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# Highly Reduced Current Collapse in AlGaN/GaN HEMTs by Combined Application of Oxygen Plasma Treatment and Field-plate Structures

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**Abstract**

**Using the oxygen plasma treatment alone, we have dramatically cut down the current collapse in AlGaN/GaN high-electron mobility transistors (HEMTS) as evidenced by more than an order of magnitude reduction in normalized dynamic $R_{on}$ (NDR) with respect to that of untreated reference devices. By incorporating the field-plate (FP) structure in these oxygen plasma treated devices, we were able to further reduce the NDR by almost 45 %, demonstrating for the first time the additive effect of oxygen plasma treatment and field-plate structures in mitigating current collapse.**

## 1. Introduction

With so many desirable intrinsic properties, gallium nitride (GaN) has become one of the leading material candidates for realizing devices are capable of handling unprecedented power levels and frequencies well beyond those possible with the conventional silicon-based devices [1]. Nevertheless, the widespread adoption of GaN-based devices is still limited due to several issues, foremost of which is the well-known current collapse. Although still under debate, it is widely believed that current collapse is predominantly due to charging of traps on the AlGaN surface [2]. Accordingly, current collapse is usually addressed by schemes involving the device surface such as passivation [3], plasma surface treatment [4], or adding a cap layer [5]. Aiming for a collapse-free operation, our group has been combining some of these different schemes. Results from one of our previous works suggest that employing two different solutions to current collapse does not necessarily guarantee linear (additive) effect. For instance, we have found out that GaN cap layer has no further effect on the reduction of current collapse in the devices subjected to oxygen ($O_2$) plasma treatment [6].

Meanwhile, field-plate (FP) technology is a well-known approach for achieving not only high breakdown voltages but also reduced current collapse by reducing the electric field strength at the drain edge of the gate [7]. Furthermore, we have found out that the partial depletion of 2DEG electrons can be instantly recovered by field effect of a positively biased FP electrode [8]. In this work, we demonstrate for the first time highly-suppressed current collapse in AlGaN/GaN HEMTs by combined application of $O_2$ plasma treatment and field-plate structures.

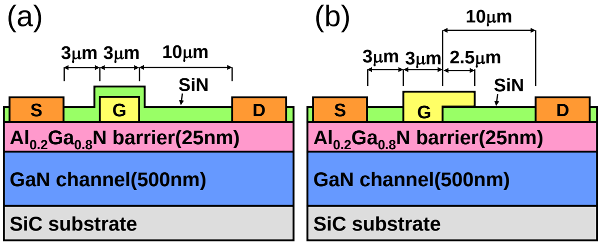


Fig. 1. Simplified schematic cross-section of (a) device A ($O_2$ plasma-treated device without FP) and (b) device B ($O_2$ plasma-treated device with FP).

## 2. Experimental

Three different devices were fabricated and investigated in this work, namely, device A ($O_2$ plasma-treated device without FP), device B ($O_2$ plasma-treated device and with FP), and device C (without $O_2$ plasma treatment and without FP). The device fabrication started with the formation of mesa isolation structures by inductively coupled plasma reactive ion etching (ICP-RIE), using a gas mixture of $BCl_3/Cl_2$. To form the drain and source ohmic electrodes, a Ti/Al/Mo/Au (15/60/35/50 nm) metal stack was then deposited by electron beam evaporation and annealed under N2 atmosphere at 880 ˚C for 30 s. For devices A and B, prior to SiN passivation, the AlGaN surface was subjected to $O_2$ plasma treatment using a plasma power of 100 W and exposure time of 1 min. The gate window was then formed by removing portions of the SiN film by dry etching, followed by Schottky gate (device A) or Schottky gate and FP formation (device B) with Ni/Au (50/150 nm) bilayer. The reference device C was fabricated using exactly the same procedure as that of device A, minus the $O_2$ plasma treatment. The simplified schematic cross-section images of devices A and B are shown in **Figs. 1 (a)** and **(b)**, respectively.

After confirming that the devices have essentially identical DC characteristics, we then performed current collapse evaluation by carrying out stress- and time-dependent dynamic $R_{on}$ measurements [8]. A train of gate pulses alternating between –5 V (OFF-state) and +1 V (ON-state) was applied to the gate terminal. At every pulse on-time duration (ton), the corresponding $V_{ds}(t_{on})$ and $I_{ds}(t_{on})$ were recorded and used to compute the resulting dynamic $R_{on}$. We used the normalized dynamic $R_{on}$ (NDR), which is defined as the ratio of dynamic $R_{on}$ to static $R_{on}$, to represent the degree of current collapse.

## 3. Results and Discussion

**Figures 2 (a) and (b)** show the dependence of NDR on $t_{on}$ for devices A and C respectively. Compared with the reference device C, device A exhibited lower corresponding NDR, suggesting the effectiveness of $O_2$ plasma treatment alone in reducing current collapse. As proposed by Del Alamo and co-workers [9], NDR can be expressed as a sum of pure exponential terms in the form:

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

where, $\alpha_i$ represents the magnitude of the trapping process with time constant $\tau_i$. Fitting the experimentally measured NDR with the above relationship, we were able to obtain the best fit curves (solid curves) and the corresponding exponential terms (dashed curves) given in Fig. 2. Each dashed curve represents a trap level with associated ($E_C - E_t$) energy value. By performing a detailed analysis using Shockley-Read-Hall (SRH) statistics [10], we came up with the conclusion that $O_2$ plasma treatment leads not only to significant reduction in surface trap densities, as suggested by its corresponding smaller $\alpha_i$ values, but also to elimination of the two deepest trap levels traps 5 and 6.

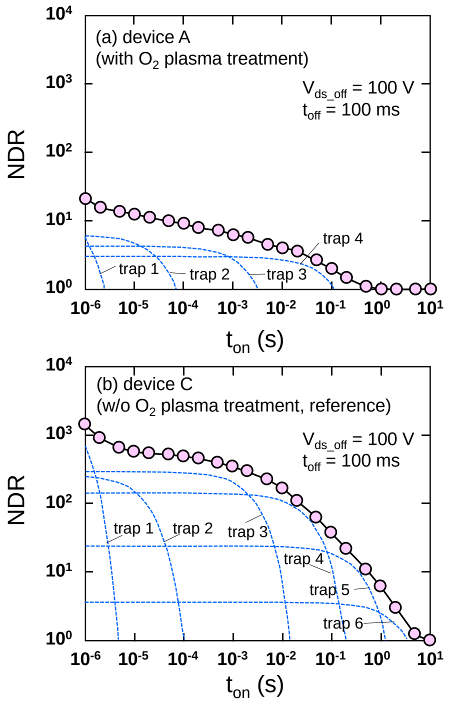


Fig. 2. Measured (solid data points) and calculated (solid curves) normalized dynamic Ron (NDR) dependence on $t_{on}$ of (a) device A ($O_2$ plasma-treated device without FP) and (b) reference device C. Dashed curves are extracted exponential terms each representing a trap level.

To investigate if further reduction of current collapse is possible with the application of FP structures, we then performed dynamic $R_{on}$ measurements under different $V_{ds\_off}$ for devices A and B. As can be seen in Fig. 3, device B exhibited smaller NDR values, which seems to be further reduced with increasing $V_{ds\_off}$. At $V_{ds\_off}$ = 250 V, a 45 % reduction in NDR was achieved. We believe that the effectiveness of the combined approaches is due to the fact that each method offers non-overlapping solution to current collapse. While $O_2$ plasma treatment reduces and/or eliminates surface trap densities responsible for current collapse, the FP structure not only reduces the peak electric field that leads to surface charging at the drain edge of the gate but also instantly recovers by field effect of a positively biased FP electrode the partial depletion of 2DEG.

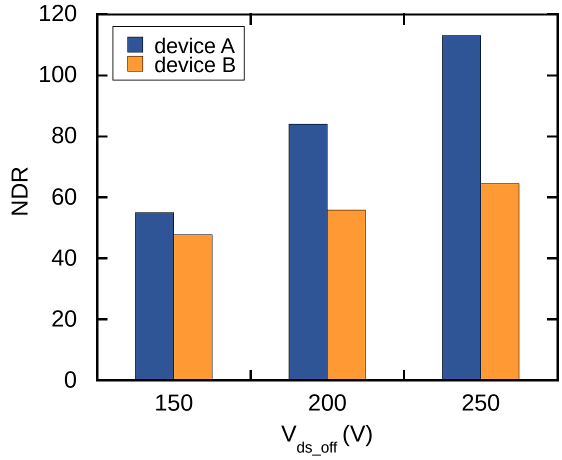


Fig. 3. $V_{ds\_off}$ dependence of NDR for device A ($O_2$ plasma-treated device without FP) and device B ($O_2$ plasma-treated device with FP).

## 4. Conclusions

In summary, by oxygen plasma treatment alone, we have dramatically reduced the current collapse in AlGaN/GaN high-electron mobility transistors (HEMTS) as evidenced by more than an order of magnitude reduction in normalized dynamic $R_{on}$ (NDR) with respect to that of untreated reference devices. By incorporating the field-plate (FP) structure in these $O_2$ plasma treated devices, we were able to further reduce the NDR by almost 45%, thereby demonstrating for the first time the additive effect of $O_2$ plasma treatment and field-plate structures in mitigating current collapse. We believe that the efficacy of the combined approaches is due to the fact that each method offers non-overlapping solution to current collapse.

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