Kink effect in AlGaN/GaN high electron mobility transistors by electrical stress*

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The kink effect is studied in an AlGaN/GaN high electron mobility transistor by measuring DC performance during fresh, short-term stress and recovery cycle with negligible degradation. V_{dg} plays an assistant role in detrapping electrons and short-term stress results in no creation of new category traps but an increase in number of active traps. A possible mechanism is proposed that electrical stress supplies traps with the electric field for activation and when device is under test field-assisted hot-electrons result in electrons detrapping from traps, thus deteriorating the kink effect. In addition, experiments show that the impact ionization is at a relatively low level, which is not the dominant mechanism compared with trapping effect. We analyse the complicated link between the kink effect and stress bias through groups of electrical stress states: $V_{ds} = 0$-state, off-state, on-state (on-state with low voltage, high-power state, high field state). Finlly, a conclusion is drawn that electric field brings about more severe kink effect than hot electrons. With the assistance of electric field, hot electrons tend to be possible to modulate the charges in deep-level trap.

Keywords: high electron mobility transistors, AlGaN/GaN, kink effect, stress states

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1. Introduction

AlGaN/GaN high electron mobility transistor (HEMT) shows a promising performance for high-frequency and high-power applications.[1] In recent years, GaN HEMT devices with various structures have been designed and fabricated, such as enhancement mode (E-Mode) HEMT,[2] and metal–insulator–semiconductor high electron mobility transistor (MIS-HEMT).[3] Although the reliability has been improving, numerous issues related to defects and traps are not fully understood and solved yet, such as the kink effect. Kink effect, resulting from the shift in threshold voltage, is an increase of varying degrees in the drain current at a certain drain/gate voltage. For an intuitive understanding, it is commonly taken to be a charging–discharging process. Different methods have been tried to describe this phenomenon, including simulation.[4] Meneghesso *et al.*[5] identified the kink effect with a nonmonotonic behaviour as a function of photon energy under illumination. By the analysis of the cathode luminescence spectrum, a direct correlation between the presence of the "kink" and the presence of abroad yellow band was demonstrated in Ref. [6]. The link between the kink and factors, such as cryogenic temperatures and fluorine-based treatment, has also been discussed in Refs. [7] and [8]. Experiences show that the kink effect is more likely to relate to the deep level traps in GaN HEMTs other than the impact ionization in GaAs devices. In Ref. [5] the nonmonotonic relation between the kink effect and the electric field was discussed. The kink effect has been considered as a specific kind of current collapse and degradation after long-time electrical stress.[9]

In this paper, we discuss the influence of electrical stress on the magnitude of ΔI_d in the kink effect. In the experiments, the stress bias in the kink effect short-term stress (60 seconds) approach is utilized to study the phenomenon, thereby avoiding the influence on the performance of device. Stress and recovery experiments are carried out next, showing that off-state stress may cause more severe current slump. Then, a mechanism is possibly proposed that the stress results in the activation of traps, thus enhancing the kink effect. Finally, we analyse the donminant factors for different kink magnitudes, with short-term elec-

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trical stress divided into three states: V_{ds} = 0-state, off-state, on-state (on-state with low voltage, high-power state, high field state). This also verifies our proposal that electric field mechanism overweighs the hot-electron induced mechanism for traps activation.

2. Device fabrication and experimental setup

The AlGaN/GaN HEMT layer was grown by metal organic chemical vapour deposition (MOCVD) on a sapphire substrate. The heterostructure consisted of a nucleation layer, a 1-μm-thick GaN buffer layer and an un-doped 20-nm-thick AlGaN barrier layer. The Al mole fraction of the AlGaN was 30%. From the Hall measurement we know that the two-dimensional electron gas (2DEG) electron mobility and concentration are 1267 $cm^2/V{\cdot}s$ and 1.12×10^{13} cm^{-2} at room temperature, respectively. The devices fabrication started with mesa isolation which was formed by inductive coupled plasma (ICP) with the etch-depth of 200 nm. Ohmic contacts consisting of Ti/Al/Ni/Au (22 nm/140 nm/55 nm/45 nm) were annealed in a nitrogen ambient at 850 °C, yielding a contact resistance typically around 1.0 Ω·mm. First passivation film 60-nm-thick Si_3N_4 was deposited on the sample by plasma enhanced chemical vapour deposition (PECVD). Finally, the Ni/Au Schottky gate was deposited by electron-beam evapouration. The second passivation film Si_3N_4 with a thickness of 200 nm was deposited. Direct current characteristics before or after stress were measured by Agilent B1500A semiconductor parameter analyser.

Figure 1 shows a bell-shape relation of the I_d to the V_{gs} estimated by $G_{d,peak}$ (G_d at the peak of each of output curves of different gate voltages), with the maximum value being at the V_{gs} = −2.5 V. For increasing V_{gs} from the pinch-off voltage value of −5 V to 0 V, the $V_{ds,kink}$ (defined as the voltage where the output conductance reaches the peak) has a nonmonotonic behaviour as a function of V_{gs}. ΔI_d is obtained in the same way as that in Ref. [10]. We extract all the parameters from the inset, which shows the kink effect we observe in the dc I_d–V_{ds} characteristics at room temperature without any stress. Meanwhile, we believe that the trapping effect is strongest and most easily observed at V_{gs} = −2.5 V when the Fermi energy level is equivalent to the trap level.[11] Based on what we can see by experience, the bell-shape curve generally represents the situation due to multiple interaction factors.[12,13] For the devices, we believe, the kink is the result of trapping effect, which is influenced by several factors, such as current, temperature and electric field. Each of them dominates the influence on the kink effect when the device operates at a certain voltage.

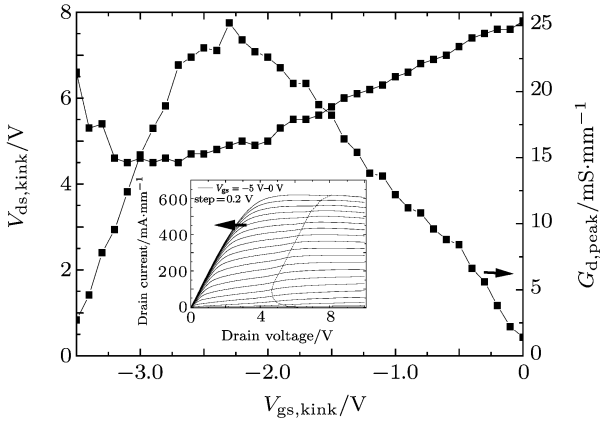


Fig. 1. Curves for $V_{ds,kink}$ versus V_{gs} and $G_{d,peak}$ versus V_{gs}, with V_{gs} −3.5 V–0 V, each point 0.1 V.

Commonly, the method of electrical stress is utilized to estimate the degradation of devices. Experiments show that short-term stress has little influence on the performance of GaN HEMT; therefore, we consider the short-term stress (60 s) and recovery experiments (short-time recovery for 1 min and long-time recovery for 5 min) as an effective approach to the assessment of the influence of various factors on kink behaviour in AlGaN /GaN HEMT.

3. Results and discussion

The on-state stress and off-state stress are applied to the device for 60 s with bias voltages V_{gs} = 0 V and V_{ds} = 5 V, and V_{gs} = −20 V and V_{ds} = 20 V, respectively, which are shown in Figs. 2(a)–2(d). The increase of $G_{d,peak}$ after hot electron stress is less than 30%. When $G_{d,peak}$ is used as a measure of the drain current variation, ignorable current change in the kink effect is seen in Fig. 2(a). However, current slump is seen after off-state stress with $G_{d,peak}$ is twice what it was, which is shown in Fig. 2(c). The variation of gate current with drain voltage shows a rise after stress but without abrupt growth in gate current at $V_{ds,kink}$. Both drain and gate currents recover to the fresh state, indicating no creation of traps. Therefore, the enhancement of the kink effect is probably due to the traps activated in the AlGaN barrier layer and the GaN buffer layer, especially after OFF-state stress. And this happens to the opposite process to the recovery of kink we observe after illumination.

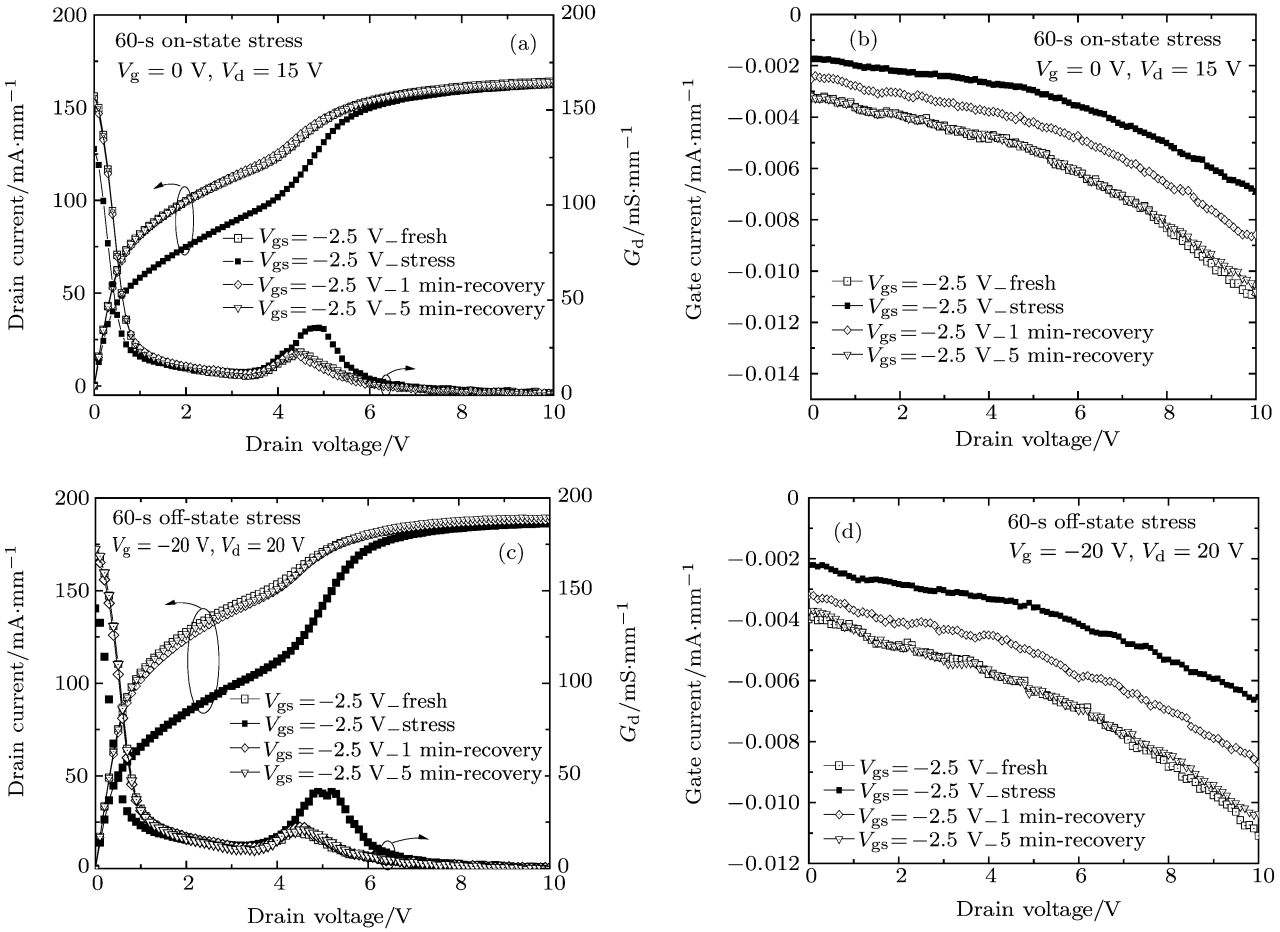


Fig. 2. Output curves ($V_{gs} = -2.5$ V) before and after 60-s short-term stress test ($V_{gs} = 0$ V and $V_{ds} = 15$ V) and after short and long term recovery test (a), I_{gs}–V_{ds} curves ($V_{gs} = -2.5$ V) before and after 60-s short-term stress test ($V_{gs} = 0$ V and $V_{ds} = 15$ V) and after short and long term recovery test (b), output curves ($V_{gs} = -2.5$ V) before and after 60-s short-term stress test ($V_{gs} = -20$ V and $V_{ds} = 20$ V) and after short and long term recovery test (c), and I_{gs}–V_{ds} curves ($V_{gs} = -2.5$ V) before and after 60-s short-term stress test ($V_{gs} = -20$ V and $V_{ds} = 20$ V) and after short and long term recovery test (d).

In Fig. 3, we choose the off-state curve above at a gate bias of −2.5 V (a little high above the threshold voltage), where the kink effect is most obviously seen to show the curves for ΔI_d versus V_{dg} we extracted from the fresh and stress curves. We divide each of the curves into two stages, a rapidly increasing region (RIR) and slowly increasing region (SIR). The ΔI_d (80 mA/mm) after off-state stress is about twice as large as the fresh one. It is obvious that applied stress steepens the ΔI_d curve at the bias voltage 6.4 V $< V_{dg} <$ 8.5 V (RIR) and the increasing rate slows down gradually when V_{dg} is larger than 8.5 V (SIR). Also, we observe that the demand of detrapping electrons on the V_{dg} is almost a constant 6.4 V both before and after stress, which means that the stress has no influence on detrapping voltage but the quantity of detrapping. So we obtain the following statement that off-state stress results in more serious trapping effect and that V_{dg} has an assistant effect on the detrapping behaviour without any creation of new category of traps. With the assistance of the electric field, hot electrons tend to be possible to modulate the charges in the deep-level traps.

The transfer characteristic shift (not shown) takes place at $V_{ds} < V_{ds,kink}$ (pre-kink region) compared with that at $V_{ds} > V_{ds,kink}$ (post-kink region), which is another expression of kink effect. Besides, in the same short-term stress process, gate current has a similar trend of current decrease and recovery. Impact ionization, as one of the main explanations for the kink effect, is characterized by the bell-shape gate current. However, like some other researchers, we have not observed the so-called bell-shape current in the I_{gs}–V_{gs} curves. By this, the ionization is still at a relatively low level even after the short-term stress.[14]

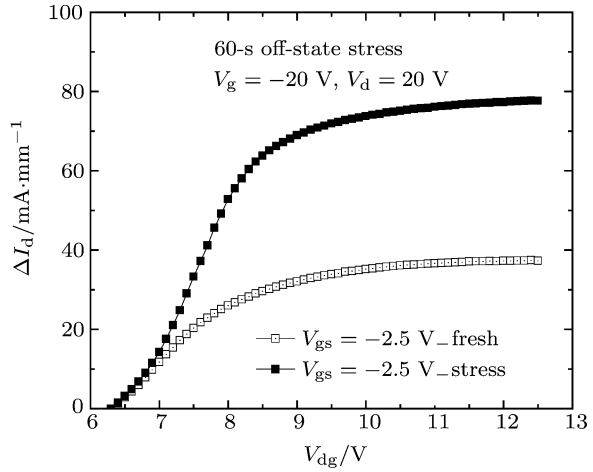


Fig. 3. Curves for ΔI_d versus V_{dg} curve ($V_{gs} = -2.5$ V), before and after 60-s short-term stress test ($V_{ds} = 20$ V and $V_{gs} = -20$ V).

To confirm this, I_d versus $1/(V_{ds} - V_{ds\text{-}sat})$ curves for both fresh and stress cases are plotted with the same values as those we used above as shown in Fig. 4. Fresh and stress curves each show such a nonlinear dependence on the $1/(V_{ds} - V_{ds\text{-}sat})$ observed in our experiments. Proposed in Ref. [10] was a physical model for the kink effect in InAlAs/InGaAs HEMTs with taking the impact ionization to be the dominating mechanism, where the formula $\Delta I_d|\text{large}V_{ds} = -1/(V_{ds} - V_{ds\text{ -sat}})$ holds true. A comparison between them shows that the electrons detrapping from traps are independent of the pre-kink electron concentration and there may exist other function that dominates, so that the impact ionization at large V_{ds} values is not the main mechanism. Instead, we find that $\ln(\Delta I_g)$ seems to be a linear function of $1/(V_{ds} - V_{ds\text{-}sat})$ at large V_{ds} values, which needs further understanding.

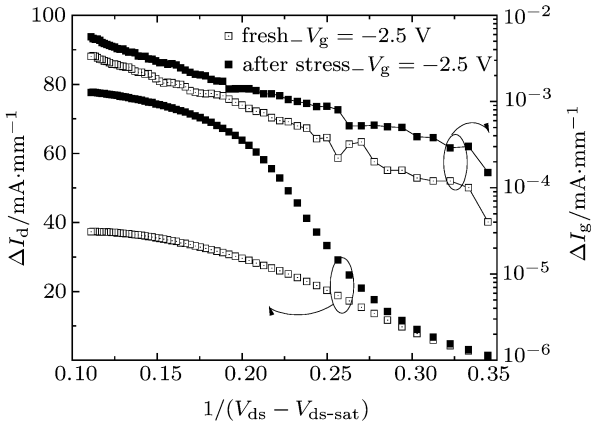


Fig. 4. Curves for kink drain and gate magnitude versus $1/(V_{ds} - V_{ds\text{-}sat})$ before and after 60-s short-term stress test ($V_{ds} = 20$ V and $V_{gs} = -20$ V).

It is probably proposed that electrical stress supplies traps with the electric field for activation and when dc test is carried out field-assisted hot-electrons lead electrons to detrap from traps, thus enhancing the kink effect. Then, a series of short-term stresses under several sets of bias condition tests is launched to verify the exact dependence of the kink effect on stress bias voltages (V_{gs} and V_{ds}). But factors such as current, temperature, electric field and strain need taking into consideration.

Therefore, devices are stressed under various stress conditions to determine the factors, which result in different enhancements of the kink effect as described above. Figure 5 shows five groups of the increasing percentage of $G_{d,peak}$ after stress. Dramatic enhancement larger than 50% is obvious in the off-state, high-field state with higher V_{ds} bias and $V_{ds} = 0$ state with higher negative V_{gs} bias. In comparison, no more than 30% increase takes place in the on-state with low voltage, the high-power state and the $V_{ds} = 0$ state with lower negative V_{gs} bias.

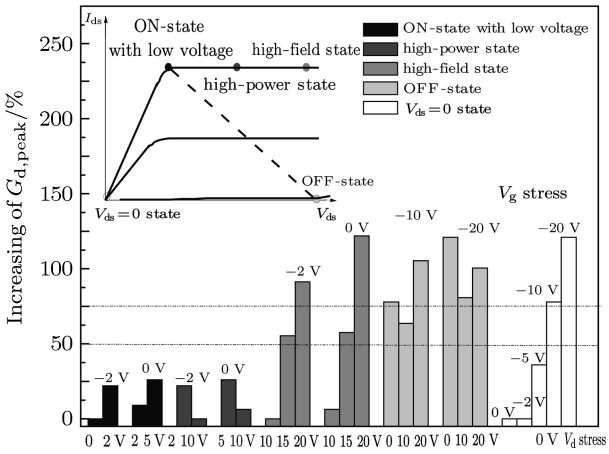


Fig. 5. Increasing percentage of $G_{d,peak}$ after various stress conditions.

In the following, we discuss the reasons for different kink magnitudes, with electrical stress divided into three states: $V_{ds} = 0$-state, off-state, on-state (on-state with low voltage, high-power state, high field state).

A rise and fall is seen in the bar chart when the applied stress is changed from the on-state with low voltage to the high-power state, followed by a dramatic increase as the device is stressed in the high-field state. Three important factors, i.e., current, temperature and electric field, are considered to determine the influence of the on-state stress on kink effect. In the on-state with low V_{ds} voltage, the enhancement is increased slightly with the current which appears to be the main factor. Also, the self-heating effect is obvious

in the high-power state, which suggets that current turns out to be a mild factor. Temperature causes the reduction in percentage, as the electron mobility in the 2DEG decreases due to the expected stronger polar optical phonon scattering. Now we come to analyse the high-field state. We note that electric field-assisted hot electrons enhance the activation of traps, thus worsening the kink effect.

In off-states with gate stress voltage both −10 V and −20 V, we can see an over 50% increase of $G_{\mathrm{d,peak}}$ with different V_{ds} stress biases. Compared with (−20, 0) stress, (−20, 10) stress with higher V_{dg} shows a relatively small increase. Elastic energy density tends to be lowered due to a higher V_{dg}. This may in turn hinder the appearance of the trapping behaviour on the source side, thus leading to a lower enhancement in the kink effect. With the increase of V_{ds} bias, kink effect is more easily observed, probably owing to the stronger peak elastic energy caused by a higher V_{dg} electric field which offers more chance for trapping behaviour on the drain side of the device.

We find that dramatic enhancement in the off-state is comparable to that in the high-field state and also that in the $V_{\mathrm{ds}} = 0$ state with higher negative V_{gs} bias. In comparison, less enhancement takes place in the on-state with low voltage, the high-power state and the $V_{\mathrm{ds}} = 0$ state with lower negative V_{gs} bias. This result suggests that it is not current but mostly electric field that enhances the kink effect.

In addition, we pay more attention to the $V_{\mathrm{ds}} = 0$ state stress in which negative gate voltage is applied. In this condition, we can stress both sides of the device simultaneously with a high electric field but without any channel current. Experiments in $V_{\mathrm{ds}} = 0$ state show that the increasing percentage of $G_{\mathrm{d,peak}}$ monotonically increases to V_{gs} bias. This also proves that electric field brings about more severe kink effect than the hot electrons.

Obviously, $V_{\mathrm{ds}} = 0$ state confirms our conclusion that the kink effect becomes more severe even without the effect of hot electrons as we see significant enhancement in the $V_{\mathrm{ds}} = 0$ state with negligible current. But it is still needed to further study whether the traps related to kink effect are in the AlGaN barrier layer or the GaN buffer layer. Besides, other experiments and technology should be designed to further understand the trapping effect in AlGaN/GaN HEMTs.

4. Conclusion

The kink effect is observed in our GaN/AlGaN HEMT device, with a nonmonotonic dependence of the $V_{\mathrm{ds,kink}}$ on V_{gs} and a bell-shape relation of the ΔI_{d} ($G_{\mathrm{d,peak}}$) to V_{gs}. Besides the avoidance of degradation, short-term stress (60 s) experiments show that the off-state stress may cause severe current slump, which is used as an effective approach to the assessment of the influence of various factors on the kink behaviour. Recovery experiments indicate that new traps are never created. The V_{dg} plays an assistant role in the detrapping behaviour and it is almost a constant 6.4 V both before and after stress, which means that the stress has no influence on the detrapping voltage but the extent of electron detrapping increases. A mechanism is proposed that stress supplies traps with the electric field for activation and when dc test is carried out, field-assisted hot-electrons cause electrons to detrap from traps, thus enhancing the kink effect. We discuss the donminant factors for different kink magnitudes, with electrical stress divided into three states: $V_{\mathrm{ds}} = 0$-state, off-state, on-state (on-state with low voltage, high-power state, high field state). Electric field brings about a more severe kink effect than the hot electrons. With the assistance of electronic field, hot electrons tend to be possible to modulate the charges in the deep-level traps.

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