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Effect of C- and Fe-doped GaN Buffer on AlGaN/GaN HEMT Performance on GaN Substrate Using Side-gate Modulation

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Abstract

Side-gate (SG) modulation on AlGaN/GaN HEMT performance with C- or Fe-doped buffer layer on GaN substrate is investigated. HEMT devices on C-doped GaN buffer (C-doped GaN) and on Fe-doped GaN buffer (Fe-doped GaN) are compared by using increasing negative SG voltage (V_{SG}) during the bidirectional dual-sweep SG measurements. Transfer characteristics at different applied V_{SG} bias were also measured. Our results show evident hysteresis feature and larger decreased in the drain current (I_D) in C-doped GaN as compared to Fe-doped GaN with the increased in the negative V_{SG}. This decreased in I_D at high negative V_{SG} is inferred to be due to the field modulation caused by the side-gate. Moreover, a larger transconductance decrease is evident at high negative V_{SG} for C-doped GaN as compared to Fe-doped GaN. These clearly shows that C-doped is more affected with SG modulation.

1. Introduction

Gallium nitride (GaN) based high electron mobility transistors (HEMTs) have shown great potential as power transistors due to the excellent material properties of GaN such as high carrier concentration, high saturation velocity, and high critical electric field. For optimum power device performance for the so-called GaN-on-GaN device (GaN HEMT on GaN substrate), high-quality and high-resistivity GaN substrates and buffers are desired. However, undoped GaN layer shows low resistivity (n-type conductivity) because of the unintentional residual impurities (i.e. Si) incorporated during growth. In order to increase the resistivity, these undesirable shallow donors are compensated by doping the GaN buffer layer with deep acceptors like carbon (C) [1] and iron (Fe) [2].

In our previous work [3], evidence of larger memory effect in C-doped GaN as compared to Fe-doped GaN is demonstrated. In this present work, we further investigate the SG modulation by varying the negative SG bias (V_{SG}) to modulate the HEMT channel during the dual-sweep SG measurement. In addition, we measured the transfer characteristics of the devices while simultaneously applying V_{SG} bias.

2. Wafer Structure and Device Fabrication

Both devices have the same structure but differ only on the dopant of the buffer layer. HEMT wafers are grown using metal organic chemical vapor deposition on GaN substrates. Epitaxial layers are comprised of a C- or Fe-doped GaN buffer, followed by an un-doped GaN layer where the two-dimensional electron gas (2DEG) is formed, and a 17.5-nm-thick $Al_{0.22}Ga_{0.78}N$ layer on top. Standard photolithography and lift-off techniques are used to fabricate the devices. Device mesa isolation is achieved via inductively coupled plasma reactive ion etching using gas mixture of Cl_2 and BCl_3. Source, drain, and SG ohmic contacts are deposited using electron beam deposition of Au/Ti/Al/Ti (100/30/80/20nm) metal layers, and are annealed at 840°C for 2 minutes. Then, the gate Schottky contacts are deposited via resistive evaporation of Au/Ni (180/30nm) metals. And lastly, a thin SiN_x passivation layer (3nm) is deposited using atomic layer deposition. The gate length (L_G), distance between gate and source (L_{GS}), and distance between gate and drain (L_{GD}) are 2, 3, and 3 μm, respectively. The SG contact is located at the device border with a distance separation of 6 µm (L_{SG}), and etched 100 nm below the surface.

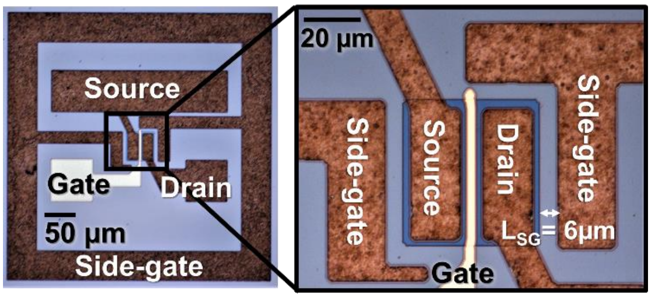

Fig. 1 Fabricated HEMT under an optical microscope (left) and the device active region at higher magnification (right).

SG modulation is done by sweeping from a maximum negative V_{SG} ($V_{SG,max}$) to V_{SG} = 8 V (forward sweep or F-sweep), and back from V_{SG} = 8 V to negative $V_{SG,max}$ (return sweep or R-sweep) while monitoring drain current (I_D) (see Fig. 2). Three values (conditions) of negative $V_{SG,max}$ were used: -40 V, -30 V and -20 V (see Fig. 2 inset). The drain-to-source voltage (V_{DS}) is biased at a constant 6 V, while the gate-to-source voltage (V_{GS}) is kept at 0 V (on state).

Inset: Test Conditions 1-3

	V_{SG} Forward Sweep	V_{SG} Reverse Sweep
1	-20 V to 8 V	8 V to -20 V
2	-30 V to 8 V	8 V to -30 V
3	-40 V to 8 V	8 V to -40 V

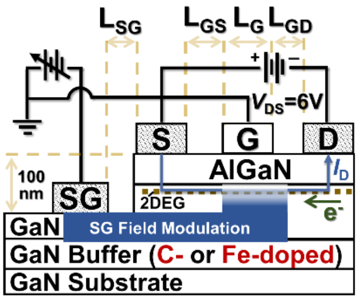

Fig. 2 Schematic of device cross-section and SG measurement circuit diagram. Inset shows the three SG test conditions used.

3. Results and Discussions

Figure 3 is the plot of I_D - V_{SG} for both HEMTs at different V_{SG} conditions. For conditions 1 - 3 of Fe-doped GaN, the I_D values are almost constant in both the F-sweep and R-sweep, where the I_D changed (ΔI_D) is < ~20 mA/mm only. On the other hand, for the F-sweep and R-sweep of C-doped GaN in condition 1, as seen in Fig. 3, the I_D are almost constant. However, for the F-sweep in condition 2 with high negative $V_{SG,max}$, the I_D increases up to $V_{SG} = V_1 = -11$ V, and then the I_D becomes almost constant for $V_{SG} > V_1$. For the R-sweep in contrast, the I_D was constant for $V_{SG} > V_2 = -19$ V, then I_D value catastrophically drops at V_2, and finally following the trend of the F-sweep for $V_{SG} < V_2$. Similarly, for the F-sweep in condition 3, where higher negative $V_{SG,max}$ is used, the I_D increases until $V_{SG} = V_1$ and then becomes almost constant for $V_{SG} > V_1$. For the R-sweep, the I_D was constant until $V_{SG} = V_3 = -24$ V, and then drastically drops at V_3, and then continues to decrease until $V_{SG} = -40$ V. The large ΔI_D ~100 mA/mm for C-doped GaN suggests that C-doped GaN is more affected by SG modulation than Fe-doped GaN. These results show that the modulation is not due to SG current leakage, but rather due to field modulation. Apparent hysteresis features in the $I_D - V_{SG}$ of the C-doped GaN are also observed for conditions 2 and 3, which imply memory effect exists. It can be noted that this hysteresis feature is absent in Fe-doped GaN.

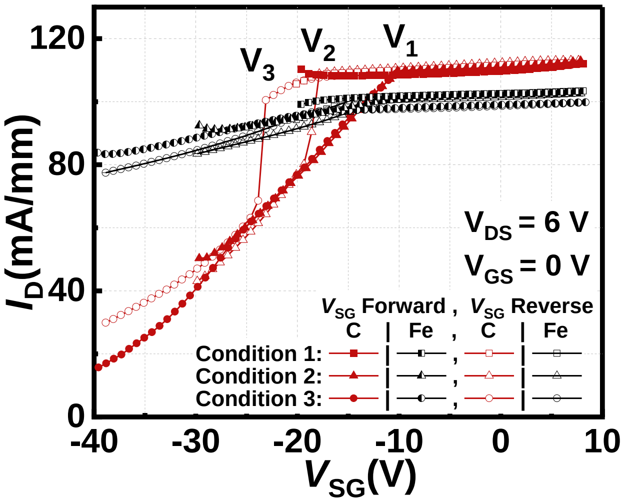

Fig. 3 I_D - V_{SG} plot of Fe-GaN and C-GaN at different V_{SG} conditions.

In addition, the transconductance (g_m) – V_{GS} and I_D – V_{GS} characteristics (transfer curve) at V_{SG} = 0 V, -20 V and -40 V are also measured. For the transfer curve of Fe-doped GaN (see Fig. 4), the maximum I_D ($I_{D,max}$) are 230 (V_{SG} = 0 V), 190 (V_{SG} = -20 V) and 150 (V_{SG} = -40 V) mA/mm. These values are almost comparable even at higher negative V_{SG} bias. The calculated threshold voltages (V_{TH}) are -1.50 V (V_{SG} = 0 V), -1.30 V (V_{SG} = -20 V), and -1.10 V (V_{SG} = -40 V). The maximum g_m ($g_{m,max}$) is slightly lower at V_{SG} = -40 V as compared to the $g_{m,max}$ at V_{SG} = 0 V and -20V. Conversely, for the transfer curve of C-doped GaN (see Fig. 5), the $I_{D,max}$ are 280 (V_{SG} = 0 V), 220 (V_{SG} = -20 V) and 80 (V_{SG} = -40 V) mA/mm. The measured $g_{m,max}$ at V_{SG} = -40 V is much lower as compared to the $g_{m,max}$ at V_{SG} = 0 V. The calculated V_{TH} = -0.80 V at V_{SG} = -40 V is shallower than the V_{TH} = -1.70 V at V_{SG} = 0 V and V_{TH} = -1.40 V at V_{SG} = -20 V. The large decrease in the $I_{D,max}$ and V_{TH} suggests that the 2DEG is depleted at high negative V_{SG} which is also inferred to be due to SG field modulation.

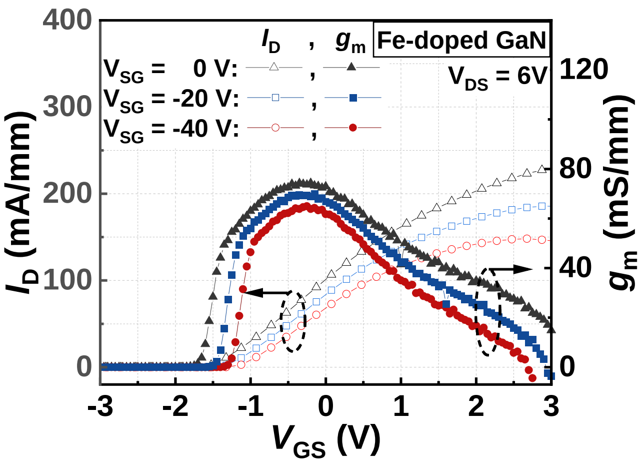

Fig. 4 Transfer curve of Fe-doped GaN at different V_{SG} conditions.

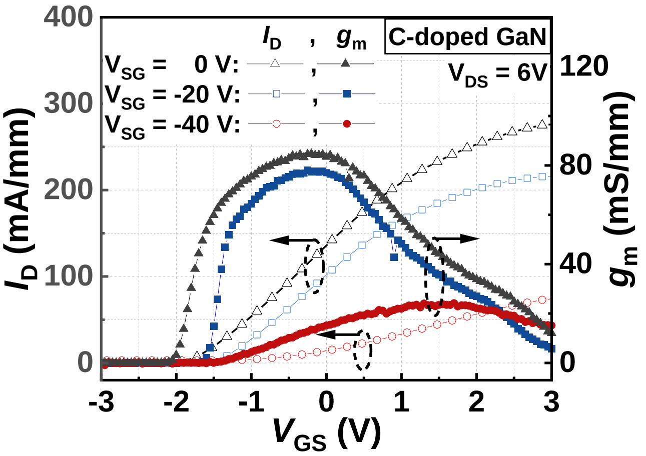

Fig. 5 Transfer curve of C-doped GaN at different V_{SG} conditions.

4. Conclusions

SG modulation of varied negative V_{SG} bias during the dual-sweep SG measurement is experimentally demonstrated for GaN-on-GaN HEMTs. It can be concluded based from the $I_D - V_{SG}$ plot that C-doped GaN has I_D wider hysteresis feature at higher negative V_{SG}. Moreover, C-doped GaN is less stable to SG modulation as compared to Fe-doped GaN, which is evident in its transfer characteristic curve at higher V_{SG} bias.

Acknowledgements

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