Extrinsic and intrinsic causes of the electrical degradation of AlGaN/GaN high electron mobility transistors*

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Abstract: Electrical stress experiments under different bias configurations for AlGaN/GaN high electron mobility transistors were performed and analyzed. The electric field applied was found to be the extrinsic cause for the device instability, while the traps were recognized as the main intrinsic factor. The effect of the traps on the device degradation was identified by recovery experiments and pulsed I–V measurements. The total degradation of the devices consists of two parts: recoverable degradation and unrecoverable degradation. The electric field induced traps combined with the inherent ones in the device bulk are mainly responsible for the recoverable degradation.

Key words: AlGaN/GaN HEMTs; electrical degradation; traps; inverse piezoelectric effect

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1. Introduction

Due to the excellent material properties of III-nitrides, the GaN-based high electron mobility transistor (HEMT) has demonstrated extraordinary performances and is one of the most promising devices for high frequency and high power microwave applications[1−3]. However, there is a large barrier exists between lab research of GaN-based HEMTs their wide deployment, the main impediment being limited electrical reliability, i.e. the degradation of I_{DSS} and P_{OUT} etc. under large electrical stress[4−9].

The failure mechanisms of the electrical degradation of AlGaN/GaN HEMTs are still a matter of debate, with the detailed understandings of the physics behind the degradation varying a great deal. As regards the external factors affecting device instability, some researchers[4−6] held that the channel current, which would introduce hot electrons, resulted in the eventual device degradation. However, some others[8−10] proposed that the applied electric field, which causes an inverse piezoelectric effect, was chiefly responsible for the decrement of electron concentration in the access region. On the intrinsic factor, some[4] have argued that the traps generated in the buffer layer, the barrier layer or the surface, and the subsequent charge trapping leads to the reduction of the two-dimensional electron gas (2DEG), while Joh *et al.*[7] claimed that the decrement of the piezoelectric polarization intensity explained the deterioration of device performance.

Accordingly, it is significant to figure out the extrinsic and intrinsic factors behind the electrical degradation of AlGaN/GaN HEMTs. The improvement of the reliability of AlGaN/GaN HEMTs requires a profound understanding of the causes of the electrical degradation. In this work, we carried out electrical stress experiments under different bias conditions to find the external factors responsible for the device degradation, and identified the intrinsic factors by the following recovery experiments and pulsed I–V measurements.

2. Experiment

The AlGaN/GaN heterostructure used in this work was prepared on a 2-inch S.I.-SiC substrate by metal organic chemical vapor deposition. The epitaxial structure consists of a 1.8-μm-thick S.I.-GaN buffer layer, followed by a thin AlN interlayer and a 20-nm-thick AlGaN barrier layer with an Al composition of approximately 28%. Finally, the structural surface was terminated by a 2-nm-thick GaN cap layer.

Device isolation was performed by mesa etching with chlorine-based plasma in an ICP-RIE system. Ti/Al/Ni/Au multilayers were electron-beam (e-beam) evaporated as source and drain ohmic contacts, followed with rapid thermal annealing at 850 ℃ for 30 s. The gate was defined by e-beam lithography, with the gate length 0.35 μm and width 1 mm. Subsequently, the Ni/Au gate was written by e-beam evaporation and the lift-off process. A Si_3N_4 dielectric film with a thickness of 200 nm was employed for surface passivation using plasma-enhanced chemical vapor deposition.

Electrical stress experiments under different bias configurations were carried out. The changes of the corresponding figure of merits (FOMs), i.e. I_{DSS}, R_{ON} and the current collapse, were recorded in real time. The bias conditions were classified into two kinds: ON state and OFF state. In the ON state, the stress bias conditions are $V_{GS} = 0$ V and $V_{DS} = 0$–27 V changing in steps of 3 V (large I_D). In the OFF state, $V_{DS} = 0$ V and $V_{GS} = 0$ to –27 V in the steps of 3 V were applied (without I_D). Although the devices were biased under ON or OFF states with different channel currents, they shared the same V_{DG}. The devices were stressed for 3 min in each step. The recovery experiments on the biased devices were conducted after the stress tests. The devices were bias-free for 7 days at first, and then exposed to ultraviolet light irradiation with a wavelength of 365 nm. During the exposure recovery experiments, the corresponding FOMs were extracted every 3 min. The bias conditions and the schematic view of the devices under test are

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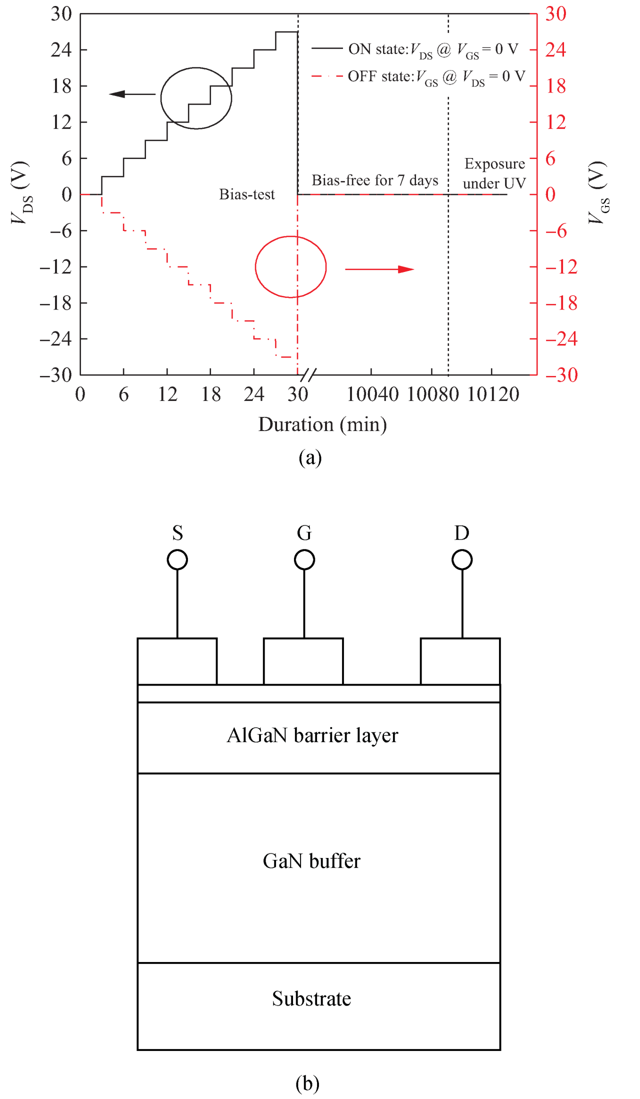

Fig. 1. (a) Bias conditions: ON state and OFF state (in the ON state, the stress bias conditions are $V_{GS} = 0$ V and $V_{DS} = 0$–27 V changing in steps of 3 V; in the OFF state, $V_{DS} = 0$ V and $V_{GS} = 0$ to –27 V in the step of 3 V were applied). (b) Schematic view of the AlGaN/GaN HEMT under test.

illustrated in Fig. 1.

3. Results and discussion

The changes of I_{DSS} and R_{ON} versus the stress (V_{DG}) are plotted in Fig. 2. The R_{ON} was measured as the total resistance between drain and source with a floating gate. The decrement of I_{DSS} for the device stressed in the ON state is about 40%, while its counterpart in the OFF state is about 45%, the degradation in both devices (with large I_D and without I_D, respectively) are almost the same. The corresponding R_{ON} rises with the decrement of I_{DSS}. This suggests that the impact of the channel current on the device degradation is almost negligible. Another phenomenon in Fig. 2 is also worth our attention. For the device stressed in the ON state, there is a drastic degradation around $V_{DG} = 21$ V, while for the one in OFF state, the critical voltage ($V_{CRITICAL}$) is around 15 V. It seems that the device stressed with a channel current shows better resistance

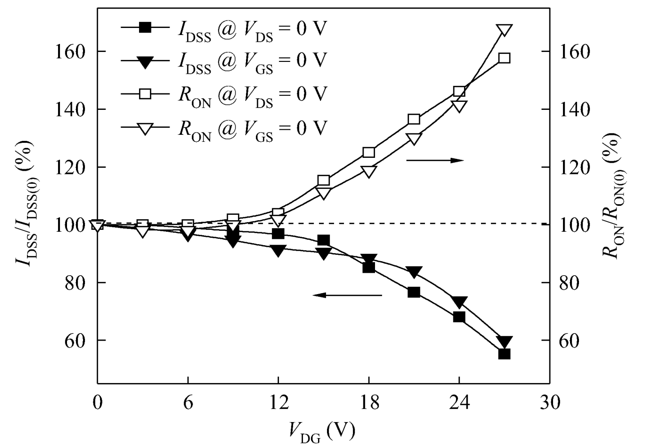

Fig. 2. Degradation of I_{DSS} and R_{ON} for AlGaN/GaN HEMTs under ON and OFF states (for the ON state, $V_{GS} = 0$ V and $V_{DS} = 0$–27 V in 3 V steps. For the OFF state, $V_{DS} = 0$ V and $V_{GS} = 0$ to –27 V in 3 V steps). The R_{ON} was measured as total resistance between drain and source with the gate floating.

to degradation than its counterpart without a channel current, which indicates that the main driver of the device performance deterioration is not the channel current. These results are similar to the phenomenon mentioned in Refs. [8, 9], which are the typical characteristic of an inverse piezoelectric effect.

According to the results mentioned above, the external factor in the device degradation can be attributed to the applied electric field, which is the common feature for different configurations. The phenomenon that the $V_{CRITICAL}$ in the ON state is bigger than that in OFF state can also be explained by the impact of the external voltage. When a high electric field is applied, due to the inverse piezoelectric properties of III-nitrides, the AlGaN barrier expands and the strain increases. When the device is biased in ON state, $V_{SG} = 0$ V, there is no electric field induced strain at the source edge of gate electrode. However, when the device is biased in the OFF state, $V_{SG} = V_{DG}$, the electric field induced strain at the source edge is as large as that at the drain edge, and the total strain under the gate is larger than its counterpart in the ON state, resulting in a relatively low $V_{CRITICAL}$.

The following recovery experiments were employed to identify the effect of traps on device degradation, as shown in Fig. 3. The recovery of I_{DSS} after recovery experiments indicates that the traps play a key role in device degradation. The trap effect in the device would capture the electrons in the channel, leading to the decrement of the I_{DSS}, and the de-trap of the electrons captured would cause the recovery of I_{DSS}. The exposure of devices to ultraviolet light irradiation is one of the common practices for the de-trap process. However, after a long period of exposure under ultraviolet light irradiation, device recovery seems to reach a saturation point, i.e. no further recovery, which is a sign of unrecoverable degradation. The degradation was not completely recovered due to: (1) permanent degradation occurs; (2) some deep level traps are introduced during the stress. The process of the recovery experiments indicates that the total degradation of the devices consists of two parts: recoverable degradation related to the trap effect, and unrecoverable degradation.

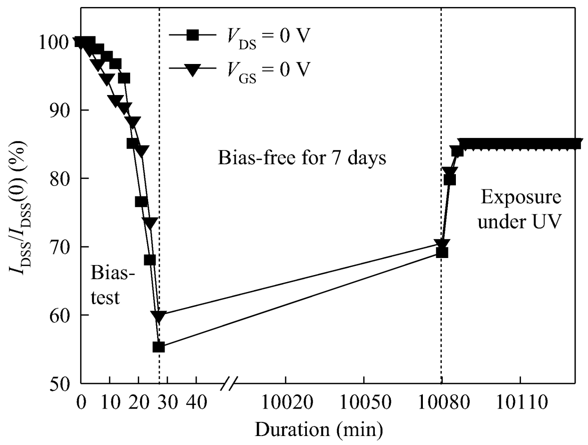

Fig. 3. I_{DSS} behaviour of AlGaN/GaN HEMTs during stress tests under different bias configurations and recovery experiments.

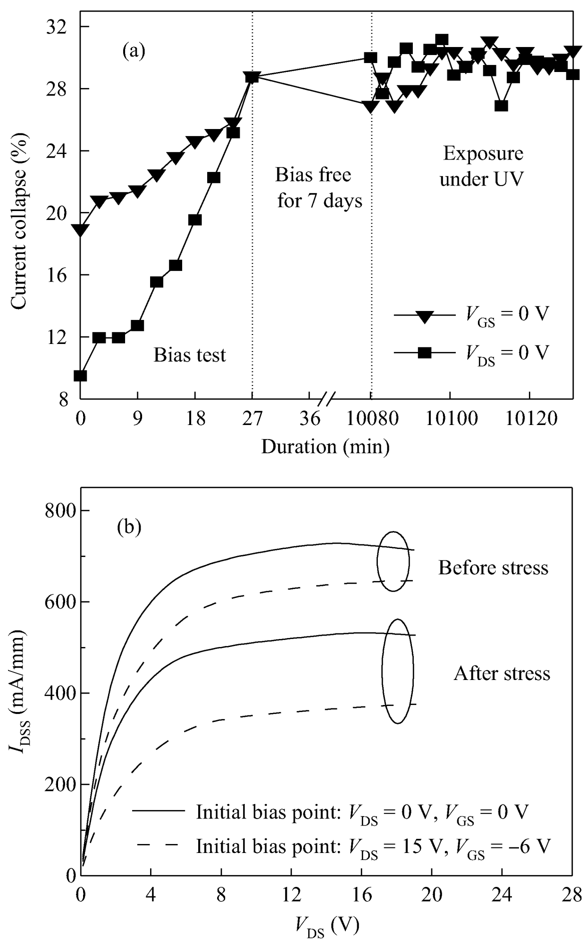

Fig. 4. (a) Current collapse during the stress tests and recovery experiments (pulse length and separation time are 4 μs and 34 μs) and (b) the typical pulsed I–V curves (measured at $V_{GS} = 0$ V) of the device stressed in the OFF state before and after the test. The initial bias points are $V_{DS} = 0$ V and $V_{GS} = 0$ V, $V_{DS} = 15$ V and $V_{GS} = -6$ V, respectively.

Pulsed I–V measurements during the stress tests were conducted to verify the traps formation and further proliferation, as plotted in Fig. 4. The pulse length and separation time are 4 μs and 34 μs, respectively, at an initial bias point at $V_{DS} = 15$ V and $V_{GS} = -6$ V. For the device stressed in the ON state, the amount of current collapse increases from 19% before stress to 28% after stress, and for the one in the OFF state, the amount from 10% to 29%. The current collapse before stress shows that there are inherent traps in the device, which is consistent with our previous work[10], and the deterioration of the collapse suggests the traps proliferate during the stress. The capture of electrons in the channel due to the trap effect and the subsequent reduction of 2DEG concentration are partially responsible for the decrement of I_{DSS} and rise of R_{ON}.

Based on the above results, besides the trap effect, the inverse piezoelectric effect probably also works during the degradation of the devices. According to this hypothesis, when the electric field applied is high enough, the strain in the AlGaN barrier layer is large enough to exceed a critical value, and subsequently relaxes through the formation of defects. The electric field induced defects in the device bulk correspond to the traps in different energy levels, and the new traps combined with the old inherent ones are mainly responsible for the recoverable degradation. Meanwhile, the intensity of piezoelectric polarization decreases with the relaxation of the AlGaN barrier layer, which would lead to the reduction of 2DEG concentration and the consequent unrecoverable degradation of R_{ON} and I_{DSS}.

4. Conclusion

Electrical stress experiments under different bias configurations were performed for AlGaN/GaN HEMTs. The external factor for the device degradation comes from the applied electric field. The effect of the traps on device performance deterioration was identified. These results suggest that the newly induced traps combined with the inherent ones in the device bulk are the main causes of recoverable degradation.

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