Degradation mechanism of PHEMT under large signal operation

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Abstract

We have studied the degradation mechanism of AlGaAs/InGaAs pseudomorphic HEMTs (PHEMTs) under large signal operation. The output power of the PHEMT is degraded with increasing drain voltage (Vd), temperature, and humidity. The deteriorated devices show a decrease of the maximum drain current (Imax) around the knee voltage (Vk) and an increase of the drain resistance (Rd). Cross-sectional transmission electron microscopy (TEM) images from the deteriorated devices reveal the existence of a damaged recess surface region at the drain side of the device. In this damaged region, a significant amount of oxygen is detected by energy dispersive x-ray spectroscopy (EDX) analysis. The damaged recess region leads to a reduced carrier density that results in decreased Imax and increased Rd. We suggest that the damaged recess region is caused by an electrochemical reaction that correlates with electric field, temperature and humidity. We have developed a special surface treatment that is applied prior to the deposition of the passivation film on the recess surface. This treatment successfully suppresses output power degradation in these devices. We demonstrate highly reliable RF operation with less than 0.2dB reduction in output power during 1000hr at Vd=5V and Tch=175°C

Keywords

AlGaAs/InGaAs PHEMT, Surface degradation, Reliability, Corrosion

INTRODUCTION

AlGaAs/InGaAs PHEMTs are commonly observed to suffer from a gradual decrease in output power during continuous RF large signal operation, the so-called "power slump" [1-2]. It has been reported that the degradation originates in the large electric field in the gate-drain gap, via the hot carriers and/or impact ionization [1-3]. The detailed physical mechanism behind the degradation is still not well-known. In particular, considering that output power degradation exhibits a positive temperature coefficient, it is difficult for the degradation to be simply explained by a hot carrier effect, since this should manifest a negative temperature coefficient.

In this paper, we have investigated the dependence of output power degradation in PHEMTs on Vd, temperature and humidity. We also discuss the degradation mechanism of PHEMTs under large signal operations. We demonstrate a special surface treatment for suppressing this power degradation.

SAMPLES AND EXPERIMENTAL

Pseudomorphic AlGaAs/InGaAs HEMTs with a 0.25 μm gate length were fabricated for this study. The T-shaped gate was patterned by electron-beam lithography. These devices were passivated with plasma-enhanced chemical vapor deposition silicon oxide. The devices were mounted on a hermetic package. These devices typically exhibit a gate-to-drain breakdown voltage (BVgd) of 18V at a gate current of 0.1mA/mm, a maximum current density (Imax) of 470mA/mm and a current gain cutoff frequency of 50GHz.

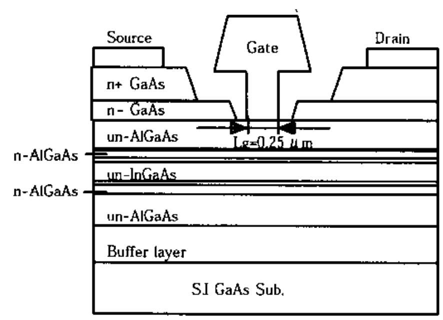

Figure 1. Cross section of AlGaAs/InGaAs PHEMT.

An RF accelerated life test was performed at 18GHz using a single stage amplifier with 600 μm total gate periphery. The input power (Pin) was set at 1dB compression at the beginning of the test. Before and after the RF life test, DC and RF

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measurements as well as TEM and EDX analysis were performed.

RESULTS AND DISCCUSSION

Figure 2 shows the changes in output power during the RF life test of PHEMTs at a Vd of 5 V and 7 V. Ambient temperature is 85 °C. When Vd was raised from 5 V to 7 V, the degradation rate was seen to accelerate. Figure 3 shows the changes in output power during RF life test of the PHEMTs at ambient temperature of 25 °C and 125 °C. When the temperature was raised from 25 °C to 125 °C, the degradation rate also increased. These results suggest that the degradation is not simply due to hot carrier effects because the degradation rate is accelerated by temperature. Figure 4 shows typical RF power characteristics of a degraded sample under RF life test (Tch=150°C, Vd=5 V, 2000 hr) compared with those of an untested sample. These characteristics indicate that the saturation power decreases without a change of the linear gain.

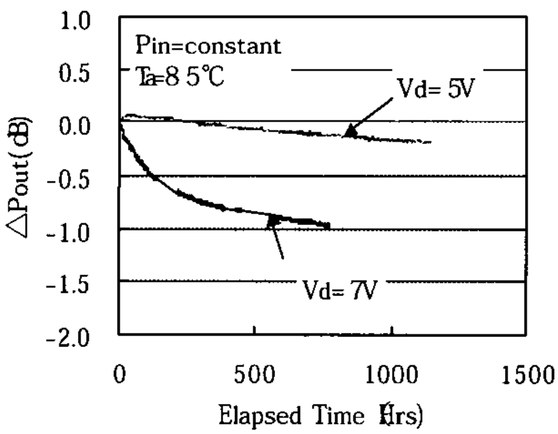


Figure 2. Pout degradation under RF life test for Vd of 5 V and 7 V. Samples are in hermetic packaging.

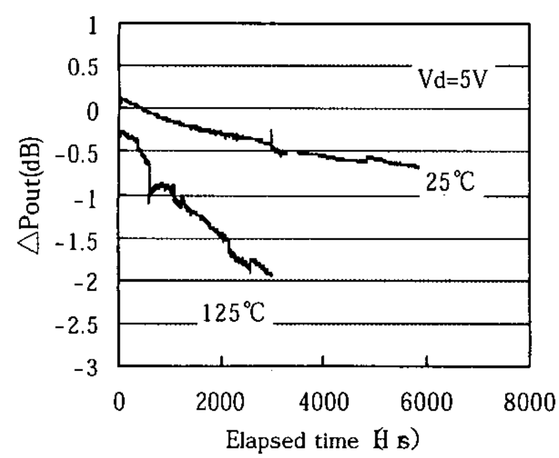


Figure 3. Pout degradation under RF life test at ambient temperature of 25°C and 125°C. Samples are in hermetic packaging.

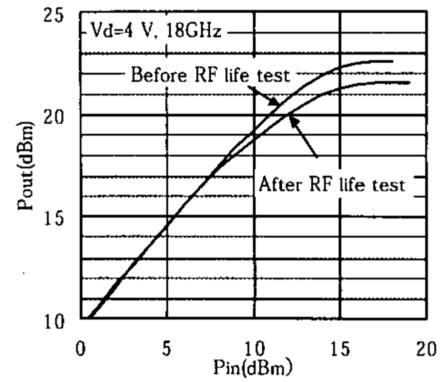


Figure 4. Power characteristics change after RF life test (Tch=150°C, Vd=5V, 2000hrs).

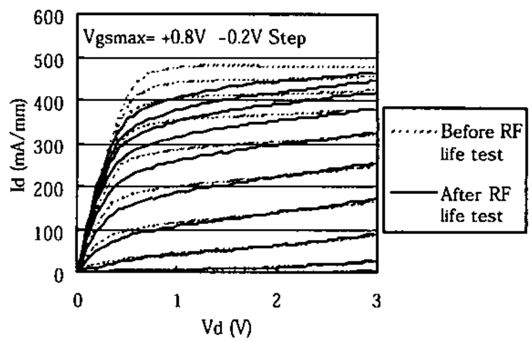


Figure 5. DC characteristics change after RF life test (Tch=150°C, Vd=5 V, 2000 hrs).

Table 1. DC characteristics change after RF life test (Tch=150°C, Vd=5 V, 2000 hrs).

	initial	After RF life test
Rs[ohm·mm]	1.3	1.1
Rd[ohm·mm]	1.5	5.0
Imax[mA/mm]	470	400
Vth[V]	-0.9	-0.9
BVgd[V]	-18	-19
BVgs[V]	-16	-16

Figure 5 and Table 1 show typical DC characteristics and figures of merit before and after RF life test. In the Id-Vd characteristics, Id around Vk decreases, and Rd increases. These changes in the DC and RF characteristics were observed at different life test conditions. The increase in Rd coupled with the fact that Rs and Vth remain unchanged indicates that the degradation occurred on the drain side of the device.

Figure 6 shows a cross-sectional TEM image of a degraded device. A degraded surface region was always observed at the GaAs and AlGaAs surface in proximity to the recess on the drain side of the device. A degraded region was not observed in virgin samples.

Figure 7 shows EDX spectra of the degraded region on the drain side. Besides Ga, As and Al, a significant amount of oxygen is observed. Figure 8 shows a correlation between Imax reduction and the thickness of the degraded region as measured from TEM images in different degraded samples. A thicker degraded layer leads to a larger Imax reduction. These results indicate that the degraded region at the drain side of the device reduces the carrier density, causing Imax to decrease, Rd to increase, and eventually the power to decrease.

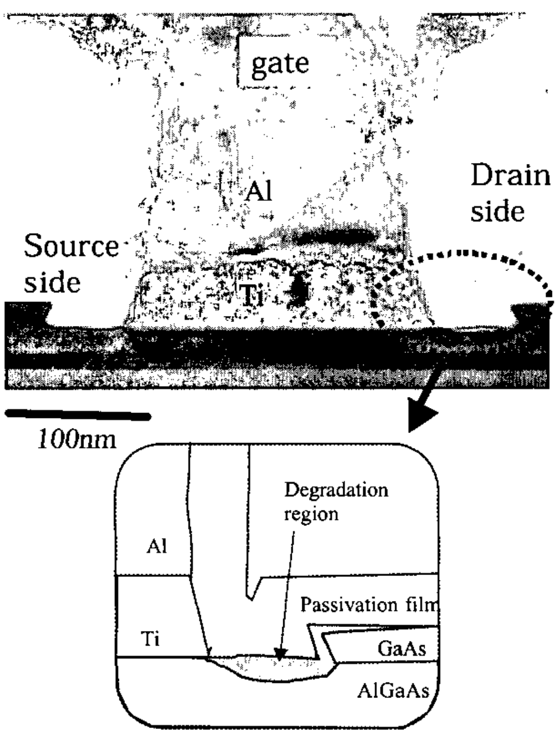


Figure 6. TEM photograph of a degraded device under RF life test.

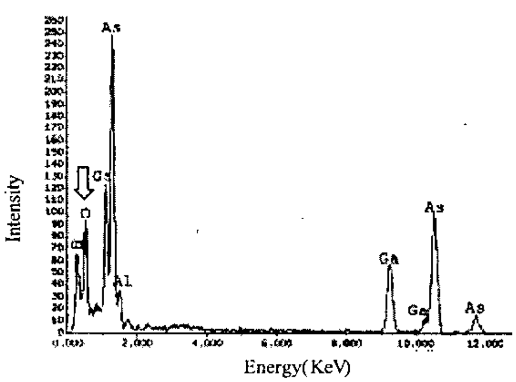


Figure 7. EDX spectra of degraded region.

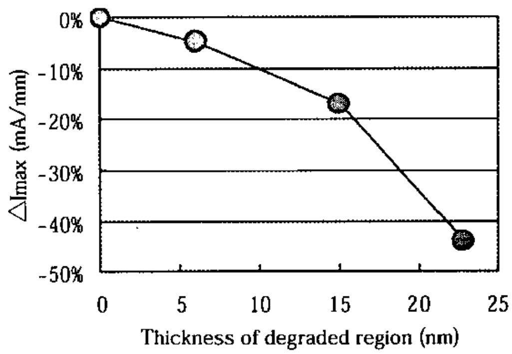


Figure 8. Imax change during RF life test as a function of thickness of degraded region.

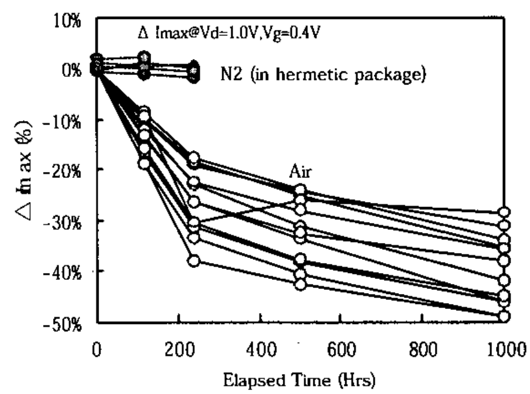
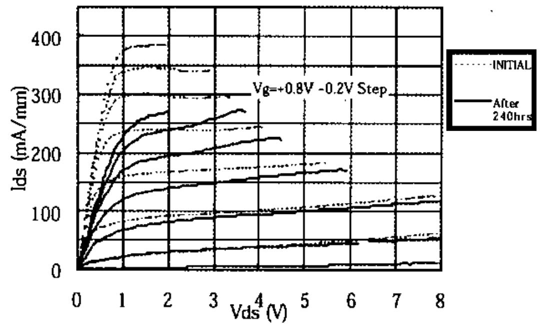


Figure 9. Imax change during DC life test in hermetic package and in air (Tch=150°C, Vd=4V, Id=150mA/mm).

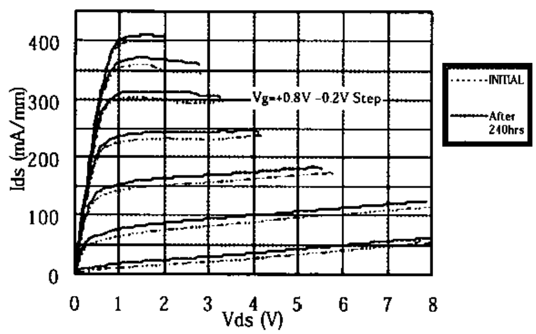
To investigate the mechanism of surface degradation, we performed DC and RF life tests in air (relative humidity about 50%). Figure 9 shows Imax change during DC life test (Tch=150°C, Vd=4 V, Id=150 mA/mm) for samples in a hermetic packaging and exposed to air without a cap. Imax degradation was accelerated in air, compared with identical samples under N_2 in hermetic packaging. Pout degradation under RF life test was also accelerated in air. A degraded surface region was also observed in the samples stressed in air. Moreover, the degradation also occurs under the off-state bias test (Vgs=-3 V, Vd=4 V) in air (not shown here).

In this off-state condition, the voltage between gate and drain is sufficiently lower than the breakdown voltage to expect that the effect of impact ionization is relatively small. This suggests that oxygen or H_2O must play a more important role than impact ionization. Under a negative bias, As reacts with H_2O resulting in corrosion of the semiconductor [4-5]. This reaction has a positive temperature dependence that corresponds with that of device degradation. The electrochemical reaction (corrosion) enhanced by temperature and electric field might be occurring between oxygen or H_2O and the semiconductor surface. These results indicate that the degradation can be suppressed if we could make the surface inactive for oxygen or H_2O.

Towards this goal, we have developed a new surface treatment that is applied prior to the deposition of the passivation film. This special treatment suppresses device degradation. Figure 10 shows Id-Vd curve change after DC stress test (Tch=230°C, Vd=5 V, Ids=100 mA/mm, 240 hrs).



(a) Without surface treatment



(b) With surface treatment

Figure 10. DC characteristics change during DC stress test (Tch=230°C, Vd=5 V, Id=100 mA/mm, 240hrs) of samples (a) without and (b) with surface treatment.

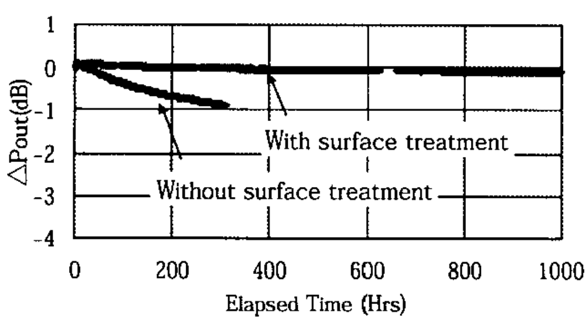


Figure 11. Pout change during RF life test (Tch=175°C, Vd=5 V) of samples with and without surface treatment.

Degradation of DC characteristics is not observed in the samples with the surface treatment.

The surface treatment was performed in a baking furnace under H_2 gas flow in order to make the surface inactive. XPS analysis showed that oxidation of Ga and As were reduced after the surface treatment (not shown). The surface treatment was designed to reduce reaction of the surface with oxygen or H_2O, resulting in improving the Imax degradation.

This surface treatment results in a highly reliable RF operation with an output power reduction after 1000hr with Vd=5 V at Tch=175°C that is smaller than 0.2dB measurement accuracy (Figure 11).

CONCLUSIONS

The recess surface degradation at the drain side of the device was found to be the cause of gradual degradation of PHEMTs under RF large signal operation. This was concluded through direct observations of device cross sections using TEM. The output power during large signal operation is degraded with increasing drain voltage (Vd), temperature, and humidity.

From these results, we conclude that an electrochemical reaction (corrosion) enhanced by temperature and electric field might be occurring between oxygen or H_2O and the semiconductor surface.

A special surface treatment has been developed to eliminate this reaction. This has been effective in suppressing the degradation of the device.

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