GaN substrate. Systematic study of materials properties and device characteristics exhibits that GaN-on-GaN AlGaN/GaN HEMTs are promising candidate for new generation high power device applications.

Acknowledgement

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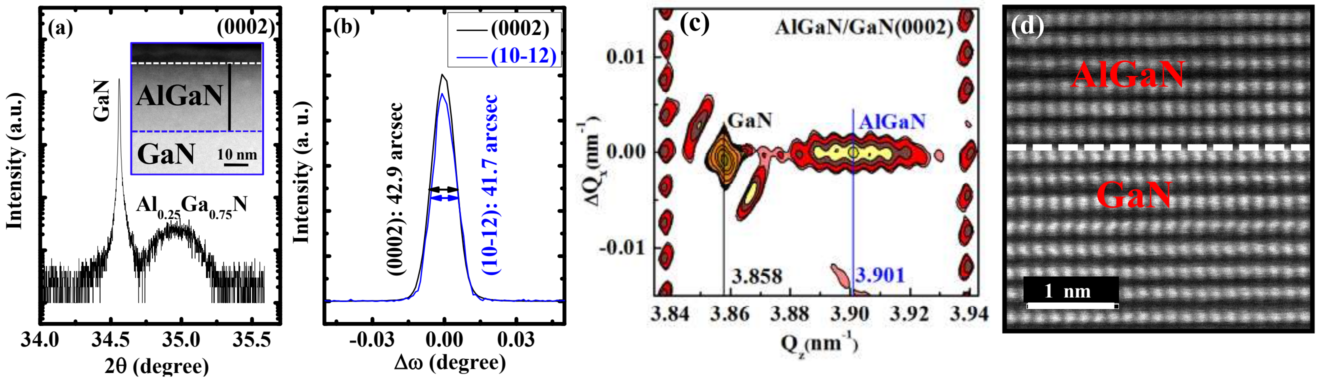

Fig.1. (a) HR-XRD results (inset: cross-sectional TEM), (b) (0002) and (10-12) scan, (c) (0002) reciprocal space map, and (d) HR-TEM of AlGaN/GaN heterostructure on FS-GaN substrate. Ultra-low FWHM of (0002) and (10-12) peaks indicates low dislocation density or high quality of AlGaN/GaN heterostructure on FS-GaN substrate.

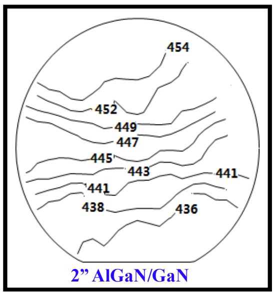

Fig.2. R_{sh} mapping on 2 inch FS-GaN substrate.

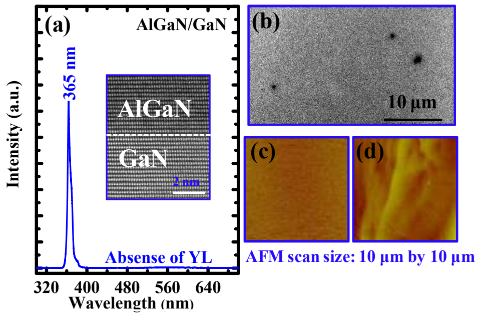

Fig.3. (a) PL spectra and (b) CL image of AlGaN/GaN on FS-GaN substrate. AFM image (c) before and (d) after AlGaN/GaN epi.

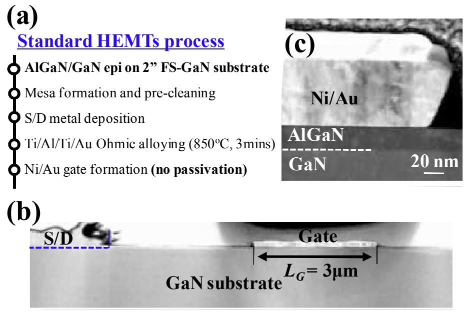

Fig.4. (a) standard HEMTs fabrication process, cross-sectional TEM of (b) HEMTs devices, and (c) Ni/Au/AlGaN/GaN gate stack.

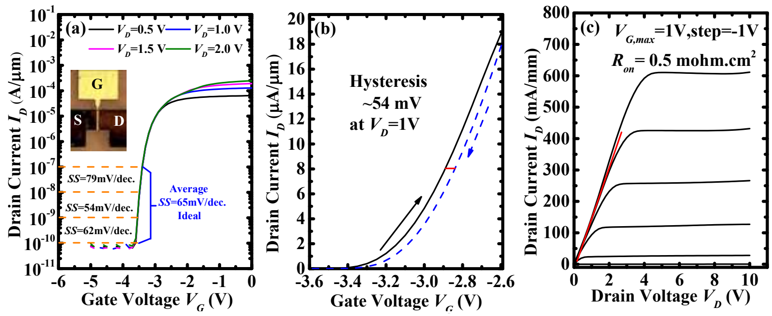

Fig.5. (a) I_D-V_G with ideal *SS*, and inset shows the image of the fabricated devices, (b) hysteresis I_D-V_G, and (c) I_D-V_D curve of AlGaN/GaN HEMTs.

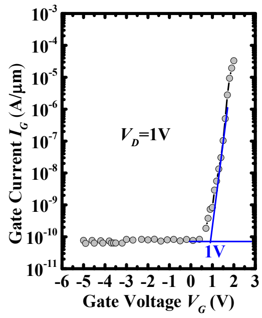

Fig.6. I_G-V_D curve of AlGaN/GaN HEMTs.

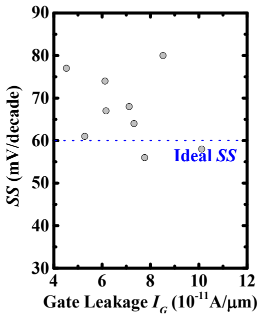

Fig.7. *SS* as a function of I_G of AlGaN/GaN HEMTs.

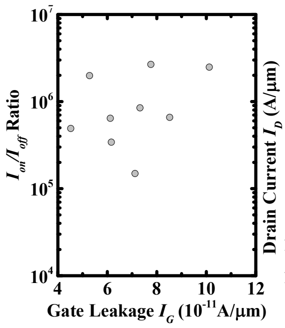

Fig.8. I_{on}/I_{off} ratio vs I_G of AlGaN/GaN HEMTs on FS-GaN substrate.

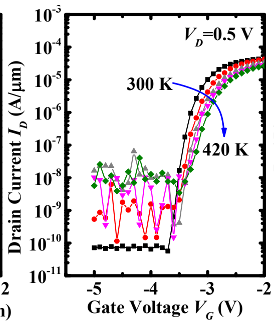

Fig.9. I_D-V_G plots under *T* from 300 K to 420 K.

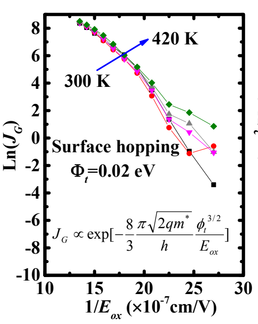

Fig.9. Ln(J_G) vs $1/E_{ox}$ under *T* from 300 K to 420 K.

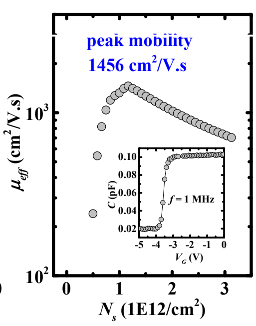

Fig.10. μ_{eff} vs N_s of AlGaN/GaN HEMTs on FS-GaN. Inset shows *C*-*V* plot at 1 MHz.

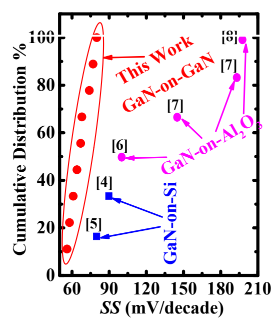

Fig.11. Benchmarking of *SS* for GaN-on-GaN HEMTs (this work) and oxide passivated GaN-on-Si (or Al_2O_3) HEMTs.