The investigation of AlGaN/GaN HEMT failure mechanisms under different temperature conditions

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Abstract. To explore degradation law and failure mechanisms of AlGaN/GaN HEMT under different temperature conditions, the step-temperature stress experiments are carried out. The results show that the drain-source current decreases with the aging time when the junction temperature range from 139 ℃ to 200℃; while the drain-source current increases with the aging time when the junction temperature range from 200℃ to 352℃. When the junction temperature is less than 200℃, the AlGaN ionized donor atoms cause the Schottky barrier height of the AlGaN/GaN HEMT device to rise; and when the junction temperature is higher than 200℃, the diffusion of impurities oxygen in surface causes the Schottky barrier height of the AlGaN/GaN HEMT device to fall. The barrier height can affect the threshold voltage which leads to the change of drain-source current. Therefore, the degradation of the drain-source current is caused by the change of the Schottky barrier height.

Introduction

The GaN materials have many advantages including large band gap, high electron saturation velocity, good thermal conductivity, and etc. They have shown excellent performance in high power and high temperature applications. The AlGaN/GaN high electron mobility transistors (HEMTs) are representative of the GaN-based microelectronic devices, which can be widely used in energy exploration, radar systems and anti-missile systems. However, the performance of GaN HEMTs are affected by many factors, such as the production processes, complex structures, special polarization effects, high electric field stress and etc. Therefore, the reliability problem of AlGaN/GaN HEMTs have become a hot issue of current research, especially for the device working under high temperature or high electric field conditions [1][2].

The degradation of the GaN HEMTs have been investigated extensively. Pazirandeh et al. found that the gate voltage of GaN HEMTs increased gradually with the aging time under the constant voltage and power when the case temperature was 150℃ [3].Dammann et al. found that the leakage current of GaN HEMTs decreased first and then increased with the aging time under different surface temperature using the drain-current step-stress tests. But the explanation of the phenomenon was limited [4]. Yang Zhen et al. considered that the degradation of saturation drain current is caused by the positive shift in V_T under semi-on DC stress [5]. Through the step temperature stress experiments under high electric field, Wu and his colleagues found that the maximum drain current remained unchanged at low temperature, whereas the current rapidly decreased with the aging time under high temperature. The reason was because the stressed samples developed pits and trenches to trap carriers under the gate edge on the drain side of the device [6]. From the present study, there is no consistent result on the degradation process of the GaN HEMTs, nor the failure mechanism is explained in detail.

To explore failure mechanisms, this paper studied the degradation process, and the corresponding mechanism of GaN HEMTs with aging time under different temperature conditions. The experimental GaN HEMT devices were loaded rated power and step temperature stress. Based on the consistency of failure mechanisms at different temperature [7], the forward Schottky barrier

height was measured in order to obtain the failure mechanisms of GaN HEMTs under different temperature.

Experiment

The GaN HEMT devices used in this study were produced by Cree. The testing took place in a thermostatic platform. The devices were stressed by the step temperature at V_{DS}=28V and I_{DS}=500mA. The initial temperature of the platform was set as $20°C$, and the temperature was raised by $25°C$ every 24 hours. After working 24 hours at each temperature, the devices were removed from the platform. Then, the samples were cooled to room temperature and measured.
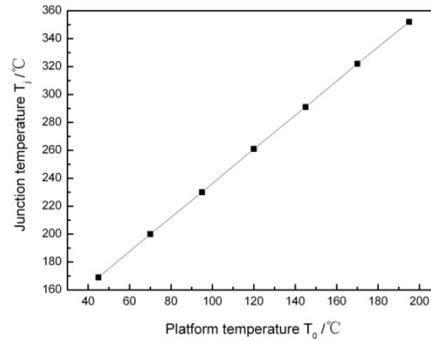

Fig. 1 The function of the junction temperature and platform temperature

To prevent the self-excited oscillation of the devices, this paper designed the protection circuit. During the experiments, the junction temperature can be estimated through the real-time monitoring case temperature of the devices. Based on the correlation between the track recorded case temperature T_C and the platform temperature T_0, the expression of T_C can be determined by: T_C=0.986×T_0+41.57. Through the infrared measuring experiments, the correlation between the junction temperature T_j and the case temperature T_C was determined by: T_j=1.24×T_c+63.01. So the relationship between the junction temperature and the platform temperature is derived to be: T_j=1.22×T_0+114.56, as it is shown in Fig. 1. The output characteristic curves and the forward Schottky characteristic curves were measured by the Agilent B1500.

Results and Discussion

The output characteristic curves (V_{GS} = -2.2V) of the GaN HEMT under the step-temperature stress experiments are displayed in Fig. 2. It shows that the drain-source current I_{DS} decreases with the aging time when the junction temperature is below $200°C$. However, when the junction temperature increases above $200°C$, the I_{DS} begin to increase with the aging time. The degradation of I_{DS} with the aging time under V_{DS} = 13V is shown in Fig. 3, where the solid line represents the maximum drain source current I_{DSM} as a function of the aging time, and the hollow line represents the normalized degradation ratio of I_{DSM}.
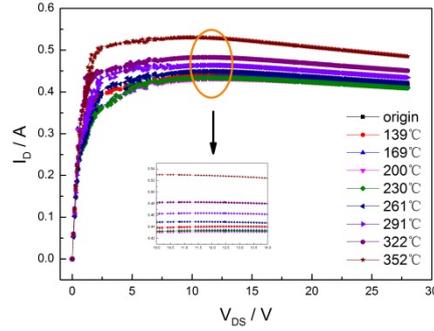
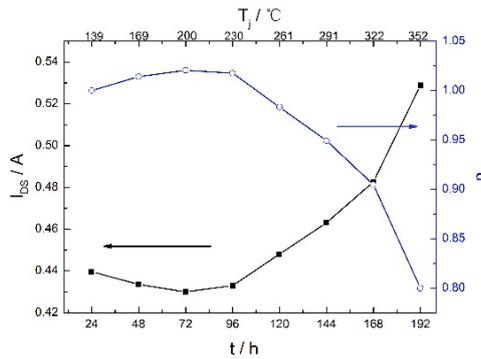Fig. 2 Output characteristic curves after different temperature stress

Fig. 3 The degradation of the drain current with aging time

When the junction temperature is below 200 ℃, the I_{DSM} of the GaN HEMT decreases with the aging time. After working at the junction temperature of 200℃ for 24 h, the degradation ratio of I_{DSM} is 3%. To avoid the measurement error, a group of GaN HEMT devices standing at the room temperature are compared, with the degradation ratio in I_{DSM} less than 0.8%. This indicates that the degradation of I_{DSM} working at the junction temperature below 200℃ is not caused by the measurement error. When the junction temperature is above 200℃, the I_{DSM} increases with the aging time. When the device works at the junction temperature of 352℃ for 24 h, the changes of I_{DSM} are more than 20%. According to the failure criterion, the experiments are finished.

The failure mechanisms of I_{DS} under different junction temperature conditions are analyzed as follows. In the saturation region, the equation of the drain current is:

$$I_{Dsat} = \frac{\kappa}{2}(V_G - V_T)^2$$

where κ is a constant, which is related to the electron mobility. V_T is threshold voltage. It is known that the I_{DS} depends on the constant κ, gate voltage V_G and threshold voltage V_T. The gate voltage V_G keeps constant (V_{GS} = -2.2V) under the same electrical stress test condition. For HEMT devices, the scattering mechanism is mainly acoustic wave scattering and the test environment is room temperature, so the electron mobility is not changed. As a result, the I_{DS} mainly depend on the threshold voltage V_T under the room temperature. Due to the value of V_T and V_G are negative, the I_{DS} will increase with the negative shift of V_T. As is shown in Fig. 4, the variation of the threshold voltage corresponds exactly with the degradation of the I_{DS}.
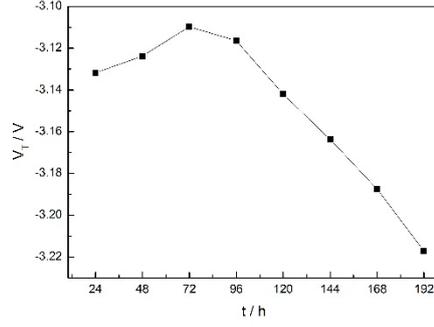
Fig. 4 The degradation of the threshold voltage with aging time

Because the threshold voltage is determined by the AlGaN / GaN HEMT Schottky barrier height [8], we analyze the changes in the barrier height under different conditions. It shows in Fig. 3 that the degradation of I_{DSM} with aging time is non-monotonic, implying that there should exist different failure mechanisms in the total degradation. In different temperature ranges, the main degradation mechanisms are different. When the junction temperature is below 200℃, some of the AlGaN donor atoms will ionize. The free electrons from the ionization can drift to the quantum well so that the AlGaN / GaN barrier depletion region widens, and the barrier height increases [9]. The rise of the barrier height leads to the positive shift of V_T. Through the XPS analysis, it is found that the AlGaN have adsorbed some oxygen impurities [10]. When the junction temperature is above 200℃, the oxygen can easily diffuse into the AlGaN barrier layer and combine with Al, resulting in the Al-O bond. This is the main reason of the reduction of the AlGaN / GaN Schottky barrier height [11], which causes the negative shift of V_T .

Verification

To verify the changes of the barrier height, the forward Schottky characteristic curves are measured. The quantitative changes in the barrier height can be obtained according to the current formula of the classical hot electrons emission theory:
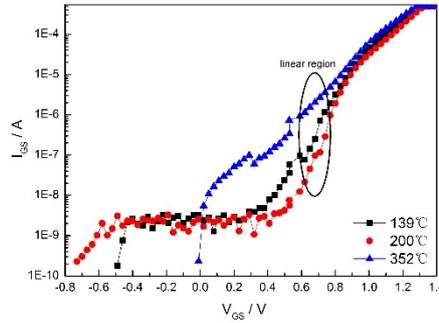

Fig. 5 The forward Schottky I-V characteristic curves in semi-logarithmic

$$J = A^* T^2 \exp\left(-\frac{q\varphi}{kT}\right)\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \tag{1}$$

where A* (equal to 34.2A / cm^2 * K^2 at room temperature) is the Richardson effective constant, φ the barrier height and T the temperature, respectively.

The current of the AlGaN / GaN Schottky contact can be expressed as:

$$I = AA^* T^2 \exp\left(-\frac{q\varphi}{kT}\right)\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \tag{2}$$

where A(equal to 1.39×10^{-6} cm^2) is the Schottky contact area. The equation (2) can be converted by the logarithmic transformation:

$$\lg I = \frac{\lg e}{kT} * \frac{q}{n} * V + \lg AA^* T^2 + \lg e * \frac{-q\varphi}{kT} \tag{3}$$

Therefore, the forward Schottky I-V characteristic curves in semi-logarithmic is shown in Fig. 5. In the linear region of the middle part in the semi-logarithmic curves, the main mechanism of the forward Schottky current is thermionic emission. Then the straight lines can be fitted in the linear region. The intersection with the vertical axis can be expressed as:

$$\text{Intercept} = \lg A^*AT^2 + \lg e * \frac{-q\varphi}{kT} \tag{4}$$

So the barrier height can be determined as follows:

$$\varphi = \frac{kT}{q\lg e} * \lg \frac{A^*AT^2}{Intercept} \tag{5}$$

The expression (5) indicates that the Schottky barrier height decreases as the increase of the intercept. Fig. 5 shows that the intercept will decrease with the aging time when the junction temperature is below 200℃, resulting in the increase of the barrier height. When the junction temperature is above 200℃, the intercept will increase with the aging time and hence, the decrease of the barrier height. The barrier height is obtained and listed in Table 1. When the junction temperature is below 200℃, the I_{DS} will decrease because the barrier height of the GaN HEMT increases, resulting in the positive shift of V_T. When the junction temperature is above 200℃, I_{DS} will increase because the barrier height of the GaN HEMT decreases, resulting in the negative shift of V_T.

Table 1   the barrier height after different temperature stress

Junction temperature /℃	Barrier height /eV
139	1.11
169	1.15
200	1.22
230	1.17
261	1.08
291	0.99
322	0.93
352	0.81

Conclusion

In the GaN HEMT step-temperature stress experiments, the evolution of drain source current with the aging time shows the non-monotonic degradation characteristics. The current decreases under low temperature first, then it increases under high temperature. Considering the degradation process, the forward Schottky characteristics curves of the GaN HEMT are measured in order to verify the changes of the Schottky barrier height. It is found that when the junction temperature is less than 200 ℃, the ionization of AlGaN donor atoms leads AlGaN/GaN barrier height to rise, resulting in the positive shift of V_T. When the junction temperature rises above 200℃, the diffusion of oxygen impurities in surface causes the Schottky barrier height of the GaN HEMT device to fall, thus, resulting in the negative shift of V_T. Therefore, the degradation of the drain-source current is caused by the change of the Schottky barrier height.

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