ON THE RELIABILITY OF ACCELERATED TESTING IN AlGaAs/InGaAs/GaAs PHEMTs

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The study of different stress on device characteristics of AlGaAs/InGaAs/GaAs PHEMTs has been researched and developed in this report. Many catastrophic degradation mechanisms such as hot-electron, gate-drain breakdown, I_{DS} , I_G , V_P and gate Schottky barrier effects are discussed in detail. In addition, the accelerated testing of the temperature-dependent effects on I_D , G_m and Schottky barrier are examined.

Keywords: PHEMT; Stress

1 INTRODUCTION

While hot-electron related reliability issues have been widely studied in Si MOS devices and integrated circuits, the behavior of compound semiconductor FETs is much less assessed. In particular, devices such as AlGaAs/InGaAs/GaAs pseudomorphic high electron mobility transistors (PHEMTs) have been proved successful in a variety of applications, including low noise amplifier at Q-band [1], V-band monolithic power amplifiers [2], and MMIC power amplifiers at Ka-band [3] and W-band [4]. The use of the AlGaAs/InGaAs heterojunction in PHEMTs provides several advantages over MESFETs and conventional AlGaAs/GaAs HEMTs, and the advantages include: (1) larger conduction band discontinuity, which ensures better electron confinement; (2) the excellent electronic transport properties of InGaAs, which allow improved frequency performances. However, the InGaAs channel layer has a small band-gap, which favors impact ionization. Thus, the effects of hot-electron and impact ionization on device reliability need to be studied.

Since the behavior of the Schottky barrier under hot-electron test is also much less discussed. In this work, the mechanisms for the Schottky barrier change before and after hot-electron stress are examined. We have also performed measurements of other DC characteristics to investigate further the change of the device characteristics under hot-electron test. In addition, we will probe into temperature effects of device characteristics because it plays an important part during its operation. We also discuss the hot-electron

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related phenomena in AlGaAs/InGaAs/GaAs PHEMTs, *i.e.* breakdown walkout in PHEMTs [5]. This phenomenon is a creation and filling of electron traps by hot carriers in the gate-drain region [6, 7]. The temperature-dependent characteristics of AlGaAs PHEMTs with temperature ranging from 300 K to 420 K with step of 30 K will be studied.

2 RESULTS AND DISCUSSION

2.1 The AlGaAs/InGaAs/GaAs PHEMT Structure

The AlGaAs/InGaAs/GaAs structure consists of a 3000 Å-thick undoped GaAs buffer layer, a 150 Å-thick InGaAs undoped channel layer, a 20 Å-thick undoped AlGaAs spacer layer, a 200 Å-thick *n*-type AlGaAs donor layer, and a 300 Å-thick heavily doped cap layer. The Hall mobility at room temperature and 77 K are $5650 \text{ cm}^2/\text{V}\cdot\text{sec}$ and $17,300 \text{ cm}^2/\text{V}\cdot\text{sec}$, corresponding to the two-dimension carrier densities $2.46 \times 10^{12} \text{ cm}^{-2}$ and $2.03 \times 10^{12} \text{ cm}^{-2}$, respectively. The gate dimension of the devices is $0.25 \mu\text{m} \times 160 \mu\text{m}$. The schematic cross-sectional view of the AlGaAs/InGaAs/GaAs structure is shown in Figure 1(a).

2.2 Hot-electron Tests of AlGaAs PHEMT

2.2.1 Degradation due to Hot-electron and Impact Ionization

Hot-electron (HE) and impact ionization (II) play important roles in the reliability of PHEMTs devices, since: (1) the gate must be very short ($L_g \leq 0.25 \mu\text{m}$) for higher frequency applications, therefore the fields soar to very high values for relatively low drain bias; (2) the device must be biased deep into saturation to get higher output power; (3) the channel layer must have a small band-gap for good confinement, which favors impact ionization; (4) the large mobility makes the channel electrons easily quit to heat up. Hence, it is necessary to study PHEMT reliability from HE and II standpoints. Figure 1(b) shows the HE-related phenomena in an AlGaAs PHEMT.

In the InGaAs channel layer, impact ionization is triggered when a hot-electron scattering with a lattice atom may provide a valence band electron with sufficient energy to leap into the conduction band. Some of the holes generated by impact ionization overcome the valence band discontinuity entering the donor layer, may be collected by the gate electrode and result in an increase of gate current, may be trapped in AlGaAs/InGaAs heterojunction or under the gate electrode, causing a degradation in transconductance (G_m), drain current (I_D), and pinch-off voltage (V_p).

2.2.2 Gate-drain Breakdown Walkout

Gate-drain breakdown (GDB) is the main factor limiting the power-handling capability of compound semiconductor heterostructure FETs, which are biased in the saturation region in most analog applications. The I - V characteristics of AlGaAs PHEMTs before and after stress for 60 minutes at $V_{DS} = 7 \text{ V}$, $V_{GS} = 0 \text{ V}$ are shown in Figure 2. It should be noted that the stress has induced a significant drop of the drain current I_{DS} at high drain voltage, and it is so called breakdown walkout, which is attributed to hot-electron related effects reported by Menozzi. The gate-drain breakdown walkout is believed to be caused by creation and filling of electron traps in the gate-drain region and by attendant widening of the depletion region, that results in a reduced electrical field and increased breakdown voltage [8, 9]. End resistance measurements [10] indicate that the drain-to-channel resistance R_D increases after a hot-electron stress, R_D is increased by about 12% after the stress, while on the source

FIGURE 2 The I - V characteristics of AlGaAs/InGaAs/GaAs PHEMTs before and after stress for 60 minutes at $V_{DS} = 7\text{ V}$, $V_{GS} = 0\text{ V}$.

position shifts towards higher V_{DS} after the stress. This is because the stress induced a decrease of the pinch-off voltage, which meant that, at the same V_{GS} value, the maximum field in the channel is lower in the stressed device than it is in the unstressed one [14].

2.2.4 An Increase of I_{DS} in the Saturation Region

Figure 2 indicates also that the hot-electron stress has yielded an increase of I_{DS} in the saturation region, the physical mechanism is a reduction of negative charge in deep traps and DX-centers or an accumulation of positive charge located under the gate, which lead to pinch-off voltage shifts towards further negative V_{GS} values, as shown in Figure 3. If ΔI_{DS} is due to a shift in the pinch-off voltage ΔV_p , then the correlation between ΔI_{DS} and ΔV_p can be

FIGURE 3 The transfer curve of AlGaAs/InGaAs/GaAs PHEMTs before and after stress for 60 minutes at $V_{DS} = 7\text{ V}$, $V_{GS} = 0\text{ V}$.

explained according to the following simple model: $\Delta I_{DS}(\Delta V_{GS}) = I_{DS}(V_{GS} - \Delta V_p) - I_{DS}(V_{GS})$. Substituting $I_{DS}(V_{GS} - \Delta V_p)$ with its first Taylor polynomial term, we can obtain $I_{DS}(V_{GS} - \Delta V_p) = I_{DS}(V_{GS}) - G_m(V_{GS})\Delta V_p$; hence $\Delta I_{DS}(V_{GS}) = -G_m(V_{GS})\Delta V_p$ [15]. If we use the model to fit our experimental data (see Fig. 4), the result is different from [15]. The possible explanations are: (1) short channel effects arise and mix up with the pinch-off voltage degradation; (2) there are more interface states present at AlGaAs/InGaAs heterojunction due to generation by hot carrier bombardment, which causes the channel carrier density reduction due to the charges trapping and mobility decrease due to the addition surface scattering, inducing the I_{DS} and G_m degradation. Hence, the effects of carriers trapped between AlGaAs/InGaAs heterojunction mix up with the pinch-off voltage shift effect. The last phenomenon is probably the dominant one, since the maximum G_m is slightly decreased after the stress (see Fig. 3). In addition, if we shift the stressed transfer curve back (see Fig. 3) and compare with Figure 4, we can find that at $V_{GS} < -0.6$ V, after the hot-electron stress the shape of G_m is almost unchanged (see Fig. 3) and the fit line is also perfect (see Fig. 4). However, at $V_{GS} > -0.6$ V, the phenomena behave in the opposite way. This is because the effects of the addition surface scattering are more and more evident with further increasing V_{GS} towards positive values and mixing up with the pinch-off voltage shift effect. Hence, when $V_{GS} > -0.6$ V, the shape of G_m and the fit line begin to degrade (see Figs. 3 and 4) after the stress.

2.2.5 A Bell-shaped Behavior of I_G

Figure 5 shows I_G as a function of V_{GS} at various V_{DS} from 5.5 V to 7.5 V, in 0.5 V steps. I_G presents a typical bell-shaped behavior previously observed in MESFETs [16] and AlGaAs/GaAs HEMTs [17]. At $V_{GS} < -1.2$ V, I_G is dominated by reverse current and I_D becomes negligible since the device is in pinch-off condition. In fact, the reverse leakage current mechanisms include mainly (1) thermionic emission; (2) thermionic field emission; (3) field emission. Thermionic emission reverse leakage current is affected by image-force barrier height lowering, and both thermionic field emission and field emission are tunnelling mechanisms that depend on Schottky barrier width and height [18].

FIGURE 4 ΔI_{DS} and $-G_m\Delta V_p$ as a function of V_{GS} . The ΔI_{DS} and G_m have been calculated at $V_{DS} = 2$ V. ΔI_{DS} is the I_{DS} current change after 60 minutes of stress at $V_{DS} = 7$ V, $V_{GS} = 0$ V.

FIGURE 5 Gate current versus gate bias measured at different V_{DS} values of AlGaAs/InGaAs/GaAs PHEMTs, before (solid line) and after (dashed line) stressing at $V_{DS} = 7\text{ V}$, $V_{GS} = 0\text{ V}$ for 60 mins.

The relationship between reverse leakage current density and Schottky barrier height is [19]

$$J_r = A^* T^2 \exp\left(\frac{-q\phi_B}{kT}\right) \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (1)$$

where J_r is the reverse leakage current density, and ϕ_B is the Schottky barrier height.

The thermionic emission reverse leakage current is affected by image-force barrier height lowering, and the image-force barrier height lowering depends on the electric field at metal–semiconductor interface and it can be written as

$$\Delta\phi_B = \left[\frac{qE_m}{4\pi\epsilon\epsilon_S} \right]^{1/2} \quad (2)$$

where $\Delta\phi_B$ is the image-force barrier height lowering, and E_m is the electric field at the metal–semiconductor interface.

Then the thermionic emission reverse leakage current density, accounting for image-force barrier height lowering may be expressed as

$$J_r \sim A^* T^2 \exp\left(\frac{-q\phi_B}{kT}\right) \exp\left(\frac{q\Delta\phi_B}{kT}\right) \quad (3)$$

if we assume the metal–semiconductor Schottky barrier may be approximated as a triangular barrier as shown in Figure 6(a). Then, the slope of the triangular potential barrier is the electric field at the metal–semiconductor interface, and the electric field at the metal–semiconductor interface will rise with increasing V_{GS} towards negative values. Hence, the image-force height lowering increases with increasing $|V_{GS}|$ values (see Eq. (2)). From Eq. (3), we can know that the thermionic emission reverse leakage current will increase with increasing $|V_{GS}|$ values due to an increase of image-force barrier height lowering decreasing the effective Schottky barrier height. Furthermore, the tunnelling current increases with increasing $|V_{GS}|$ values (since barrier width and height reduce with increasing $|V_{GS}|$ values).

FIGURE 6 (a) Triangular barrier approximation for a metal–semiconductor barrier, before (solid line) bias and after (dashed line) reverse bias. The source is floating. (b) Triangular barrier approximation for a metal–semiconductor barrier, before (solid line) and after (dashed line) stressing. The source is floating.

Consequently, at $V_{GS} < -1.2$ V region, the reverse leakage current increases with increasing V_{GS} towards negative values.

At $V_{GS} > -1.2$ V, the mechanisms are similar to the previous report [20]. I_D increases with increasing V_{GS} towards positive values and there are more and more electrons transferring in the high-field region between gate and drain, which makes the impact ionization rate rise. The holes generated by impact ionization will be collected by gate electrode and therefore $|I_G|$ increases up to $V_{GS} = -0.5$ V (see Fig. 5). However, at $V_{GS} > -0.5$ V region, the longitudinal electrical field in the gate-drain region decreases with further increasing V_{GS} towards positive values. In consequence, $|I_G|$ decreases gradually again.

After 60 minutes of hot-electron stress at $V_{DS} = 7$ V, $V_{GS} = 0$ V, $|I_G|$ reduces for all different V_{GS} values at different V_{DS} steps ($V_{DS} = 5.5$ V to 7.5 V in 0.5 V steps), as reported in Figure 5. These possible explanations are: (1) the depletion under the gate expands towards the drain after the stress, and the widening of the depletion will result in reducing the maximum electrical field [21, 22] and make the impact ionization rate decrease. Thus, $|I_G|$ decreases at -1.2 V $< V_G < -0.5$ V region after the stress; (2) at $V_G < -1.2$ V region,

the decrease of reverse leakage current is also due to, after the stress, the widening of the depletion in the gate-drain region, which results in the image-force barrier height lowering decrease due to the electric field at the metal–semiconductor interface reducing and the tunneling current reduction due to the barrier width increasing (see Fig. 6(b)). In consequence, $|I_G|$ decreases at $V_G < -1.2$ V region after the stress. Equally, the reverse current decreases at $V_G > -0.5$ V region after the stress; (3) the resistance of the drain access region (R_D) increases by about 12% after the stress, it is consistent with the hypothesis of the widening of the depletion in gate-drain region. In addition, we have also measured reverse bias characteristics of the gate-drain diode with source floating, as shown in Figure 7(a), in order to further identify that the depletion in the gate-drain region is widened by the hot-electron stress. Figure 7(a) shows that the reverse current of the gate-drain diode with source floating decreases after a hot-electron stress of 60 mins at $V_{DS} = 7$ V and $V_{GS} = 0$ V, indicating the image-force barrier height lowering decreases after the stress (the decrease of the image-force barrier height lowering is due to the widening of the depletion in the gate-drain region, see Figure 6(b) and Eq. (3)). Thus, the depletion in the gate-drain region is widened certainly by the stress.

2.2.6 A Further Discussion of the Schottky Junction

After a hot-electron stress, there are two main mechanisms that will influence the characteristics of Schottky barrier height. One is the effect of the depletion widening, and the other is the effect of the carriers trapping under the gate. The widening of the depletion under the gate can cause a reduced peak electric field [22, 23] and a decrease of image-force barrier height lowering (see Eq. (2)), which results in a larger effective Schottky barrier height and a smaller reverse leakage current density (see Eq. (3)). On the contrary, the carriers trapping under the gate may cause an increase of the electric field at metal–semiconductor interface and result in a smaller effective Schottky barrier height due to the image-force barrier height lowering increasing (see Eq. (2)). Hence, if we measure the reverse bias characteristics of the

FIGURE 7 The reverse bias characteristics of the gate-drain diode of InGaP PHEMTs. (a) The source is floating. (b) The source and drain are shorted.

Schottky junction with source and drain shorted, we can find that after the hot-electron stress, the case is opposite to the reverse bias characteristics of the Schottky junction with source floating, as reported in Figure 7(b). These possible explanations are: (1) when the source is floating, the effect of the depletion widening dominates the device characteristics, and results in a larger effective Schottky barrier height and smaller reverse leakage current after the stress (see Fig. 7(a)); (2) when source and drain are shorted, we not only consider the effect of the carriers trapping in the gate-drain region, but also in the gate-source region. Therefore, the effect of the carrier trapping becomes the dominant mechanism, which will result in a smaller effective Schottky barrier height and a larger reverse leakage current after a hot-electron stress (see Fig. 7(b)).

2.3 Temperature-dependent Characteristics of AlGaAs PHEMTs

PHEMT power amplifiers play an important role in microwave-integrated circuits. A huge amount of heat will be generated because they consume a lot of dc power; this influences the performance and the reliability of devices and circuits. Therefore, the study of the change in device DC characteristics under different operational temperatures allows us to understand further the thermal behavior of the devices. In addition, knowledge of the temperature in DC characteristics of PHEMTs is essential to be able to improve device reliability and to optimize device design and performance. In this section, we get an understanding of the influence of temperature on DC characteristics of AlGaAs PHEMTs and allow one to investigate the possibility of improving device stability.

2.3.1 Thermal Effects of I_D and G_m in the Saturation Region

The I - V characteristics and transfer curve of AlGaAs PHEMTs with different temperature ranging from 300 K to 420 K with steps of 30 K are shown in Figures 8 and 9. At lower V_{GS} values, an increase of the I_D and G_m in the saturation region is due to a slight increase of the magnitude of the pinch-off voltage with increasing temperature. The correlation between pinch-off voltage and temperature is shown in Figure 10, and the magnitude of the pinch-off voltage increase with increasing temperature may be due to the trapped electrons compensated by holes generated by heat or an accumulation of holes located under the gate. At higher V_{GS} values, however, the I_D and G_m begin to degrade with increasing

FIGURE 8 The I - V characteristics of AlGaAs/InGaAs/GaAs PHEMTs with different temperature ranging from 300 K to 420 K in 30 K steps.

FIGURE 9 The transfer curve of AlGaAs/InGaAs/GaAs PHEMTs with different temperature ranging from 300 K to 420 K in 30 K steps.

temperature. It suggests that the scattering effects are more obvious with increasing temperature at higher V_{GS} values than the effects of pinch-off voltage shift. This result may be that carriers in the channel increase with increasing V_{GS} values, and the increase of the charge density induces the scattering effects increasing and mobility decreasing at higher temperature, which results in I_D and G_m degradation with increasing temperature at higher V_{GS} values.

2.3.2 Disappearance of the Kink

Figure 8 shows that a kink is observed at $V_{DS} \sim 2.5$ V at room temperature, indicating that trapping-detrapping phenomena are present [24–26]. However, the kink disappears at higher temperatures. A possible explanation is as follows: (1) At room temperature, when the drain voltage is applied, the electrons are accelerated by electrical field in the channel, and hot-electrons start injecting into adjacent layers and get trapped in deep levels. Therefore, the current reduction occurs because the number of available carriers in the active channel is decreased. As the drain voltage is further raised, the trapped electrons near the drain side are emitted, and the current increases again [27]. Thus, the kink appears at room temperature.

FIGURE 10 The pinch-off voltage versus temperature of AlGaAs/InGaAs/GaAs PHEMTs.

FIGURE 11 The mechanism of current transport in metal-semiconductor.

(2) At higher temperatures, the trapped electrons are energetic, and the traps are difficult to capture carriers. The capture/emission phenomena of traps then are less obvious at higher temperatures than at room temperature. Therefore, the kink disappears at higher temperatures.

2.3.3 Thermal Effects of the Schottky Junction

Experimental studies of metal–semiconductor contacts have shown that most of the metal–semiconductor combination form depletion layer contacts. The conduction properties of such contacts are determined by the actual transport mechanism, as shown in Figure 11, which can be due to:

- (1) Thermionic Emission (TE): the carriers surpass the top of a barrier and give rise to rectifying behavior.
- (2) Thermionic Field Emission (TFE): the tunnelling of hot carriers through the top of the barrier.
- (3) Field Emission (FE): the carriers tunnel through the whole barrier.
- (4) Recombination in the space.

TE and TFE are temperature-dependent (TFE and TE increase with increasing temperature), while FE is temperature-independent [21].

FIGURE 12 The forward-bias characteristics of gate-to-drain Schottky diode of AlGaAs/InGaAs/GaAs PHEMTs.

FIGURE 13 The reverse-bias characteristics of gate-to-drain Schottky diode of AlGaAs/InGaAs/GaAs PHEMTs.

The forward bias characteristics of the Schottky junction are shown in Figure 12, the turn on voltage reduces with increasing temperature, due to an increase of TE and TFE. Figure 13 shows the reverse bias characteristics of the Schottky junction, the gate leakage current tends to a point at higher $|V_{GS}|$ values. It suggests that the FE mechanism is more and more obvious with increasing $|V_{GS}|$ values. This result may be because the width of the depletion reduces at higher $|V_{GS}|$ values, causing larger tunnelling current, which results in the FE becoming a main mechanism at higher $|V_{GS}|$ values. Thus, the gate leakage current tends to a point at higher $|V_{GS}|$ values.

3 SUMMARY

In this report, the most important degradation mechanisms of AlGaAs PHEMTs (such as gate-drain breakdown walkout or the bell-shaped of I_G) are studied and discussed. In all of the devices under test the degradation mechanisms can be attributed to trap-related phenomena that can be split into two major categories: (1) the carriers trapped under the gate electrode or between AlGaAs/InGaAs heterojunction after accelerated tests, that give rise to a shift of the threshold voltage (ΔV_T) or a degradation of G_m and I_{DS} ; (2) the creation of traps in the gate-drain region, resulting in a permanent increase of the gate-drain breakdown voltage.

In conclusion, experimental results indicate that hot-electron and temperature effects in AlGaAs PHEMTs should be carefully evaluated if the improvement of long-term reliability is needed.

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