Reliability and degradation mechanism of AlGaAs/InGaAs and InAlAs/InGaAs HEMTs

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The long-term stability of AlGaAs/GaAs and InAlAs/InGaAs high electron mobility transistors (HEMTs), tested under high drain voltage and/or high temperature operation is reported. HEMTs with high In content in the active channel, alternatively fabricated on InP substrates and on GaAs substrates covered by a metamorphic buffer (MHEMT), are compared. Despite the high dislocation density in the buffer layer MHEMTs and InP based HEMTs exhibit comparable reliability. AlGaAs/GaAs HEMTs are more reliable than their InAlAs/InGaAs counterparts, especially when operated at high drain voltage. Failure mechanisms are thermally activated gate sinking, Ohmic contact degradation and hot electron induced degradation.

1. Introduction

High electron mobility transistors (HEMTs) are widely used for high speed low noise amplifiers, power amplifiers and digital circuits. Beside manufacturing cost and yield, reliability and longevity of the circuits are mandatory for system applications. This paper summarizes the reliability of AlGaAs/InGaAs pseudomorphic HEMTs on GaAs substrate (PHEMT) and of InAlAs/InGaAs HEMTs alternatively grown on InP substrate (InP HEMT) and on GaAs with a metamorphic buffer (MHEMT). The major degradation mechanism observed under high drain voltage and/or high temperature operation will be presented and discussed.

Figure 1 shows typical cross sections of the epitaxial layer structures used to fabricate the different devices. The essential difference of the layer structures is the In content of the channel. High indium content is desirable since the mobility and thus the maximum switching speed is increasing with the In

![Cross-sections of HEMT epitaxial layer structure.](image-url)
content. PHEMTs with indium contents up to 25% can be grown on GaAs substrate. High speed InP HEMTs or MHEMTs contain up to 80% indium in the channel. The main advantages of the MHEMT technology are larger substrate diameters at reduced cost and better mechanical stability of GaAs substrates. The lattice mismatch between the GaAs substrate and the HEMT layers is accommodated by a high dislocation density in the metamorphic buffer layer.

In the following section reliability of the different HEMT structures as determined by biased accelerated lifetime tests will be compared. In the third section the main degradation mechanisms are discussed and their influence on various device performance parameters is presented.

2. Reliability of low power devices

The long-term stability of HEMT devices is determined by biased temperature accelerated lifetime tests. Contrary to expectations it has been found that the high dislocation density in the metamorphic buffer has no negative impact on the long-term stability of MHEMTs at low power [1]. Fig. 2 compares the relative change of transconductance at a fixed bias point of MHEMT and InP HEMT at a channel temperature of $T_{ch} = 253 \, ^\circ C$. Similar degradation rates were found for both devices. For DC biased accelerated stress tests the failure criterion is usually defined as a 10% degradation of maximum transconductance or a 20% reduction of the operating drain current.

Figure 3 shows the degradation of the maximum transconductance, obtained at three different channel temperatures, for depletion MHEMTs designed for low noise analog W-band (75–110 GHz) applications. The median lifetime is calculated using a failure criterion of 10% reduction of the maximum transconductance and the lognormal distribution. The median lifetime at operating conditions is extrapolated using the Arrhenius equation

$$t_{50\%} = t_0 \exp \left( \frac{E_a}{kT} \right),$$

where $t_{50\%}$ is the median time to failure, $k$ is the Boltzmann constant and $E_a$ is the activation energy. Figure 4 shows the Arrhenius plot for depletion MHEMTs. By extrapolation, an activation energy of 1.9 eV and a median lifetime of Ohmic contact resistance. As shown in Fig. 5 the median lifetime of enhancement MHEMTs is approximately one order of magnitude smaller as compared to depletion MHEMTs.

The lifetime of the enhancement MHEMT still meets the lifetime requirements for space applications which is $10^6$ h at 125 °C [2, 3]. The reasons for faster degradation of enhancement MHEMTs as compared to depletion MHEMTs is presently under investigation and may be caused by the smaller gate to
channel distance and/or the smaller recess length, which leads to a higher electrical field on the drain side.

Chou et al. [3] compared the lifetime of 0.1 µm PHEMTs and InP depletion HEMTs. Both have lifetimes exceeding $10^8$ h at a channel temperature of 125 °C. The failure mechanism was ascribed to Ohmic contact degradation for the InP HEMTs and to Schottky contact degradation for the pHEMTs.

3. Reliability of HEMTs for power applications

The lower band gap energy of InP based HEMTs and MHEMTs complicates the fabrication of highly reliable devices suitable for power applications. Nevertheless, very promising long-term stability of MHEMTs with 40% In content in the channel, tested at high power, has been demonstrated [4]. Figure 6 shows the relative change of the drain current versus aging time of a 0.25 µm power MHEMT with refractory gate metal. The stress conditions were: $T_{ch} = 185$ °C, $V_d = 4$ V and power density per gate width of 0.5 W/mm. The increase of the drain current is possibly caused by the capture of holes generated by impact ionization. If the holes are captured close...
to the gate they lead to a negative shift of the threshold voltage of about 40 mV and thus to an increase of the drain current.

Power PHEMTs with double recess were investigated at drain voltages up to 10 V [5]. Figure 7 shows the very slow degradation of the drain current occurring at channel temperature $T_{ch} = 250 \, ^\circ\text{C}$, drain voltage $V_{DS} = 5 \, \text{V}$ and power per gate width of 1 W/mm. No significant effect of the gate recess length on lifetime was found. Based on a 10% drain current degradation failure criterion and the lognormal distribution we found a median lifetime of 4100 h at $T_{ch} = 250 \, ^\circ\text{C}$. This result demonstrates state-of-the-art reliability. Chertouk et al. [6] reported a lifetime of 3500 h at $T_{ch} = 275 \, ^\circ\text{C}$, $V_{d} = 5 \, \text{V}$ and power per gate width of 1 W/mm [6].

4. Degradation mechanisms

4.1 Gate sinking

Gate sinking designates the thermally activated diffusion of a constituent of the gate metal into the semiconductor, resulting in a decrease of the distance between the metal–semiconductor interface and the active channel. Canali et al. [7] first reported this failure mechanism for power GaAs MESFETs with Ti/W/Au gate. Using Auger spectroscopy the authors found Au diffusion through inter-spersed W and Ti layers into the GaAs in a device that failed after RF stress at $T_{ch} = 185 \, ^\circ\text{C}$. They also observed a decrease of the pinch off voltage. The decrease of the gate to channel distance causes a positive shift of the threshold voltage $V_{th}$ and an increase of the maximum transconductance $g_{m,\text{max}}$.

The gate sinking mechanism has been positively identified for the first time with TEM cross-section analysis. Figure 8 compares the cross-sections of stressed and an unstressed InAlAs/InGaAs HEMT with Pt–Ti–Pt–Au gate. The stress conditions were $T_{ch} = 235 \, ^\circ\text{C}$ for 230 h and $P = 0.2 \, \text{W/mm}$. Before stress the Pt–semiconductor interface is smooth. After stress the Pt layer appears thicker and the interface is rough due to Pt diffusion into the semiconductor. The transfer characteristic before and after stress is shown in Fig. 9. The positive threshold voltage shift of 120 mV corroborates the gate sinking. A stabilization bake may be used to generate an intentional initial gate sinking to reduce the subsequent sinking during device operation [8, 9]. Ishida et al. [10] found that gate sinking of InAlAs/InGaAs HEMTs can be reduced by replacing Ti gates by Mo gates, exploiting the better thermal stability of refractory gate metals. The $g_{m,\text{max}}$ degradation in Fig. 9 is mainly caused by the increase of the source and drain resistance due to the degradation of the Ohmic contacts, as discussed in the following section.

4.2 Ohmic contact degradation

Ohmic contact degradation is caused by thermally activated metal–metal and metal–semiconductor interdiffusion [11]. Owing to the high activation energy above 1.5 eV, Ohmic contact degradation is not a major reliability concern for operation at ambient temperature [12]. It may limit the temperature to be used for highly accelerated lifetime tests, since failure mechanism with

![Reference device](image1.png) ![After: $T_{ch}=235\,^\circ\text{C}$ for 200h, $P=0.2 \, \text{W/mm}$](image2.png)

**Fig. 8** TEM cross-section of MHEMT with Pt/Ti/Pt/Au gate before and after stress.
lower activation energy may be masked. Therefore accelerated lifetime tests should also be performed at moderately elevated temperature.

Lee et al. [13] compared the degradation of AuGe/Ni and AuGe/Pt Ohmic contacts with and without Ti–Pt–Au overlay metal. For AlGaAs/GaAs HEMTs they found a more rapid degradation caused by the overlay metal. In order to investigate this degradation mechanism the effect of the metal layer composition on the contact resistance was studied by storage test of transmission line measurement (TLM) structures. Figure 10 shows that the long-term stability is improved by increasing the Pt thickness, while W–Au metal overlay metal shows the slowest degradation rate of all studied metals. These results suggest that the degradation is caused by the diffusion of gold through the Ti and Pt barriers and that W is the most effective barrier metal.

The increase of the contact resistance of AuGe/Ni contacts for InAlAs/InGaAs HEMTs is more rapid than for AlGaAs/GaAs HEMTs. Figure 11 shows the degradation of the AuGe/Ni Ohmic contact at 215 °C without overlay metal. The more pronounced degradation may be attributed to the outdiffusion of In into the contact [14]. By using WSi as Ohmic contact metal the outdiffusion is suppressed and the long-term stability of the Ohmic contact of InAlAs/InGaAs HEMTs is improved [15].

4.3 Hot electron degradation Hot electron degradation is caused by the electric field between gate and drain contact which accelerates the carriers in the channel. If the field is high enough some hot electrons can overcome the conduction band discontinuity or, if the kinetic energy of the electron is higher than the band-gap, the hot electrons may cause impact ionization. The electron–hole pair is separated by the electric field, trapping the holes close to the gate contact and leading to a negative shift of the threshold voltage.
Adverse effects induced by hot carriers are gain degradation, shift of the threshold voltage and increase of the drain resistance [16]. The gain degradation and the increase of the drain resistance are due to the generation of surface traps in the SiN passivation layer between gate and drain [17]. Electrons captured by these traps decrease the electric field between gate and drain and thus increase the parasitic drain resistance. These traps are also responsible for the increase of the breakdown voltage, the so-called breakdown walkout [18].

5. Conclusion Excellent long-term stability has been achieved for InAlAs/InGaAs and AlGaAs/GaAs HEMTs, especially for low power devices. Work still needs to be done to improve the reliability of high power devices operated at drain voltages exceeding 5 V. Gate sinking, Ohmic contact degradation and hot electron degradation, the major degradation mechanism of HEMTs due to temperature and electric field induced stress, have been observed and discussed.

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References