# Time-dependent degradation of threshold voltage in AlGaN/GaN high electron mobility transistors*

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This paper gives a detailed analysis of the time-dependent degradation of the threshold voltage in AlGaN/GaN high electron mobility transistors (HEMTs) submitted to off-state stress. The threshold voltage shows a positive shift in the early stress, then turns to a negative shift. The negative shift of the threshold voltage seems to have a long recovery time. A model related with the balance of electron trapping and detrapping induced by shallow donors and deep acceptors is proposed to explain this degradation mode.

**Keywords:** AlGaN/GaN high electron mobility transistor, off-state stress, electron detrapping, degradation

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## 1. Introduction

The GaN high electron mobility transistor (HEMT) technology becomes increasingly attractive for a variety of high-frequency and high-power applications. In spite of the impressive attributes of this technology and the outstanding performance that has been demonstrated, the robustness of these devices at high reverse bias is still a challenge. Detailed physical understanding of the failure mechanism in GaN HEMTs is essential before this technology can be widely adopted.

A few years ago, Joh[1,2] demonstrated the existence of a critical voltage beyond which the gate diode degrades. The most striking manifestation of this is an irreversible sudden rise in the reverse bias gate current and the onset of a drain current degradation. In fact, it is the inverse piezoelectric effect[3–8] in which a defect formation could happen through the strain relaxation; a degradation occurs when a critical elastic energy is reached, due to the mechanical strain produced by the electric field. More recently, Marcon[9] indicated that not only does the gate degradation appear beyond the critical voltage but also the time necessary to observe the degradation ($t_{BD}$) has a strong voltage dependence. Then Meneghini[10] demonstrated that devices can show permanent damage even below the critical voltage. In 2012, Fu[11] observed a critical voltage in the high stress voltage range, beyond which the HEMT device starts to recover from the degradation induced by early lower voltage stress. The recovery process is explained by a high electric field induced electron detrapping mechanism.

The inverse piezoelectric effect,[12] time-dependent degradation effect and field-dependent degradation effect significantly help us understand the dependence of the degradation mechanism on the stress conditions. In this paper, we find a time-dependent drain current recovery mechanism and show the change rules of the threshold voltage during stress time below the critical voltage. A model is proposed to explain the degradation mechanism of the electrical parameters. By nonlinear fitting, time constants of electron trapping and detrapping are identified.

## 2. Experimental details

The AlGaN/GaN HEMT in this work is grown by metal–organic chemical vapor deposition on SiC. The heterojunction consists of a 2-μm thick GaN buffer and a 22-nm thick $Al_{0.23}Ga_{0.77}N$ barrier layer with a 1.5-nm thick GaN cap layer. The gate patterns are made by optical lithography with $L_g = 0.8$ μm and $W_g = 100$ μm. The source to drain spacing $L_{sd}$ is 4 μm. Ti(20 nm)/Al(180 nm)/Ni(55 nm)/Au(45 nm) metals and Ni(40 nm)/Au(500 nm) metals are used to form the source and the gate, respectively. Ohmic contacts are formed by rapid thermal annealing at 870 °C for 50 s in $N_2$ ambience. The recessed gate is formed by dry etching using an inductively coupled plasma reactive ion etching system and the etching depth is 3–4 nm. Finally, the device is passivated by a 120-nm thick SiN film deposited by plasma-enhanced chemical vapor deposition at 280 °C. During stress, several device parameters have been measured by an HP4142B. The initial threshold voltage and transconductance are −2.6 V and 325 mS/mm, respectively.

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## 3. Experiment and discussion

First, we carry out step-stress experiments in the off-state. With the source grounded and $V_{gs} = -5$ V, increasing positive voltages from 0 V to 40 V in steps of 1 V are applied to the drain. At each voltage step, the device is continuously stressed for 1 min, during which $I_{goff}$, $I_{dmax}$ and $V_{th}$ are quickly measured to evaluate the resulting device performance (Table 1). As shown in Fig. 1, no degradation in $I_{goff}$ and $I_{dmax}$ can be observed by stressing the device with voltages lower than 21 V. During the whole stress time, we do not observe a current slump or boom, indicating that no permanent damage occurs and that the critical voltage is greater than 40 V.

**Table 1.** Device parameters monitored during the experiments.

| Parameter | Definition |
|---|---|
| $I_{goff}$ | leakage current, measured at $V_{gs} = -5$ V and $V_{ds} = 0.1$ V |
| $I_{dmax}$ | maximum drain current, measured at $V_{gs} = 1$ V and $V_{ds} = 6$ V |
| $V_{th}$ | gate voltage, measured at $I_{ds} = W_g \times 1$ mA/mm+$I_{pinch\ off}$[13] |

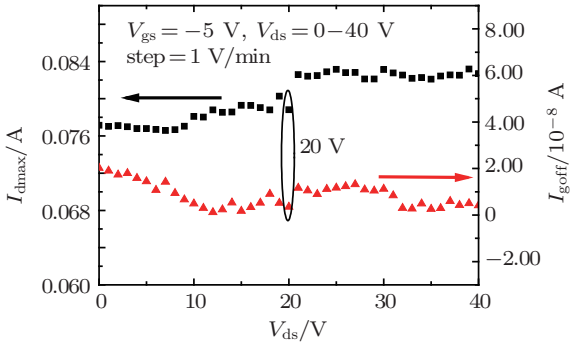



**Fig. 1.** (color online) Changes in $I_{goff}$ and $I_{dmax}$ for an HEMT submitted to a drain step stress experiment.

In order to achieve a better description of the degradation process, we have carried out a set of off-state experiments at fixed $V_{gs} = -5$ V, $V_{ds} = 20$ V, with the source grounded. It is worth noticing that this voltage level is smaller than the critical voltage of degradation and even smaller than the voltage at which the recovery process occurs due to the field-dependent effect.[11] Moreover, the voltages of $V_{gs} = -5$ V and $V_{ds} = 20$ V are within the normal operating voltage of a device.

First, we choose 15 fresh devices to carry out the experiments mentioned above, finding that $V_{th}$ has different changing trends, as shown in Table 2. According to this statistical law, obviously the mainstream is the first one and the two other phenomena may be caused by mobile charge or different device initialization. Therefore, we focus on the first case.

**Table 2.** Statistics of devices with different changing trends of $V_{th}$ under the same stress condition.

| $V_{th}$ | First increase then decrease | Increase | Decrease |
|---|---|---|---|
| Quantity | 10 | 2 | 3 |

The results obtained by stressing on the same HEMT three times (#1, #2, #3) are reported. The duration of each experiment is 3000 s with an interval of 20 min. It can be observed that $I_{goff}$ rises by less than 3% in both the second and the third experiments (Fig. 2). No significant degradation occurs, so the relative repeatability of this device is guaranteed for each experiment.

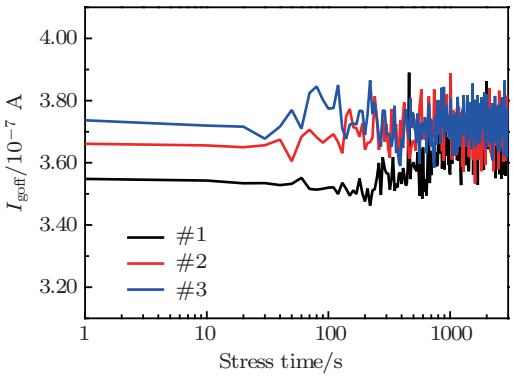



**Fig. 2.** (color online) Variation of $I_{goff}$ during off-state stress (duration = 3000 s, interval = 20 min). The stress conditions are $V_{gs} = -5$ V, $V_{ds} = 20$ V and $V_s = 0$ V.

At the beginning of the off-state stress, the shift of $V_{th}$ increases (Fig. 3), well correlated to a decrease in $I_{dmax}$ (Fig. 4). After this initial period, $V_{th}$ shifts to a negative bias and $I_{dmax}$ starts to increase. Figure 4 shows two groups of curves. The trend of the upper group extracted by output characteristics (3 s after stress) is similar to the rest one measured by pulses (1 ms after stress).

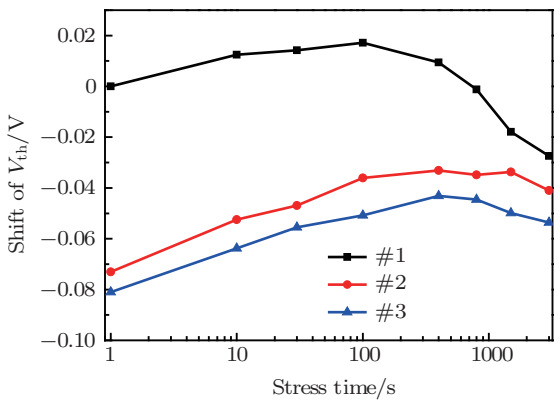



**Fig. 3.** (color online) Variation of shift of $V_{th}$ during off-state stress (duration = 3000 s, interval = 20 min). The stress conditions are $V_{gs} = -5$ V, $V_{ds} = 20$ V, and $V_s = 0$ V.

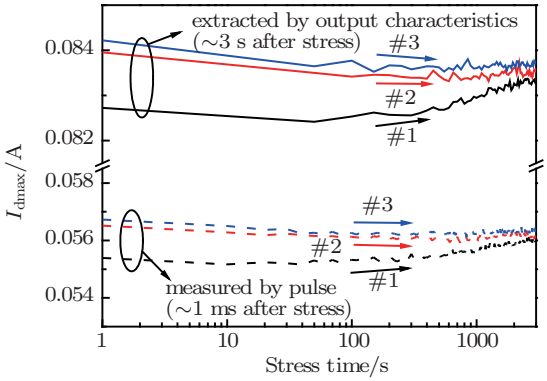



**Fig. 4.** (color online) Variation of $I_{dmax}$ during off-state stress (duration = 3000 s, interval = 20 min). The stress conditions are $V_{gs} = -5$ V, $V_{ds} = 20$ V and $V_s = 0$ V. The upper group of curves is extracted by output characteristics (3 s after stress) and the lower group of curves is measured by pulses (1 ms after stress).

The following model is proposed to explain the degradation of the electrical characteristics of HEMTs submitted to off-state stress. According to the variation trend of the experiment parameters, the whole experiment is defined as two processes. In the first one, when a reverse bias is applied to the gate, the potential of the drain is the highest. Therefore, the shallow ionized donors on the surface or in the barrier layer between the gate and the drain can be immediately filled by electrons ($e^-(1)$) coming from the gate (Fig. 5(a)). The accumulation of negative charge in the AlGaN layer forms a virtual gate, resulting in a decrease in $I_{dmax}$ (Fig. 4). It is a process of electron trapping leading to an increase in the shift of $V_{th}$ (Fig. 3). In Fig. 4, the difference between the two groups of curves is that the upper one is a quick process of detrapping, which is the inverse process of trapping.

The second process is as follows. At $V_{gs} = 0$ V, all acceptors under the Fermi level are generally occupied by electrons (Fig. 5(b)). Due to the negative potential of the gate, the Fermi level on the left moves up away from the conduction band, resulting in an electric potential difference between the Fermi level of metal and that of electrons, which equals to $-V_{gs}$. Electrons in the AlGaN above the Fermi level have enough energy to detrap to the buffer.[14,15] The generated ionized acceptor traps are accumulated in the AlGaN layer (Fig. 5(c)). This leads to a negative shift of $V_{th}$ (Fig. 3).[16] Hence, $I_{dmax}$ increases (Fig. 4).

In fact, both electron trapping and detrapping co-exist throughout the two processes. In the first 100 s, electron trapping is the dominant process. Because of the limited amount of shallow ionized donors, the process of electron trapping gradually saturates, leading to a decrease in this effect (Figs. 3 and 4). This phenomenon is also a result of the Coulomb screening,[17] which reduces the field due to the newly trapped charge and suppresses further the conduction. During the stress time, the Coulomb field associated with this newly trapped virtual-gate charge will result in a local field between the traps and the gate corner reversing, tending to prevent further injection of electrons. However, electron detrapping is a continuous process and has a long recovery time. It is not apparent until 100 s (Figs. 3 and 4). All these cases above demonstrate that the two processes are unified and that different device initialization can induce variation trends of $V_{th}$ under the same stress condition. After removing the off-state stress, it is easy to obtain electrons from the valence band for the shallow acceptors, but difficult for the deep acceptors (Fig. 5(d)). Therefore, although there is a recovery process for $V_{th}$ and $I_{dmax}$ (Figs. 3 and 4), they can return to the initial values.

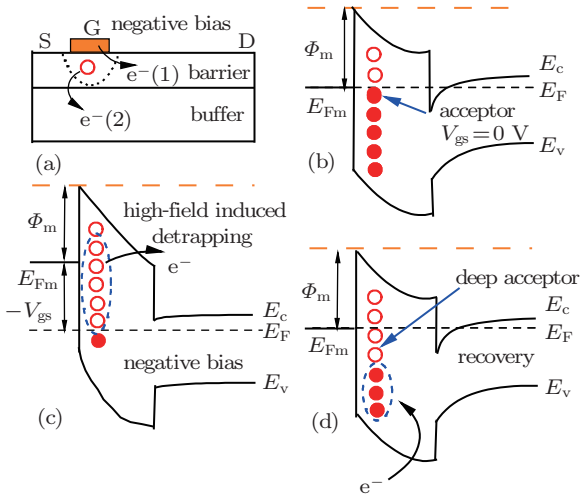
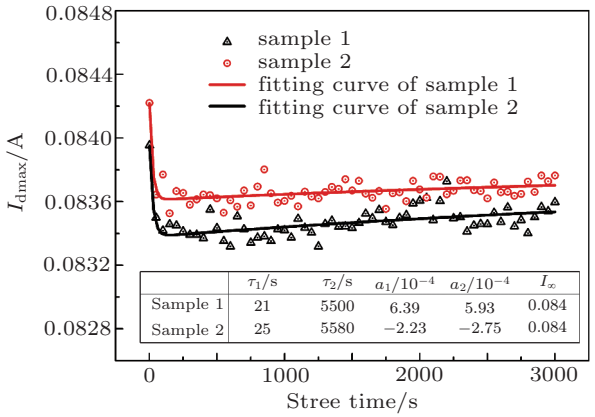



**Fig. 5.** (color online) Schematic description of the model used to explain the degradation of the electrical characteristics of HEMTs submitted to off-state reverse-bias stress. (a) Cross-section view of the AlGaN/GaN HEMT in stress. (b) Stress condition $V_{gs} = 0$ V; (c) stress condition $V_{gs} = -5$ V, $V_{ds} = 20$ V, $V_s = 0$ V; (d) recovery process.

Based on the above model, by combining the electron trapping and detrapping, the fitting function can be expressed as[18]

$$I_{fitted} = a_1 \exp(-t/\tau_1) + a_2 \exp(-t/\tau_2) + I_\infty. \quad (1)$$

The fitting is performed to minimize the sum of $|I_{data} - I_{fitted}|^2$ at the measured points. In this formula, $a_i$ is the fitting parameter and positive (negative) values of $a_i$ correspond to the trapping (detrapping) processes. Here, $a_i$ represents the magnitude of the trapping (detrapping) process of time constant $\tau_i$. We can respectively obtain $\tau_1$ and $\tau_2$ from the two processes. In Fig. 6, two sets of time constants are extracted from the fitting curves, indicating that the process of electron trapping is short and the latter is a continuous process. It is consistent with the conclusion we obtained above.




| | $\tau_1$/s | $\tau_2$/s | $a_1/10^{-4}$ | $a_2/10^{-4}$ | $I_\infty$ |
|---|---|---|---|---|---|
| Sample 1 | 21 | 5500 | 6.39 | 5.93 | 0.084 |
| Sample 2 | 25 | 5580 | −2.23 | −2.75 | 0.084 |

**Fig. 6.** (color online) The fitting curves of $I_{dmax}$ during off-state stress. Stress conditions are $V_{gs} = -5$ V, $V_{ds} = 20$ V and $V_s = 0$ V. The inset gives the time constants of electron trapping and detrapping extracted from the fitting curves.

## 4. Conclusion

In this paper, we have developed a model capable of explaining the time-dependent behavior of threshold voltage in an AlGaN/GaN HEMT submitted to off-state stress ($V_{gs} = -5$ V, $V_{ds} = 20$ V, $V_s = 0$ V). It is demonstrated that below the critical voltage, the changes of $V_{th}$ during the stress time are induced by electrons trapping and detrapping, which are related to the deep acceptor level ionization. The time constants of the whole experimental process are identified, which are consistent with the argument. The results support the existence of time-dependent degradation for HEMT, which suggests several paths to enhance the electrical reliability of GaN HEMTs.

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