Improved current collapse in AlGaN/GaN HEMTs by O_2 plasma treatment

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Abstract

In this paper, we report on the effect of O_2 plasma treatment on the gate leakage and current collapse characteristics for AlGaN/GaN high-electron-mobility transistors (HEMTs). The O_2 plasma treatment was effective to significantly reduce the dynamic on-resistance by 1/20, as compared to that for the standard AlGaN/GaN HEMT with no plasma treatment. It was found that the gate leakage current was not affected by the O_2 plasma treatment and the dynamic on resistance of O_2-plasma-treated HEMTs was rather insensitive to the kinds of passivation films.

INTRODUCTION

AlGaN/GaN high-electron-mobility transistors (HEMTs) are attractive for use in next-generation, low-loss, high-voltage, and high-temperature power applications. To achieve high-efficiency operation in power AlGaN/GaN HEMTs, current collapse must be minimized since it gives rise to a significant increase in dynamic on resistance under high drain voltage operation, leading to a detrimental increase in the conduction loss. An O_2 plasma treatment is widely used in AlGaN/GaN HEMT processing and is known to give various effects on the device performance. Hong et al. reported that the gate leakage current was reduced by applying an O_2 plasma treatment on the access region of AlGaN/GaN HEMTs [1]. Lee et al. reported that the O_2 plasma treatment on the surface of InAlN/GaN HEMTs resulted in the reduced gate leakage current and enhanced high-frequency performance [2]. Meyer et al. reported that O_2 plasma treatments resulted in improved pulsed I-V characteristics with degraded gate-leakage and gate-breakdown characteristics [3-4]. Lee et al. used remote O_2 plasma treatment in a gate-recess region of AlGaN/GaN HEMTs and obtained improved gate leakage and current collapse characteristics [5]. Although a number of previous studies have been made on O_2 plasma treatments, no detailed studies have been reported on the effect of O_2 plasma pre-treatment for surface SiN passivation on the current collapse characteristics.

In this paper, we describe the performance of AlGaN/GaN HEMTs suffering from O_2 plasma as a pre-treatment before SiN passivation and demonstrate dramatic improvements in the current collapse with no significant changes in gate-leakage and gate-breakdown characteristics.

DEVICE STRUCTURE AND FABRICATION PROCESS

Fig. 1 shows the cross section of our AlGaN/GaN HEMTs fabricated on a SiC substrate. The epi-structure consists of a 500 nm undoped GaN channel layer and a 25 nm undoped AlGaN barrier layer. The Al composition in AlGaN was 20 %. AlGaN/GaN HEMTs were fabricated using standard device fabrication processes, including BCl_3/Cl_2-based mesa isolation with an etching depth of 330 nm, ohmic metallization by e-beam evaporation of Ti/Al/Mo/Au (15/60/35/50 nm) followed by annealing at 880 °C for 30 s in N_2 ambient, and Schottky gate metallization by Ni/Au (100/200 nm). Nominal source-to-gate spacing (L_{sg}), gate length (L_g), and gate-to-drain spacing (L_{gd}) were 3 μm, 3 μm, and 10 μm, respectively. The gate width (W_g) was fixed at 100 μm. O_2 plasma treatments were conducted on the AlGaN surface with a plasma power of 100 W and a treatment time of 1 min. The device without O_2 plasma treatment was also fabricated as a reference. After the plasma treatment, SiN was deposited as a passivation layer with a thickness of 150 nm by sputtering. The device exhibited a maximum drain current of 0.54 A/mm at V_{gs} = 1 V with a threshold voltage of -2.6 V and an off-state breakdown voltage of 1000 V.

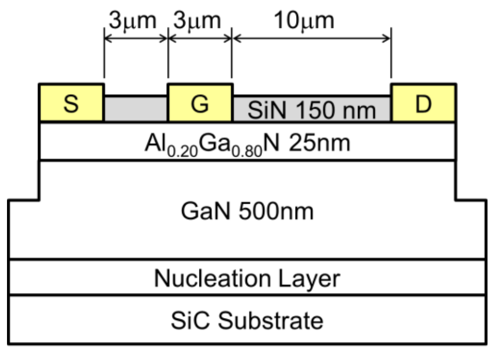

Fig. 1 Cross sectional view of fabricated AlGaN/GaN HEMT.

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RESULTS AND DISCUSSION

Fig. 2 compares two terminal gate leakage current characteristics for devices with and without O_2 plasma treatment. The leakage currents measured at a gate voltage of -150 V were 5.3×10^{-7} A/mm and 4.4×10^{-7} A/mm for devices with and without O_2 plasma treatment, respectively, indicating that the plasma treatment has a negligible effect on the gate leakage characteristics.

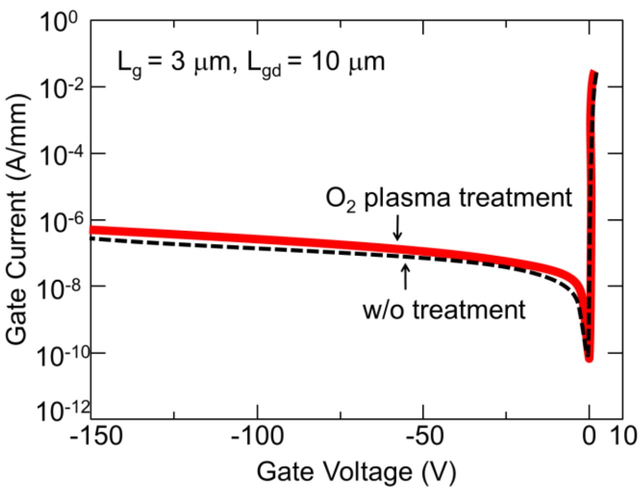

Fig. 2 Two-terminal gate current as a function of gate voltage for devices with and without O_2 plasma treatment.

Fig. 3(a) and 3(b) show drain I-V characteristics measured by a curve tracer for devices with and without O_2 plasma treatment, respectively. Measurements were made with a fixed gate voltage of 0 V, while changing the drain sweep voltage up to 50 V. It is evident that the on-resistance for the untreated device increases substantially, whereas that for the O_2-plasma-treated device hardly increases with increasing the drain bias sweep voltage, indicating that the O_2 plasma exposure on the AlGaN surface is beneficial for the reduction of drain current collapse.

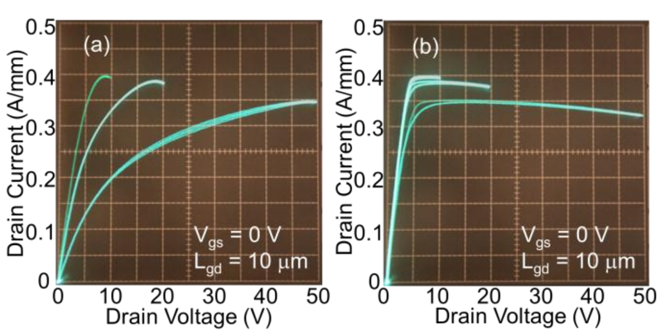

Fig. 3 Drain I-V characteristics measured at V_{gs} = 0 V while varying drain voltage swing from 10 to 50 V for devices (a) without and (b) with O_2 plasma treatment.

More detailed time response of drain current during on state is shown in Fig. 4, where the on-state duration time (t_{on}) and the off-state duration time (t_{off}) were chosen to be 1 μs and 10 ms, respectively. An off-state drain voltage of 100 V was used with a load resistance of 10 kΩ, corresponding to a static on-state drain current of less than 1/4 of the maximum drain current. More details for the pulse measurement setup were described elsewhere [6]. A quick response with a time constant of less than 1μs was observed for the device with O_2 plasma treatment. The dynamic on-resistance for the device with O_2 plasma treatment, measured at t_{on} = 1 μs, was 49 Ωmm, whereas that without plasma treatment was degraded to as high as 1093 Ωmm, indicating that O_2 plasma exposure process is effective to reduce dynamic on-resistance to a value which is about 20 times lower than that obtained without O_2 plasma treatment.

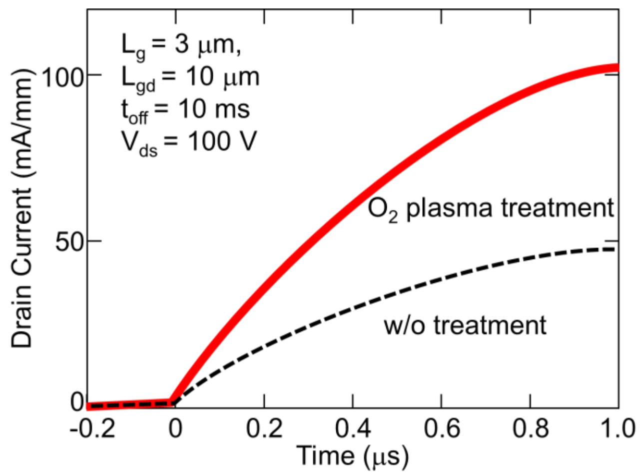

Fig. 4 Transient drain current waveform for devices with and without O_2 plasma treatment. Off-state drain bias voltage is 100 V.

Fig. 5(a) and 5(b) show the normalized dynamic on-resistance (NDR) as a function of the off-state drain voltage, where NDR is defined as the ratio of measured dynamic on-resistance and its static value. The NDR for SiN-passivated devices, shown in Fig. 5(a), was increased with increasing the off-state drain voltage. However, much lower NDR by more than one order of magnitude was obtained for the device with O_2 plasma treatment than that without plasma treatment. The effects of passivation films on NDR, including SiO_2 (140 nm) and AlN (150 nm) both of which were deposited by sputtering, are shown in Fig. 5(b). Similar improvements in NDR by applying O_2 plasma treatments were observed for both SiO_2 and AlN passivated devices. It is interesting to note that the off-state drain voltage dependence of NDR is almost the same between devices with O_2 plasma exposure irrespective of the passivation material used, suggesting that the dynamic on-resistance is primarily determined by the AlGaN surface modified by O_2 plasma treatments, and not by the material properties of the passivation film.

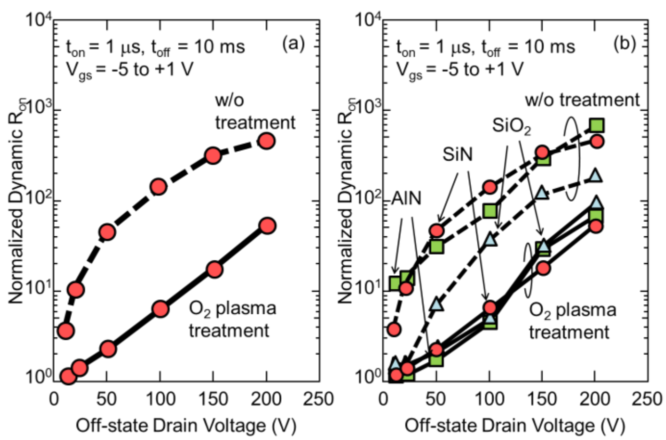

Fig. 5 Normalized dynamic on-resistance (R_{on}) as a function of off-state drain voltage for devices with and without O_2 plasma treatment. On-state duration time is 1µs. Results for devices passivated with SiN (a) and those passivated with SiN, SiO_2, and AlN (b).

Fig. 6 shows NDR for the SiN-passivated device as a function of time during on-state. The t_{off} was fixed at 100 ms and the off-state drain voltage was 100 V. The time response of NDR was expressed as a sum of exponential transients [7].

$$\mathrm{NDR} = 1 + \sum_{i=1}^{n} \alpha_i \exp\left(-\frac{t}{\tau_i}\right)$$

The broken line shows the fitted curve using the above equation with four time constants of 2.2×10^{-5}, 2.9×10^{-4}, 5.1×10^{-3}, and 4.0×10^{-2} s. Using Shockley-Read-Hall statistics assuming a thermal electron velocity of 2.4×10^{7} cm/s and a capture cross-section of 1×10^{-15} cm^2, four trap levels (E_c-E_t) were calculated to be 0.37, 0.43, 0.51, 0.56 eV. The dominant transient was due to the energy level of 0.37 eV from the conduction band.

TABLE I shows the summary of measured characteristics of AlGaN/GaN HEMTs with and without O_2 plasma treatments. Note that the O_2 plasma treatment resulted in improved current collapse without degrading most of the DC characteristics, including a low gate leakage current with a high breakdown voltage of around 1000 V. The dynamic R_{on} was decreased from 1093 Ωmm (without O_2 plasma) to 49 Ωmm (with O_2 plasma), indicating about 20 times reduction in the dynamic on-resistance by O_2 plasma treatments.

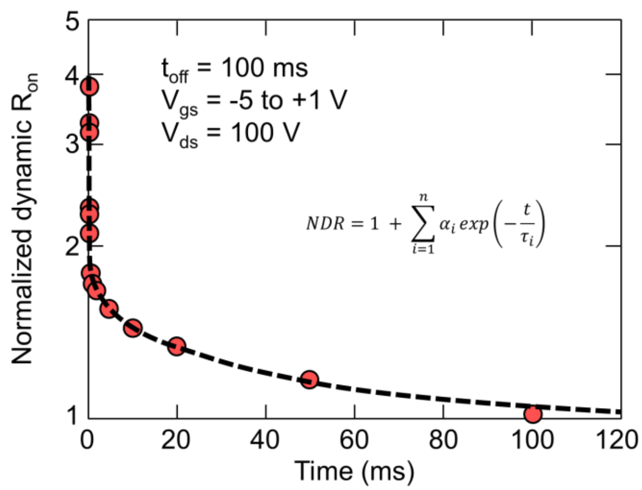

Fig. 6 NDR for the SiN-passivated device as a function of time during on state. Broken line shows the fitted curve assuming exponential transients.

TABLE I Summary of device performance.

	w/o Treatment	O_2 Plasma Treatment
I_{dmax} (A/mm) @V_{gs} = 1 V	0.53	0.54
Static R_{on} (Ωmm) @V_{gs} = 1 V	8.0	8.1
V_{th} (V)	-2.5	-2.6
Gate Leakage (A/mm) @V_{gs} = -150 V	4×10^{-7}	5×10^{-7}
V_{BR} (V) @I_d = 100 µA/mm	1010	1000
Dynamic R_{on} (Ωmm) @V_{ds_off} = 100 V	1093	49

CONCLUSIONS

We have investigated the effect of O_2 plasma treatment on the gate leakage and current collapse characteristics for AlGaN/GaN HEMTs passivated with a SiN film. The O_2 plasma exposure on the AlGaN surface was found to be effective to significantly reduce the dynamic on resistance, as compared to that for the standard AlGaN/GaN HEMT with no plasma treatment. The gate leakage current was not affected by O_2 plasma treatment and the dynamic on-resistance of the plasma-treated HEMT was rather insensitive to the kinds of passivation films. By analyzing the transient response of dynamic on resistance, the dominant trap level was determined to be located at 0.37 eV from the conduction band.

ACKNOWLEDGEMENTS

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ACRONYMS

HEMT: High-electron-mobility transistor
NDR: Normalized dynamic R_{on}
L_{sg}: Source-to-gate spacing
L_g: Gate length
L_{gd}: Gate-to-drain spacing
W_g: Gate width
t_{on}: On-state duration time
t_{off}: Off-state duration time