REAL-TIME MEASUREMENT OF INP HEMT'S DURING LARGE-SIGNAL RF OVERDRIVE STRESS

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ABSTRACT

We show that the "Nonlinear Network Measurement System" allows to accurately measure the real-time degradation of microwave active devices under large-signal RF overdrive stress. This new kind of measurements gives a better insight in the failure mechanisms. We present results of both off- and on-state degradation of InP based HEMT's.

INTRODUCTION

To avoid gradual device degradation and hence to guarantee a long lifetime, the microwave and millimetre wave circuit designer has to be aware of the instantaneous currents and voltages that are reached during the normal circuit operation. In this paper, we discuss the real-time measurement of the degradation of a microwave device during RF overdrive stress. First, we describe the measurement set-up and point out its advantages compared to other RF stress measurement systems. Then, we present the measurement results on InP HEMT's at the off-state and on-state RF stress conditions.

DESCRIPTION OF THE MEASUREMENT SET-UP

The measurement set-up being used is the HP "Nonlinear Network Measurement System" (NNMS) (1)(2), which allows to measure both the amplitude and phase of all spectral components of the incident and scattered travelling voltage waves at the device ports. The current and voltage waveforms can easily be derived once the travelling voltage waves and the biasing parameters are known.

Large-signal waveform measurements at stress conditions have already been presented (3)(4). The difference with our approach is twofold. First, the NNMS allows to simultaneously excite both ports of the DUT and to measure the four travelling voltage waves without the need of switches. This implies that it is possible to study the device degradation as a function of the phase difference between the two excitation signals. The second difference with former published results is that large-signal waveform measurements are usually made before and after the stress test. We can perform the measurements during the RF overdrive stress test. Furthermore, the DC measurements made before and after the stress test were also performed by using the NNMS set-up. This means that the reliability of devices can be characterised without the need to disconnect the device and to modify the configuration of measurement instruments.

We present here the results where we operated devices under the off-state (5) and on-state (6) breakdown conditions, which are important for several circuit types (7), such as power amplifiers and frequency multipliers. The devices under test are 0.2 µm x 100 µm InP based HEMT's fabricated at IMEC (8), but the proposed measurement procedure can be applied to any microwave device.

MEASUREMENT RESULTS UNDER OFF-STATE RF STRESS CONDITION

The pseudomorphic InP based HEMT's are biased at a DC drain-source voltage of 1 V and a DC gate-source voltage of -10.5 V. This corresponds to a DC gate-drain voltage which is 6 V beyond the gate-drain breakdown voltage BV_{gd} (defined at 1 mA/mm reverse gate current) of these devices. We have chosen this condition to increase the speed of the degradation and to be able to measure with a higher accuracy. The latter is because the AC currents at the BV_{gd} bias condition are very small considering the 60 dB dynamic range of the measurement system.

The measurement set-up, schematically depicted in Fig. 1, includes two RF sources, which enables that the phase of one excitation signal can be varied independently from that of the other excitation signal. The phase of a_1, $\varphi(a_1)$, is defined to be 0°. The $\varphi(a_2)$ is randomised, since the phase of an RF source can not be set to a predefined value. The powers of the a_1 and a_2 travelling voltage waves are respectively 7.3 dBm and 6.2 dBm. The fundamental frequency of both a_1 and a_2 is 1 GHz. The devices are electrically stressed during 10 minutes, during which the $\varphi(a_2)$ is kept unchanged. The devices are DC characterised before and after the RF stress to study the degree of the device degradation. During the stress test, a large-signal waveform measurement is performed each 30 sec.

We first examine the measurement results in the case where $\varphi(a_2)$ is equal to -152°. Fig. 2 presents the corresponding measured current and voltage waveforms. Fig. 3 shows the change of the gate-source current time domain waveform as a function of stress time. In order to investigate this evolution in detail, we have plotted on Fig. 4 the minima of these gate-source current time domain waveforms as a function of the stress time. We notice that the logarithm of the absolute value of the minimal currents is proportional to the square root of the stress time. This phenomenon has already been noticed during DC electrical stress tests on MESFETs and has been physically explained in (4)(9). The basic failure mechanism is impact-ionisation induced avalanche breakdown. This means that avalanche-generated hot electrons are trapped in the SiN passivation layer between the gate and the drain. The carrier multiplication is caused by thermionic emission of electrons from the gate and their impact ionisation in the depleted HEMT channel. Impact ionisation redirects the momenta of hot electrons and allows their injection into the SiN and the formation of traps there. The trapped negative charges can increase the surface depletion, thereby reducing the transconductance, and they relax the gate-drain field distribution, thereby suppressing avalanche breakdown. The advantage of the "Non-linear Network Measurement System" is that not only the change of the DC parameters, but also that of the instantaneous large-signal currents and voltages can be measured in real-time. The change of the minimum and that of the maximum of the gate-source current time domain waveform after 10 minutes stress time are listed in Table 1. We see that the maximum changes less compared to the minimum. This can be explained by Fig. 5, where the gate-source current (I_{gs}) waveform is plotted as a function of the gate-drain voltage (V_{gd}) waveform. The maximum of the gate-source current waveform is reached at V_{gd} equal to -9 V, while the minimum of the gate-source current waveform is obtained at V_{gd} equal to -14 V. Under the latter condition, the device is driven further into the off-state breakdown operating region, which clarifies the faster degradation.

Table 1 also shows the change of the DC gate-drain breakdown voltage and that of the maximum of the device's transconductance. The decrease of the absolute value of the gate-source current at increasing stress time is clearly reflected in an increase of BV_{gd}. Fig. 6 presents the device's transconductance, measured before and after the RF off-state stress experiment. We notice that the threshold voltage remains identical, while the transconductance drops. This result is consistent with reported measurements of MESFETs, submitted to off-state breakdown DC stress (4). Finally, we studied the reversibility of the degradation. After the stress test, the device was left unbiased at room temperature. After 5 minutes, the DC gate-drain breakdown voltage was returned to about 90 % of its original value.

The "Nonlinear Network Measurement System" enables to study the influence of the $\varphi(a_2)$ on the device reliability. Fig. 5 compares the measurement results for $\varphi(a_2)$ equal to -152° and equal to +87°. We notice that the curves are strongly dependent on the $\varphi(a_2)$. A transistor behaves as an inverter. If $\varphi(a_2)$ is nearly 180°, then the part of the b_2 travelling voltage wave, that arises from a_1, interferes constructively with the part of b_2, that is related to a_2. The opposite holds if the $\varphi(a_2)$ is nearly 0°. This implies that the instantaneous currents and voltages that are reached during one RF period strongly depend on $\varphi(a_2)$, which underlines the importance of this measurement capability of the NNMS. In fact, this can be seen as a fundamental loadpull measurement, whereby the load presented to the device is being varied at the fundamental frequency. For the microwave and millimetre wave circuit designer, the knowledge of the influence of the matching networks on the device reliability is essential to ensure a long circuit lifetime. Fig. 5 includes also the measurement results after ten minutes stress time for both values of $\varphi(a_2)$. From this Figure, Fig. 4 and the summarising results listed in Table 1, we observe that the device degradation is less for $\varphi(a_2)$ equal to +87°. This can be explained by the fact that under this operating condition the device is less driven into the off-state breakdown region and hence less stressed.

MEASUREMENT RESULTS UNDER ON-STATE RF STRESS CONDITION

We also investigated the degradation of lattice-matched InP based HEMT's under the on-state RF stress condition. The applied DC gate-source voltage is 0.1 V, which corresponds to the gate-source voltage at the maximum of the transconductance, and the DC drain-source voltage is 5 V. To avoid catastrophic breakdown, we did not apply this high DC drain-source voltage at once, but we gradually increased it. In this way, the corresponding maximum allowable drain-source voltage increases due to the breakdown walkout effect (10). The input powers at port 1 and at port 2 are both 3 dBm. The phase difference between the two excitation signals is -100°. The fundamental frequency is 750 MHz.

Fig. 7 shows the I_{gs} and I_{ds} waveforms before and after 30 minutes stress. We notice that under these extreme on-state bias conditions the instantaneous current values only have marginally changed. Similar results are obtained for other values of the $\varphi(a_2)$.

CONCLUSIONS

We have shown that large-signal waveform measurements can be considered as an extension to existing electrical stress tests. They offer the important advantage that the failure mechanisms can easier be identified. We have demonstrated on InP based HEMT's that, depending on the operating conditions (DC bias, applied RF power, etc.), different failure mechanisms are triggered under RF overdrive stress. Our experiments performed at extreme operating conditions show qualitatively that the time constant related with on-state stress is significantly larger than that of off-state stress.

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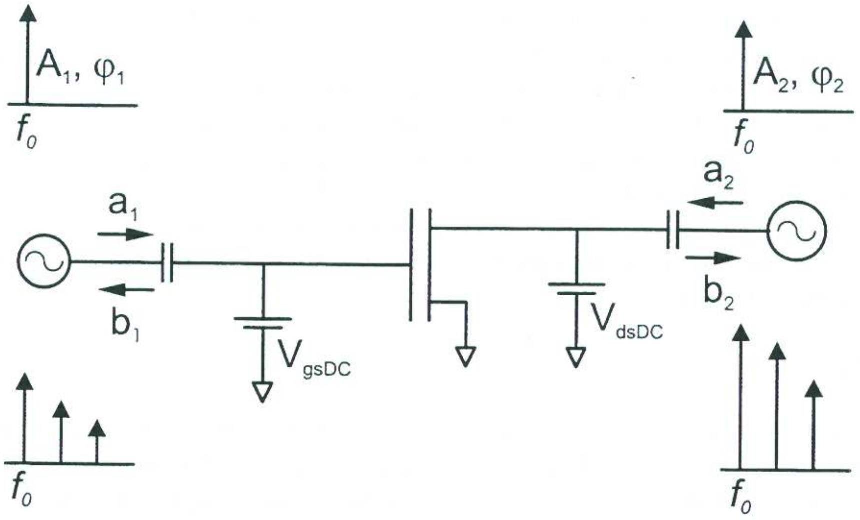

Fig. 1 Schematic overview of the NNMS measurement configuration used for the RF overdrive stress experiments.

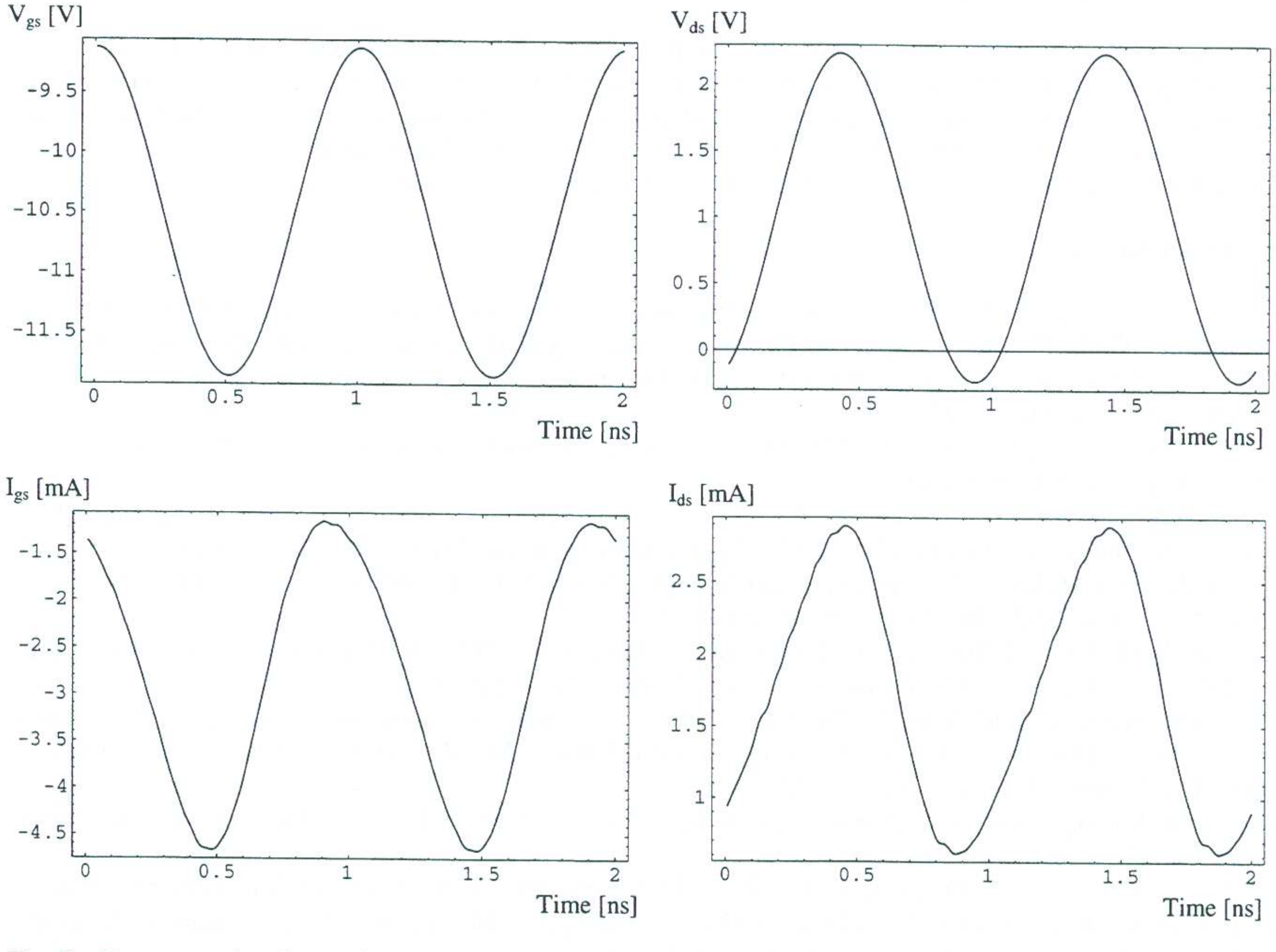

Fig. 2 Current and voltage time domain waveforms at gate-drain breakdown of a pseudomorphic InP HEMT, with $\varphi(a_2) = -152°$.

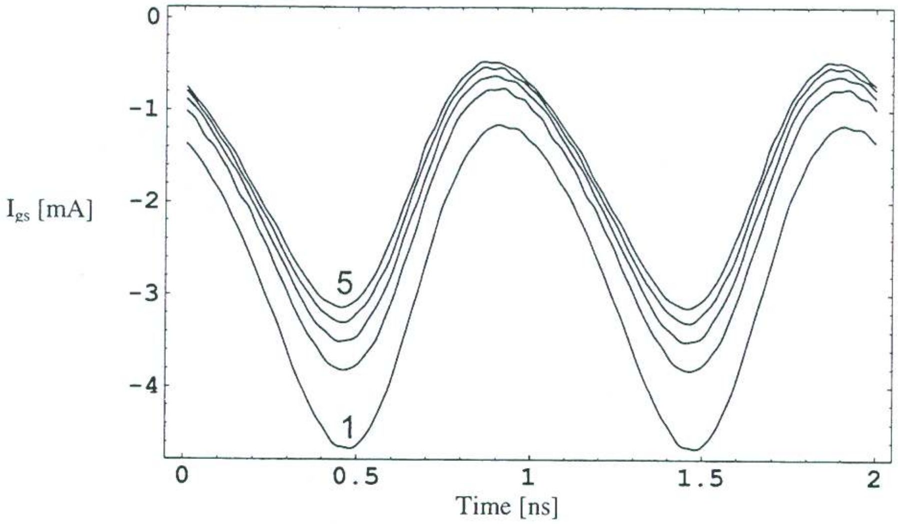

Fig. 3 Gate-source current time domain waveform at 0 (denoted by 1), 2, 4, 6 and 8 (denoted by 5) minutes stress time ($\varphi(a_2) = -152°$).

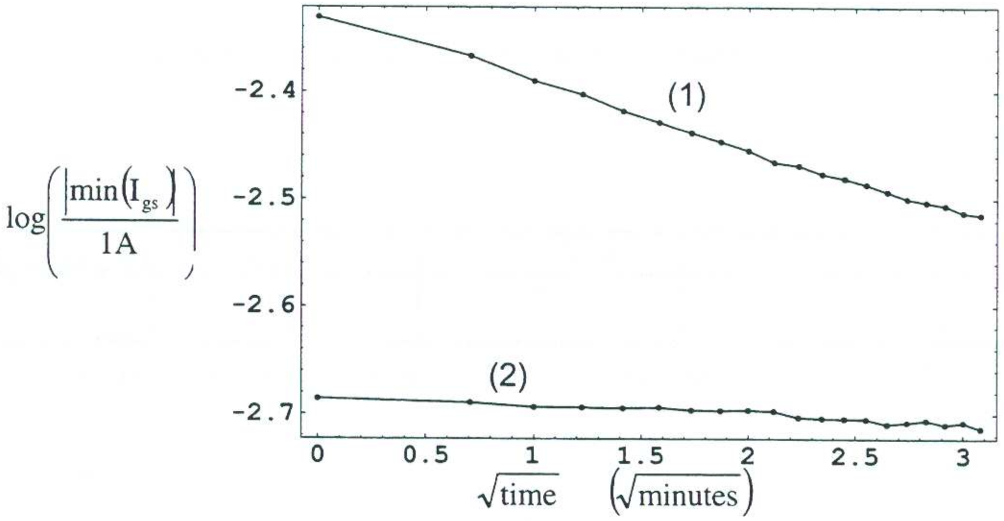

Fig. 4 Change of the minimum of the I_{gs} time domain waveform as a function of stress time with $\varphi(a_2)$ equal to -152° (1) and +87° (2).

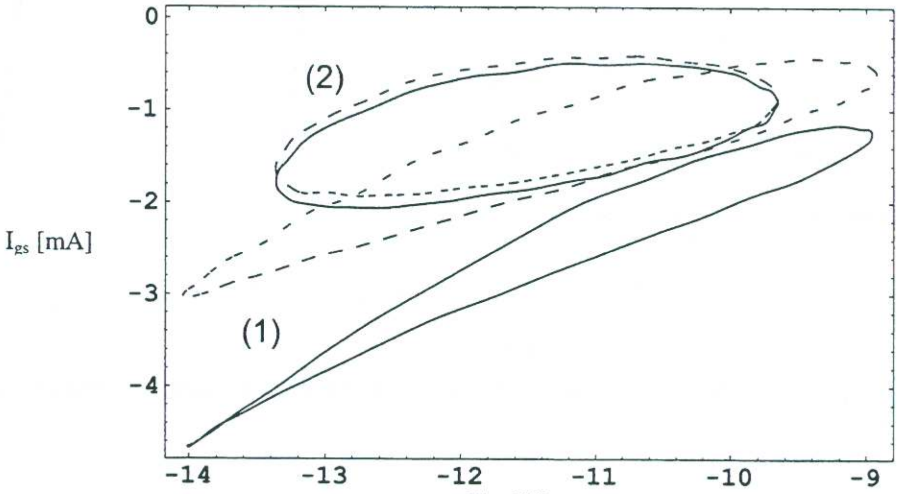

Fig. 5 I_{gs} time domain waveform versus V_{gd} time domain waveform with $\varphi(a_2)$ equal to -152° (1) and +87° (2). The solid line is at the start of the stress test and the dashed line corresponds to the measurements after 10 minutes stress.

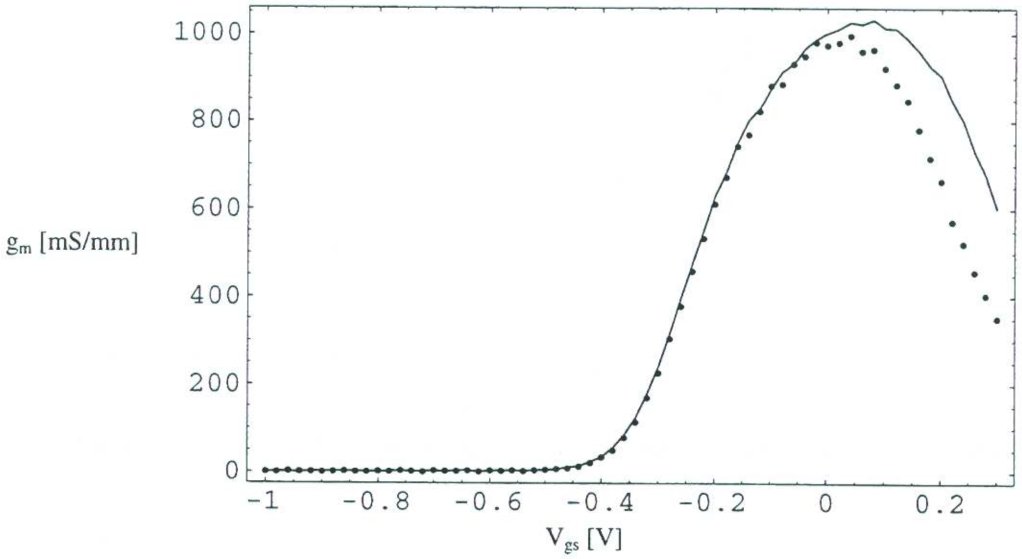

Fig. 6 Transconductance at V_{ds}= 1V before (solid line) and after (dotted line) the RF off-state stress experiment.

$\varphi(a_2)$ [°]	ΔMin(I_{gs}) [mA]	ΔMax(I_{gs}) [mA]	ΔBV_{gd} [V]	ΔMax(g_m) [mS/mm]
-152	1.6	0.70	1.0	-37
87	0.3	0.08	0.1	-5

Table 1 Overview of the change in electrical parameters after the RF off-state stress experiment.

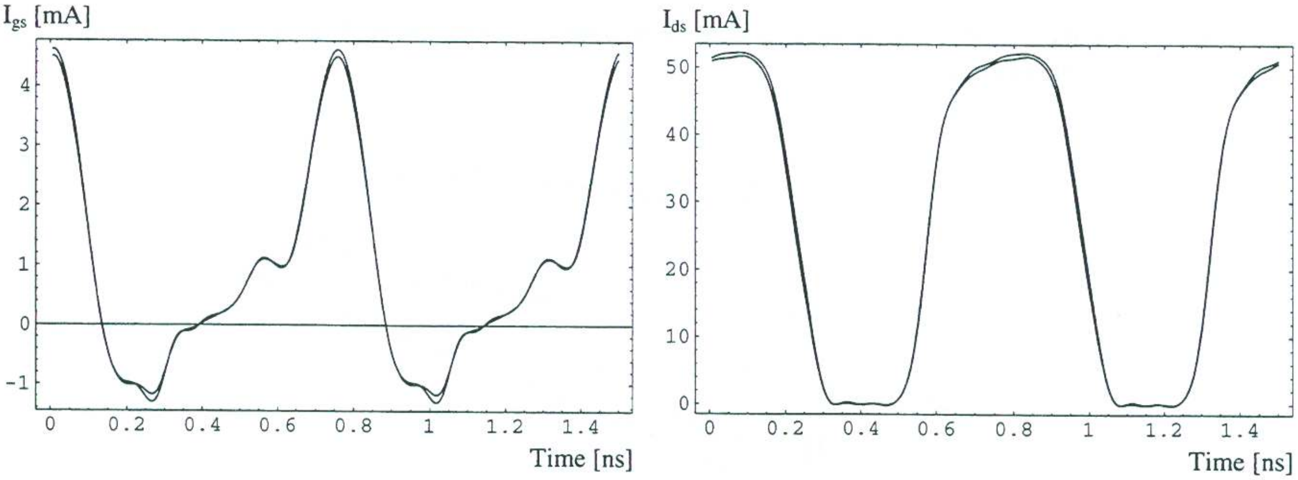

Fig. 7 I_{gs} and I_{ds} time domain waveforms for $\varphi(a_2)$= -100° before and after 30 minutes RF on-state stress (V_{gs}=0.1 V and V_{ds}= 5 V).