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Impact of oxygen in electrical properties and hot-carrier stress-induced degradation of GaN high electron mobility transistors*

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The role of the oxygen in AlGaN/GaN high electron mobility transistors (HEMTs) before and after semi-on state stress was discussed. Comparing with the electrical characteristics of the devices in vacuum, air, and oxygen atmosphere, it is revealed that the oxygen has significant influence on the electric characteristics and the hot-carrier-stress-induced degradation of the device. Comparing with the situation in vacuum, the gate leakage increased an order of magnitude in oxygen and air atmosphere. Double gate structure was used to separate the barrier leakage and surface leakage of AlGaN/GaN HEMT it is found that surface leakage is the major influencing factor in gate leakage of SiN-passivated devices before and after semi-on state stress. During semi-on state stress in the oxygen atmosphere, the electric-field-driven oxidation process promoted the oxidation of the nitride layer, and the oxidation layer in the SiN/AlGaN interface leads to the decreasing of the surface leakage.

Keywords: semi-on state stress, AlGaN/GaN HEMTs, oxygen atmosphere

PACS: 85.30.Tv, 85.30.De, 71.55.Eq, 71.55.Ak **DOI:** 10.1088/1674-1056/ac1efd

1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) are very attractive for high-power and high-frequency applications. The advantages of high critical electric field, large polarization fields, and high electron mobility allow GaN-based HEMT to have higher power densities than many other semiconductor technologies.[1–4] However, the reliability of such devices is still under investigation. When AlGaN/GaN HEMTs are used in a real application, the devices are under electric stress condition.[5,6] The high field during the switching operation increases the electron trapping at surface states of AlGaN/GaN HEMT. Therefore, the electricstressinduced degeneration test of GaN HEMT is required.

Many studies were focused on the off-state reliability of the devices, and it shows a correlation between the degradation mechanism and the physical defects (pits and cracks).[7–10] The origin of this structural degradation has been attributed to the large mechanical stresses induced by the combination of large electric fields present in the channel of GaN transistors during the off-state stress test and the large inverse piezoelectric effect of nitride semiconductors.[7] However, there are only a few studies focused on the semi-on state reliability in GaN HEMTs. Moreover, there is no report showing the role of the oxygen under the semi-on state stress in AlGaN/GaN HEMTs as far as we known.

In our study, we reveal the influence of the oxygen on the characteristics of AlGaN/GaN HEMTs under semi-on state stress. It is proposed that the oxygen has great influence on the characteristic of the device both before and after the semi-on state electric stress.

2. Device fabrication and experiment setup

Epilayers of the AlGaN/GaN HEMT used in this work were grown on the sapphire substrate by metal–organic chemical vapour deposition (MOCVD). The wafer structure consists of an AlN nucleation layer, 2-μm unintentionally doped (UID) GaN layer, a 1-nm thick AlN interlayer, and a 22-nm thick $Al_{0.3}Ga_{0.7}N$ barrier layer. The devices fabrication started with Ohmic contact formed by an alloyed Ti/Al/Ni/Au metal stack, annealed in nitrogen ambient at 830 °C for 30 s. Mesa isolation was performed by inductively coupled plasma (ICP) with an etch-depth of 120 nm. And then, surface passivation was done by depositing about 60-nm SiN with plasma enhancement chemical vapour deposition (PECVD). Finally, Ni/Au/Ni gate contacts were patterned by lithography.

The structures of the device investigated in this study in-

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clude a normal GaN HEMTs with the gate length of 1 μm and the double-gate structure to measure the surface and barrier leakage. For the normal GaN HEMTs, the distance between the gate and drain electrodes (L_{GD}) varies from 1 μm to 7 μm. The transmission line model (TLM) structure is used to measure the sheet resistivity of the devices. To investigate the influence of the oxygen on the device, the devices are measured under the atmospheres of air, oxygen and vacuum. Direct current device characterization was achieved with a Keithley 4200SCS Semiconductor Device Analyzer. The hot carrier stress was applied at the semi-on state of the devices at $V_G = -1$ V and $V_D = 30$ V with 5000 s.

3. Results and discussion

Figure 1 shows the transfer characteristics of AlGaN/GaN HEMTs in vacuum, air, and oxygen atmosphere. The drain voltages (V_D) were biased at 10 V and 0.1 V and the gate voltages were swept from −6 V to 0 V and 2 V for the $V_D = 0.1$ V and 10 V respectively. Figures 1(a) and 1(c) are at semi-logarithmic coordinate systems, and figures 1(b) and 1(d) are at linear coordinate systems. In the air and oxygen atmosphere, the drain current of the device in off-state is an order of magnitude higher than that of in the vacuum, as shown in Figs. 1(a) and 1(c). The transfer characteristics in the oxygen is similar to that in the air, which demonstrates that the oxygen plays an important role in the air to impact the electric characteristics of the devices. The insets of Figs. 1(a) and 1(c) present the gate leakages of the devices in different atmospheres with $V_D = 0.1$ V and 10 V, respectively. The gate leakages in the air and oxygen atmosphere are higher than that in vacuum with one order, which reveals that the increase of the drain current in off-state is owing to the increase of the gate current. The gate leakages consist of the barrier leakage and the surface leakage through the access region. These two leakage paths would be discussed later in detail. The saturation current of transfer characteristics in the air and oxygen atmospheres are also higher than that in the vacuum, as shown in Figs. 1(b) and 1(d). What is more, with the drain voltage at a higher level of 10 V, the increment of I_D is more obvious, which indicates that the electric field between gate and drain has significant influence on the increase of drain current in air and oxygen atmosphere. In other words, the oxygen mainly acts on the access region of gate to drain to impact the transfer curves of the devices.

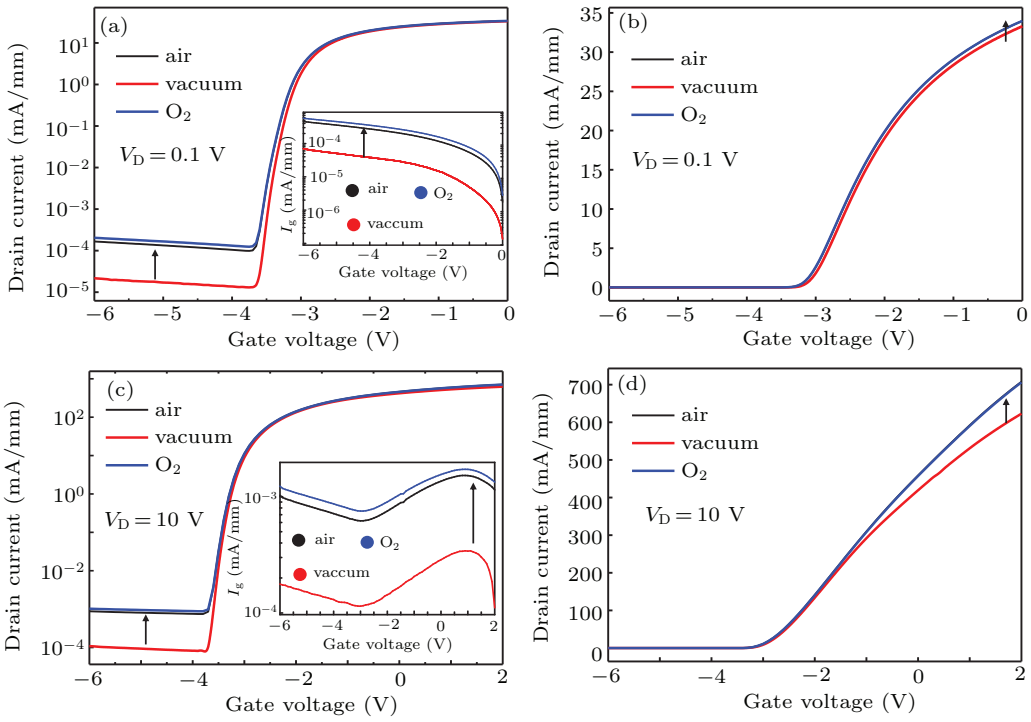


Fig. 1. The transfer characteristics of AlGaN/GaN HEMTs in vacuum, air, oxygen atmosphere at $V_D = 0.1$ V (panels (a) and (b)), and $V_D = 10$ V (panels (c) and (d)). Insets of panels (a) and (c) are the gate leakage with $V_D = 0.1$ V and $V_D = 10$ V, respectively.

To further study the influence of the oxygen on the device TLM structure is used to measure the sheet resistivity of the device in the air, oxygen, and vacuum atmospheres. Figure 2(a) shows the TLM structure from the top view, and figure 2(b) presents its cross section. In the TLM structure, the distance between each pattern is 3 μm, 5 μm, 8 μm, 13 μm, and 20 μm, respectively. As shown in Fig. 2(c), the sheet resistivity of the device in the vacuum, air, and oxygen is 422 Ω/□, 381 Ω/□, and 370 Ω/□, respectively. The sheet resistivity decreases with the increase of the oxygen proportion in the atmospheres, which shows that oxygen is a key factor to increase the current of the device in the access region.

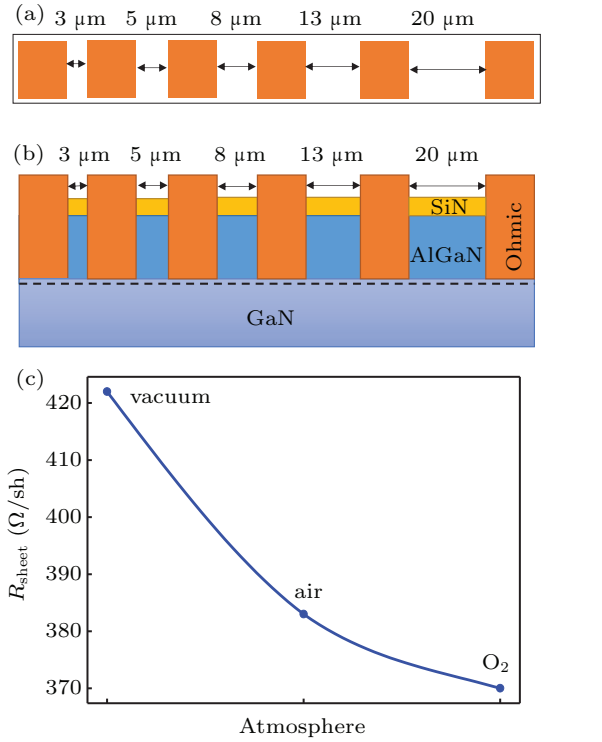


Fig. 2. The top view (a) and cross section (b) of TLM structure used in AlGaN/GaN epitaxy. (c) The sheet resistivity of the devices in vacuum, air, and oxygen atmosphere.

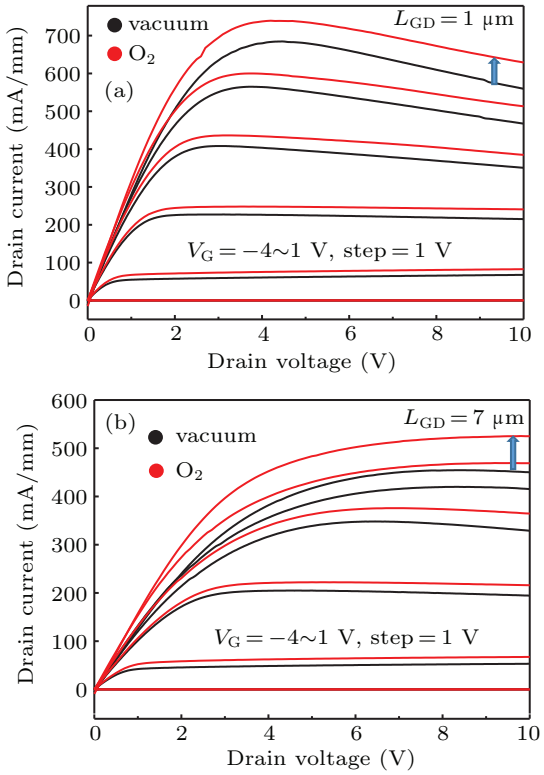


Fig. 3. The output characteristics of the devices with L_{GD} = 1 μm (a) and 3 μm (b) in the vacuum and oxygen atmosphere.

Figure 3 shows the output characteristics of the devices with the gate to drain distance (L_{GD}) of 1 μm and 7 μm at the vacuum and oxygen atmospheres. The gate voltage (V_G) is swept from −4 V to 1 V with the step of 1 V. The V_D sweep from 0 V to 10 V with the step of 0.1 V. The I_D increases more obviously with the L_{GD} increase. The drain current (I_D) in the oxygen atmosphere is obviously lower than that in the vacuum, and the on-resistance (R_{on}) has the same tendency. The R_{on} can be simply express as

$$\begin{aligned} R_{on} &= R_s + R_d + R_{ch} \\ &= 2R_{con} + R_{sh}(L_{GS} + L_{GD}) + R_{ch}, \end{aligned}$$

where R_s and R_d are the source and drain resistance, and R_{ch} is the channel resistance; $2R_{con}$ is the Ohmic contact resistance of both source and drain electrodes; the part of $R_{sh}(L_{GS}+L_{GD})$ is the resistance of access region, and R_{sh} is the sheet resistance in the access region. According to the formula above and the influence of the oxygen on the access region as figure 2 shows, the lower R_{on} in oxygen atmospheres is mainly result from the lower R_{sh} of access region. What is more, the decrease of R_{on} in oxygen atmosphere is more obviously with the increase of the L_{GD} (from 1 μm to 7 μm), which demonstrates the influence of oxygen is mainly on the access region of the devices according to the above formula. In addition, the electrical field between the gate and drain of the device with L_{GD} = 7 μm is less than that of the device with L_{GD} = 1 μm when the same drain voltage is applied, while the decrease of R_{on} is more obviously with the increase of the L_{GD}, which demonstrates that the main factor for the increase of carrier concentration is the action-area of oxygen rather than the electrical field between the gate and drain.

In the oxygen atmosphere, the absorbed O_2 at the interface of SiN/AlGaN may have the influence on the surface states of AlGaN such as exist as O^{2-},[15] which plays the role in passivation. The passivation effect has influence on the surface donor density and surface donor levels,[11] leading the increase of the I_D as shown in Fig. 3.

Figure 4 shows the transfer characteristics in the oxygen and vacuum atmosphere after the semi-on state stress measurement at $V_G = -1$ V and $V_D = 30$ V with stress 5000 s. After the semi-on state stress in the oxygen atmosphere, the off-state drain leakage decreases an order and the gate leakage decreases about half an order compared with the initial state that before stress. While for the situation of the vacuum atmosphere, there is almost no influence on the device characteristics after applying 5000-s semi-on state stress. It can be deduced that the decrease of the leakage in the GaN HEMT after semi-on stress is primarily due to the impact of the oxygen.

To further investigate the influence of the oxygen on the leakage in the devices, double-gate structure (The similar double gate structure is described in Ref. [14], as shown in the insets of Fig. 5) was used to separate the surface and the barrier leakage before and after semi-on state stress in the oxygen atmosphere. Figure 5 presents the surface and barrier leakage of the device before and after semi-on states stress mea-

surement (at $V_G = -1$ V and $V_D = 30$ V with stress 5000 s) in the oxygen atmosphere. The surface and barrier leakage of the devices without and with SiN passivation are shown in Figs. 5(a) and 5(b), respectively For the device with SiN passivation as shown in Fig. 5(a), the surface leakage is mainly through SiN/AlGaN interface. While for the device without SiN passivation layer as shown in Fig. 5(b), there is almost no surface leakage path for the un-passivation device. Therefore, the surface leakage in Fig. 5(b) is much lower than that in Fig. 5(a).

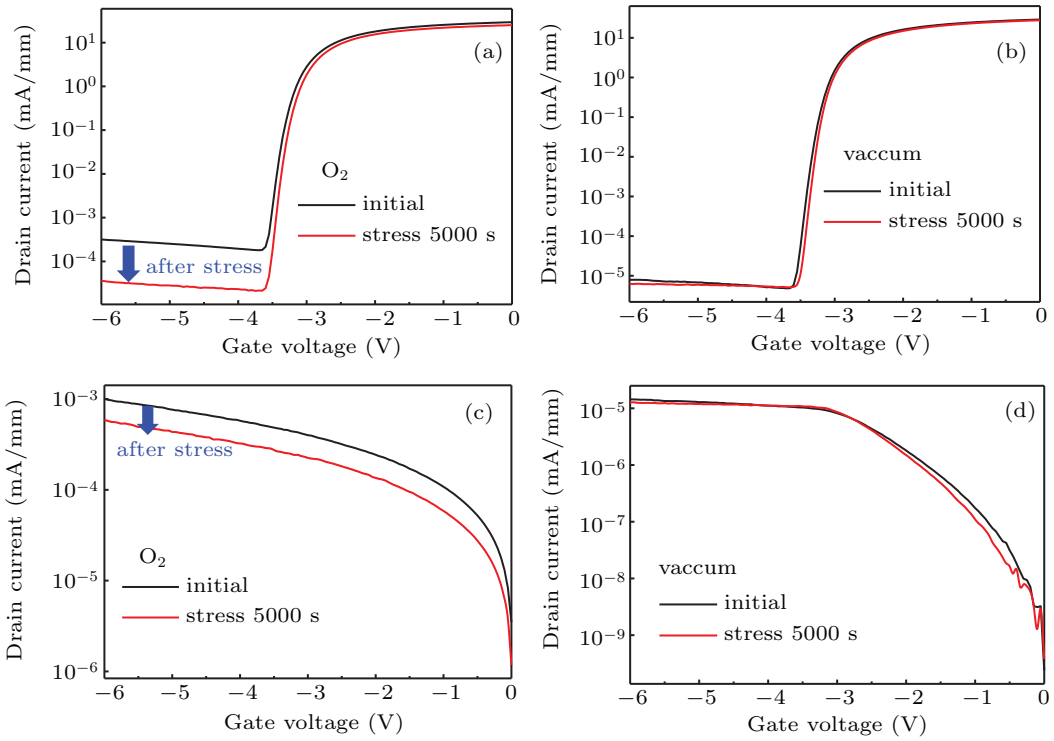


Fig. 4. The transfer characteristics of the devices before and after semi-on state stress in the oxygen atmosphere.

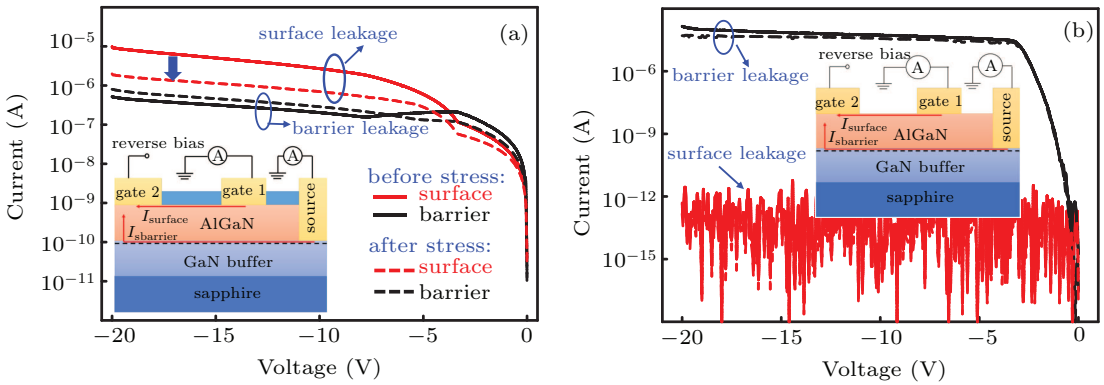


Fig. 5. Surface (black) and barrier (blue) leakage before and after semi-on states stress in the oxygen atmosphere with (a) and without (b) SiN passivation. The double-gate stucture is untilized to separate the surface and barrier leakage.

As the solid line shown in Fig. 5(a) the surface leakage is larger than the barrier leakage before semi-on stress for the device with SiN passivation, which means the gate leakages are mainly induced by the surface leakage of the SiN/AlGaN interface. After the semi-on state stress, the surface leakage decreases by an order of magnitude. The barrier leakage also decreases for the low voltage region while slightly increase for the high voltage region after semi-on state stress. Therefore, it can be concluded that the decrease of the off-state leakage after semi-on state stress is mainly result from the decrease of surface leakage of SiN/AlGaN interface. As for the device without the SiN passivation, the surface leakage is much less than the barrier leakage as shown in Fig. 5(b), which reveals that the barrier leakage is the dominant part of off-state leakage in the un-passivated devices. After semi-on state stress, the barrier leakage is slightly lower than that before stress and the surface leakage is still kept in a low level, which also proves that the surface leakage is the major factor in causing the decrease of the off-state leakage after semi-on sate stress in passivated GaN HEMT.

During the semi-on state, the electrons in the channel are more energetic than the electrons in other state of the device.

The energetic electrons of the channel scatter to the interface of SiN/AlGaN interface to turn more the oxygen molecules into O^{2-}, the energetic electrons in the channel cause the impact ionization and generate the hole which is required for the electron-chemical oxidation process.[12,13] The oxidation layer in the SiN/AlGaN interface leads to the decreasing of the surface leakage.

4. Conclusion

In this study, the role of the oxygen in AlGaN/GaN HEMTs before and after semi-on state stress was discussed. Comparing with the electrical characteristics of the devices in vacuum, air and oxygen atmosphere, it is revealed that the oxygen has significant influence on the characteristics of the device before and after semi-on state electric stress. Comparing with in the vacuum, the gate current increased an order magnitude in the oxygen and the air atmosphere and the maximum drain current increased more obviously in saturated region than that of in linear region, which means the characteristic of the devices in the oxygen is related to the electric field between the gate and the drain. In the oxygen atmosphere, the absorbed O_2 at interface of the SiN/AlGaN plays the role in passivation. The passivation effect has influence on the surface donor density and surface donor levels, leading the increase of the I_D. During semi-on state electric stress in oxygen atmosphere, the electric-field-driven oxidation process promoted the oxidation of the nitride layer. The oxidation layer in the SiN/AlGaN interface leads to the decreasing of the surface leakage that proved to be the major leakage current of the passivated GaN HEMT by double-gate structure.

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