The degradation and recovery properties of AlGaN/GaN high-electron mobility transistors under direct current reverse step voltage stress*

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Direct current (DC) reverse step voltage stress is applied on the gate of an AlGaN/GaN high-electron mobility transistor (HEMT). Experiments show that parameters degenerate under stress. Large-signal parasitic source/drain resistance (R_S/R_D) and gate-source forward I–V characteristics are recoverable after breakdown of the device under test (DUT). Electrons trapped by both the AlGaN barrier trap and the surface state under stress lead to this phenomenon, and surface state recovery is the major reason for the recovery of device parameters.

Keywords: high-electron mobility transistor, surface state, trap, recovery

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1. Introduction

AlGaN/GaN high-electron mobility transistor (HEMT) technology is looking increasingly attractive for a variety of high frequency and high-power applications due to its characteristics of wide band gap, high electron mobility, high breakdown voltage, etc. However, its deployment in the field is currently bottlenecked by degradation and reliability problems, especially gate reliability. The high reverse electrical field between the gate and the drain/source is one important reason for the degradation of HEMTs. There have been several reports about their reliability under electrical stresses. Joh *et al.*[1] proposed a degradation mechanism that involved defect formation through the inverse piezoelectric effect, which was caused by a high vertical electric field at the drain edge of the gate. They also found that surface states between the gate and drain can trap electrons that tunneled from the gate metal under a high drain–gate voltage in the OFF-state.[2] Dammann *et al.*[3] proposed that the degradation of drain and gate current were probably caused by hot electron-induced trap generation under high drain voltage. Ma *et al.*[4] found that under the on-state condition, the devices suffered from both inverse piezoelectric effects and hot electron effects. Some researchers have looked into improving HEMT reliability under electrical stress by changing device structure and fabrication processes.[5–7]

To further study the degradation of device parameters under electrical stress and the recovery when stress is removed, we analyze the gate current, drain current under DC reverse step voltage stress and large-signal parasitic source/drain resistance, and gate–source forward I–V characteristics before and after device under test (DUT) breakdown in experiments. The effect of electrons trapped by barrier traps and surface states in the degradation and recovery is investigated.

2. Experiments

The samples studied in the experiment were grown by metal–organic chemical vapor deposition (MOCVD) on SiC substrates, which have epitaxial structure consisting of a GaN buffer layer followed by an AlGaN barrier layer. Electron-beam-evaporation was used to deposit a Ti/Al/Ti/Au multilayer as Ohmic contacts. Then the contacts were rapidly thermally annealed in N atmosphere. An Ni/Au multilayer was evaporated for the Schottky contact using electron-beam-evaporation. They have 20 fingers with a gate width and length of 0.25 μm and 125 μm, respectively.

In the experiment, the V_{DS} was kept at zero and a DC reverse bias stress was applied to the gate with V_{GS} stepping from −8 V to −31 V in 1-V steps. The stress voltage was increased gradually and each voltage level lasted for 100 seconds (−8 V to −30 V). Then the gate current under stress $I_{Gstress}$, I_{Goff} (gate current at $V_{DS} = 0.1$ V and $V_{GS} = -5$ V), I_{Dmax} (drain current at $V_{GS} = 0$ V and $V_{DS} = 5$ V),[1] R_S, R_D (measured by the gate current injection technique)[8,9] were measured. The measuring time and preparation time for the next stress test is 200 seconds. Thus, the time needed for each voltage step is five minutes. When DUT breakdown occurred at 31 V, the gate current was suddenly increased to the maximum protection current 100 mA and the stress voltage was removed immediately. Then R_S, R_D, and forward I–V characteristics of

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gate–source ($V_{GS} = 0$ V to 2 V) were measured every 5 minutes. The recovery process of parameters was observed.

3. Results and discussion

Figure 1 shows changes of I_{Dmax}, $I_{Gstress}$, and I_{Goff} from 8 V to 30 V before breakdown. It can be seen that I_{Dmax} decreases slightly by about 6% and $I_{Gstress}$ increases with the increase of stress. Whereas, the change of I_{Goff} was relatively small and it remained at 10^{-5} A/mm. According to Joh *et al.*,[1] there is a critical voltage generated by the inverse piezoelectric effect, which means that I_{Goff}, R_S, and R_D in Fig. 1 should increase significantly from the critical voltage. However, no such phenomenon occurred in our experiment. Two reasons may account for this: one is the different fabrication process; the other is that the inverse piezoelectric effect vanished during the period required for us to connect wires between the removal of stress and the beginning of measurement. We are more inclined to propose the latter. In Fig. 1 of Ref. [1], $I_{Gstress}$ was increasing before reaching its stable value. This agrees well with the increasing $I_{Gstress}$ value in our experiment. But in Ref. [1], the slope of the $I_{Gstress}$ curve increased from 24 V, in our experiment, the slope of the $I_{Gstress}$ curve remained about the same. Besides the fabrication process, the difference of measurement time may be one reason that caused the difference between our $I_{Gstress}$ and theirs. We selected the moment just before removing stress to measure $I_{Gstress}$, when the stress had lasted for 100 seconds. During the 60 seconds stress in Ref. [1], the exact measurement time was not known. Further research is needed on the relationship of $I_{Gstress}$ and stress time.

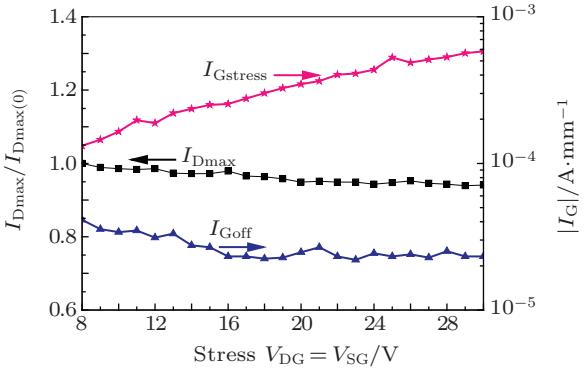


Fig. 1. (color online) Change process of normalized I_{Dmax}, $I_{Gstress}$, and I_{Goff} under DC reverse step voltage stress ($V_{DS} = 0$, $V_{DG} = -8$ V–30 V, 31 V breakdown, 1 V stepping).

TTT (thermionic trap-assisted tunneling), DT (direct tunneling), and TT (trap-assisted tunneling) are three possible generation mechanisms of gate inverse current.[10–12] The temperature of DUT was kept at 300 K, so the main generation mechanism of reverse I_G is not DT.[12] We cannot conclude whether it is TTT or TT that plays the main role in the generation mechanism of gate inverse current, but they are both induced by trapping. The value of I_{Goff} under low voltage is small, which means that the assisted tunneling caused by trapping is weak. $I_{Gstress}$ is much larger than I_{Goff} for two reasons: stronger electric fields and longer action time. With the increase of stress voltage, the $I_{Gstress}$ and stress voltage have an approximately linear relationship in an exponential coordinate system, which means that higher stress voltage will induce more traps, consistent with the traps induced by inverse piezoelectric effect.[1] Note that the I_{Goff} did not increase with stress voltage, but decreased slightly above 16 V. The reason for the decrease of I_{Goff} is that the trap caused by high stress vanishes between the period of removing stress and measuring I_{Goff}, and a few inherent traps filled with electrons are not totally released. The decrease of I_{Dmax} reflects the combined effects of the AlGaN barrier trap and the surface state.[13,14]

Figure 2 shows the whole changing process of R_S and R_D during the application and removal of stress. Like I_{Dmax}, $I_{Gstress}$, and I_{Goff}, there is no obvious critical voltage resulting in apparent change of R_S and R_D. As can be seen from Fig. 2, the values of R_S and R_D were stable from -8 V until breakdown at -31 V (120 minutes). After the breakdown, there was a significant decrease of R_S and increase of R_D. Then, the stress was removed and the values of R_S and R_D were stable until remarkable recovery at about 20 minutes to 25 minutes after breakdown. Based on the analysis of I_{Goff} in Fig. 1, the recovery caused by AlGaN barrier trap should not have such a long time interval. The effect of trapping should show a gradual change instead of a sharp change, and it should not have so large impact on values of R_S and R_D. Therefore, the change and recovery of R_S and R_D must be caused by the surface state.[13,15]

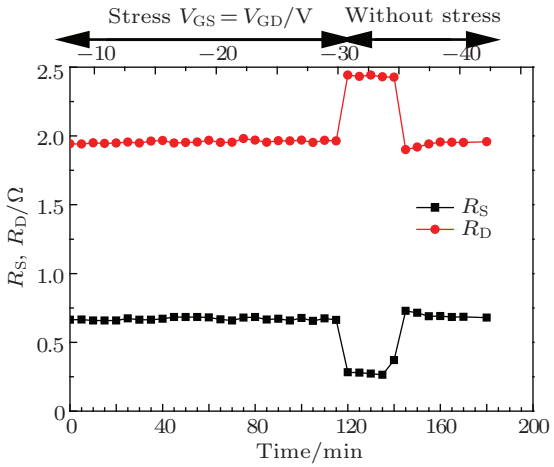


Fig. 2. (color online) Change curve of R_S and R_D with stress and without stress. Stress was removed after breakdown at 31 V, every 5 minute interval corresponds to a step of 1 V.

The distance from gate to source and drain is 1.5 μm and 2.5 μm. Therefore the electric field applied between the gate and source is higher than that between the gate and drain. The

gate side close to the source is the first to breakdown and the breakdown was recoverable. Electrons collected on surface state in the area form a mechanism similar to a conducting channel, which causes a decrease of R_S.[13,15] Then the surface state changes instead of internal traps taking effect, until that the surface state recovers to the level before breakdown after stress was removed for 25 minutes. It is the change of gate–source instead of gate–drain that causes the increase of R_D. Because we conducted the experiment with a current injection method, it is the conducting channel between the gate and source that causes part of the current division, which means that the decrease of R_S leads to the increase of R_D.[8,9] The time constant of 25 minutes for the change of surface state needs further study.

Figure 3 depicts forward I–V characteristic curves of gate–source (V_{GS} from 0 V to 2 V, the drain is not connected) at different moment after breakdown. Curve 0 is the original state of device without stress. I_{GS} increases significantly just when it breaks down, as it is shown in Fig. 3 that the I–V curve is at the top. Then the I–V curves measured every 5 minutes recover gradually and nearly reach their original value after 25 minutes. Then, there is little change. (Note: in Fig. 3, the curves on the top reach 100 mA, protection value of the measurement instrument, at about 0.2 V, then I_{GS} remains at this maximum and has no practical meaning.)

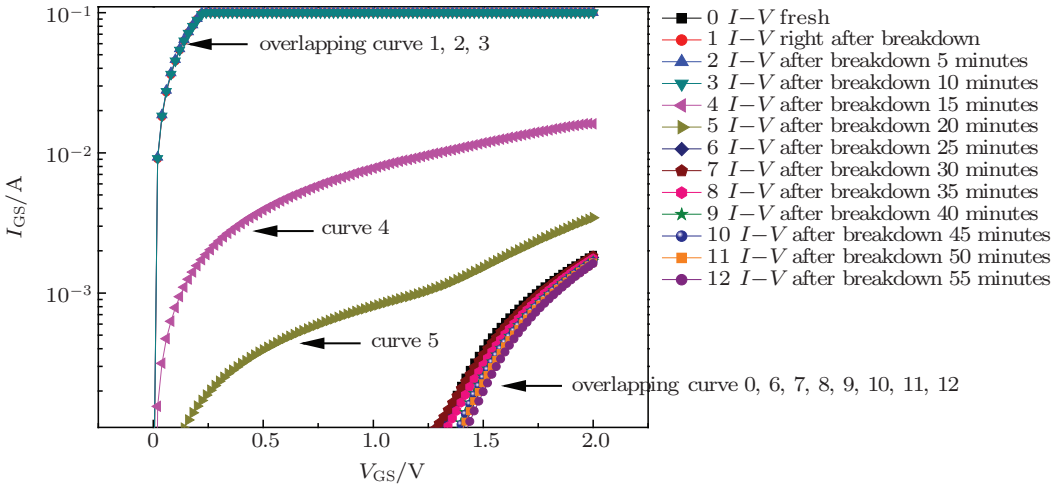


Fig. 3. (color online) Recovery process of forward I–V characteristic of gate–source (V_{GS} = 0 V–2 V; I_{GS} was set at the maximum protection current 100 mA.)

Figure 4 shows the change of I_{GS} over time at designated V_{GS}. Four points at time = 0 in x axis were I_{GS} values at the original state without stress. The horizontal dotted line through these four points is for comparison. The vertical dotted line represents device breakdown at 120th minutes. As in the analysis of Fig. 2, electrons trapped in the surface state between the gate and source form a current path similar to a conducting channel, which causes a rapid increase of I_{GS}. This big change could not be caused by a trap effect.[15] It can be seen clearly that at 145 minutes, i.e., the 25th minute after breakdown, I_{GS} is very close to the initial value at V_{GS} = 1.5 V and 2 V. With V_{GS} = 0.2 V and 1 V, I_{GS} is still larger than its initial value, but recovers significantly. This matches the change process of R_S and R_D in Fig. 2. This phenomenon again proves that the surface recovers to a normal state after stress has been removed for 20 minutes–25 minutes. (At the 120th, 125th, and 130th minutes, I_{GS} reached 100 mA, the protection value of measurement instrument; it was too high to have a practical significance.)

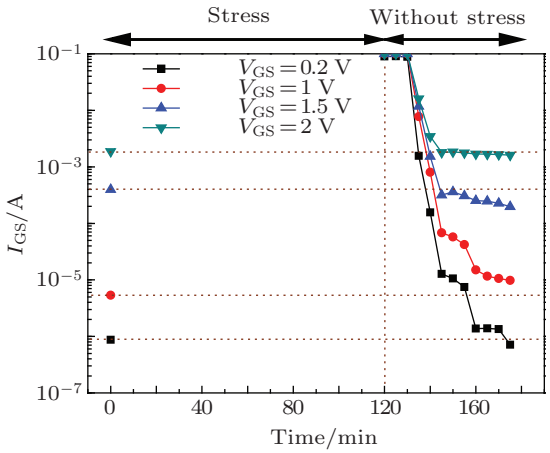


Fig. 4. (color online) Change of forward I_{GS} over time, V_{GS} = 0.2 V, 1 V, 1.5 V, 2 V. Four points at time = 0 were I_{GS} values at the original state without stress.

4. Conclusion

For AlGaN/GaN HEMTs, barrier traps are generated and the effect of the surface state is enhanced because of the in-

crease of DC reverse step voltage stress. Barrier traps vanish in ten to hundred seconds after stress is removed. However, a few inherent traps remain filled with electrons which are not released totally. The surface state recovers to the normal state at about 20 minutes–25 minutes after breakdown, reflected by the value of R_S and R_D and the gate–source forward I–V characteristics recovered. This requires a further study on the time constant for the recovery process.

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