Impact of multi-carrier RF signals on the reliability of power GaAs-FETs for space applications

Wolfgang Bösch, François Garat
ESA / ESTEC, Keplerlaan1, 2200 AG Noordwijk, NL

Abstract

For space applications an accurate estimate of the GaAs-FET lifetime is fundamental as it has a significant impact on the overall system design. The gate current is one of the most sensitive parameters regarding degradation modes, hence its behaviour under RF operation is a valid measure for lifetime. Different degradation and failure modes are analyzed and presented. The stress on the device under multicarrier operation when CW reliability data are available is simulated by means of a simplified amplifier model and the statistical properties of the applied RF signals.

Introduction

Reliability studies are typically carried out under DC or RF operation. If the RF operation is chosen, a single Continuous Wave (CW) carrier is applied to the device for several thousand hours to determine the degradation of the DC and RF parameters. DC and RF life testing are typically performed at high temperature. Recently, increase of gate current was observed during high compression RF life test at ambient temperature in GaAs-Mesfet power devices of one particular manufacturer. Life test at high temperature masked this modification of the gate current. Investigations have been performed and recommendation has been given for CW operation. The objective of this paper is to present an 'engineering approach' to investigate and simulate the stress on the device introduced when operating in compression and with modulated RF signals.

Observed degradation mode

DC life tests (High Temperature Reverse Bias [HTRB] and/or Power Burn-in) assume that the RF swing does not modify the reliability behaviour. This is true only if the RF swing is limited. Overdriving a device into compression introduces different stress mainly around the Schottky junction. On one hand forward current flows through the Schottky junction and on the other hand avalanche breakdown occurs.

Known Failure Modes

The main degradation due to the *forward current* in the Schottky diode is related to electromigration. We have also observed a slight modification in the gate sinking behaviour under such condition but in this case the forward current remains a secondary factor compared to temperature effects.

Degradations (increase of the gate leakage current) caused by reverse biasing the Schottky contact are mainly related to surface degradations introduced by high electrical fields and temperature. Voltage derating requested for space application are minimizing these types of failure modes. These kind of degradation modes are generally well addressed under DC life tests (HTRB).

Gate electromigration phenomena under RF operation are related to the average gate current. Component manufacturer specify the maximum gate current allowed in accordance with the deposit metals. An external series resistor in the gate protects the devices in case of an increase of the average current.

New Observed Degradation Mode

Limiting the average DC gate current (time average of forward and reverse gate current) does not exclude other failure modes, recently observed, that are related to a degradation introduced by the RF swing extending to the 'avalanche zone'. The characteristic of the avalanche breakdown under DC and RF is different. [1]. The degradation observed under RF life test results also in an increase of the gate current, but in addition to the two main DC degradation factors (electric field and temperature) a third factor, impact ionisation plays a major role.

Impact ionisation in the high-field region of the device, occurring under RF overdrive, generates holes that are collected by the gate, giving rise to the increase of gate current. This generation seems to modify the structure of the devices, leading to a degradation of the RF performance.

Under high temperature, the 'avalanche zone' (RF and DC) is moved toward higher values [2]. Therefore, the gate current degradation can be masked by RF life test at high temperature due to a decrease of the impact ionisation phenomenon.

Thermal behaviour of this type of degradation remains unclear. Because the degradation is masked by a high operating temperature, the behaviour at low temperature has not been specifically investigated yet and remains unknown.

RF life tests are expensive and difficult to carry out. A good understanding of the degradation phenomena due to impact ionisation is necessary prior to identifying DC life test conditions. We expect to be able to correlate results of DC life tests with possible RF degradation.

H.Hasegawa & al. [3] succeeded to correlate the RF overdrive operation reliability with DC life test on the Schottky diode biased in the avalanche zone by applying a DC current source. The current generated by impact ionisation seems to be the main factor for this degradation mode. The gate current drift is therefore correlated to the quantity of minority carrier (holes) generated by the avalanche phenomena. It is, therefore, important to limit this generation of carriers under nominal RF operation.

In the past it was commonly assumed that a reliable operation of a GaAs Mesfet device is guarantied by a proper limitation of the DC gate current (either by using external resistors and/or limiting the RF overdrive of the device). Due to the recently observed phenomena this is not sufficient any more. Therefore an additional constraint on the RF drive level applies to ensure a long life operation.

Life tests, in our particular case performed at 1dB compression at ambient temperature did not produce any degradation of the gate current. Consequently, we assume that the current (minority carriers) generated under such condition do not affect the reliability behaviour of devices. The following paragraphs will present an estimation of the stress under multicarrier operation, when CW reliability data is available.

Nonlinear model of the device

The output voltage and current swings in an overdriven condition for a class A operation are limited in the following ways: The maximum output voltage swing across the device is determined by the RF breakdown voltage of the gate/drain junction (V_{br}) and the knee voltage V_1. The maximum current reaches the limit at I_{d1} when the gate is in forward bias condition. Maximum thermal limitations of the device will of course apply for any voltage/current combination. Fig. 1 illustrates the simplified I/V characteristics and a resistive load-line for maximum RF output power.

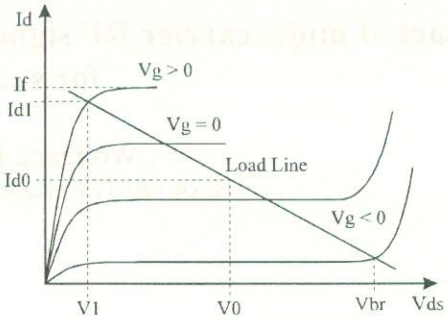

Figure 1 I/V characteristic of a typical device and the ideal load line for maximum output power

Because of trapping effects and other memory effects in the device, the avalanche breakdown characteristic of the gate/drain junction is a function of frequency. Therefore the static V_{br} measured with DC is not representative for RF operation [4]. Pulsed V_{br} measurements give more accurate estimates of the breakdown phenomena. Fig. 2 shows typical results of DC and pulsed measurements [1]. The RF avalanche breakdown of the junction can be modelled by a linear ohmic relation or by a pn junction. For simplicity we assume a linear relationship with an equivalent R_{br} of 40 ohms for a 1mm device (Fig. 2).

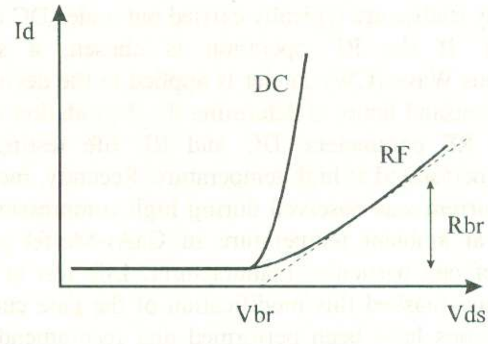

Figure 2 Breakdown under DC and RF, equivalent breakdown resistance Rbr

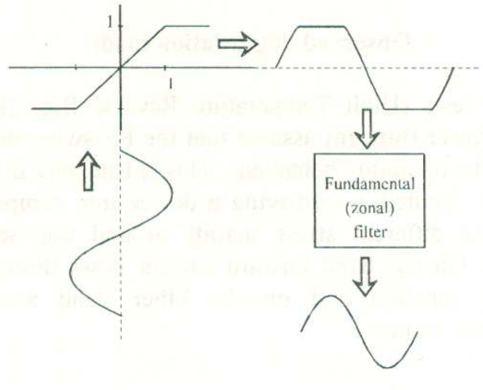

Figure 3 Simplified amplifier model for Pin/Pout simulation

Utilizing a linear voltage clipper limiting positive and negative input voltages as it is shown in Fig. 3 good agreement between measured and simulated compression characteristic of a typical RF device was found. Hence this model is sufficient to characterize the behaviour at the 1dB compression point and closer to saturation.

Fig. 4 shows the calculated Pin/Pout characteristic of an ideal voltage clipper that is driven by a sinusoid (CW), a two carrier signal and a multi-carrier signal. The simulations were done with IMAL [5]. The clipping level of the model was set to ±1. The related compression characteristics of the three input signals is also illustrated.

The 1dB compression for a CW input signal results at a 2dB overdrive condition. For the same overall input power a two carrier signal would already be 2dB in compression, but would yield 1dB less output power with reference to the CW case. The compression for a two carrier signal starts already at the -3dB input power level because of the 3dB high power peaks. The saturated output power in the CW case is 2.1dB above the clipping level (0dB) [6] and for the two carrier and multi carrier case the saturated output power is about 1.2 dB lower.

Signal statistics

Fig. 5 shows the probability density function (PDF) of a sine wave with an amplitude normalized to one, a two tone signal and an uncorrelated multi-carrier signal (gaussian distribution). All the signals have the same power level, therefore the two-carrier signal shows a $\sqrt{2}$ higher voltage peak than the sine wave. The gaussian signal has voltage peaks as high as 3.0 which corresponds to 10dB power peaks above the average signal power.

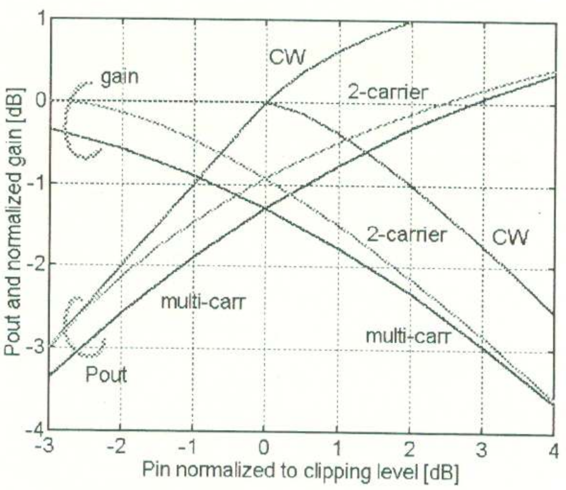

Figure 4 Pin/Pout characteristic of an ideal voltage limiter

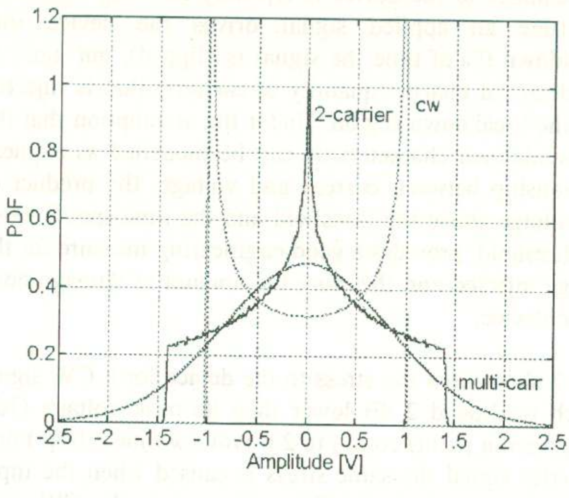

Figure 5 Probability density function of a CW, 2-carrier and multicarrier signal

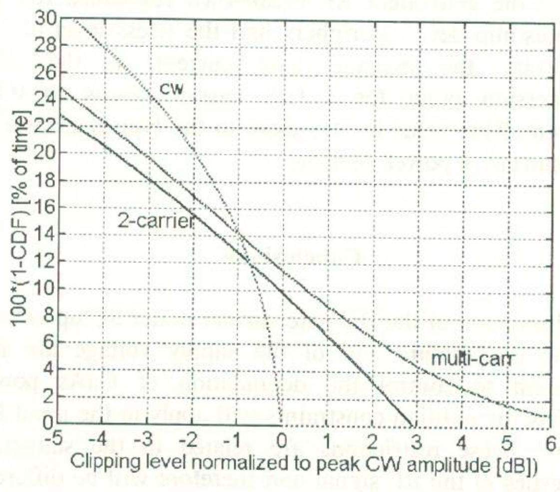

Figure 6 Cumulative probability density function of CW, 2-carrier and multicarrier signal.

Integration of the PDF results in the cumulative distribution function CDF, which gives the absolute probability that a given amplitude level of the signal is exceeded. For periodic signals it is also a measure of how much time in average the amplitude of the signal is above a given threshold. Fig. 6 illustrates the percentage of time when the instantaneous amplitude of a CW, a two carrier and a multi-carrier signal is clipped. The abscissa is in logarithmic scale and represents the clipping level normalized to the peak amplitude (1.0) of the CW sine wave. Reading from Fig. 6, a sine wave is clipped 20% of the time due to the breakdown (only on one side) when the clipping level is set 2dB below the peak amplitude which corresponds to the 1dB compression point in Fig. 4. The same amount of one sided clipping (20%) is reached when a two-carrier signal is clipped at 3.8dB and a multi-carrier signal at 3dB below the reference (2dB Pin in Fig. 4).

The damage to the device is typically not only related to the time an applied signal drives the device into breakdown (% of time the signal is clipped), but more to the electrical charge (quantity of carriers) that is injected into the breakdown region. Under the assumption that the RF breakdown characteristic can be modelled as a linear relationship between current and voltage, the product of the voltage above the threshold and the time spend above the threshold, provides a good engineering measure for the charge injected and therefore the amount of damage done to the device.

Fig. 7 shows that the stress to the device for a CW signal which is clipped 2 dB lower than its peak voltage (1dB compression point) comes to 2.6 [volts x time /100]. For a 2-carrier signal the same stress is caused when the input power is reduced by 1.5dB in reference to the CW case. For a multi-carrier signal the input drive has to be backed off by 3.8dB.

Taking the equivalent RF breakdown resistance Rbr of 40 ohms/mm device periphery and the stress level of 2.6 [V*s/100], the average gate current at the 1dB compression point for a CW carrier comes to 0.65 mA/mm. This value is very close to the typical measured gate current of power devices.

Conclusions

The limitation of the DC gate current under RF operation, of the temperature and of the supply voltage are not sufficient to control the degradation of GaAs power Mesfets. In addition constraints will apply to the input RF power. These restrictions are related to the statistical properties of the RF signal and therefore will be different for a CW, modulated CW, 2-carrier or multi-carrier operation. It has been shown that the stress in the avalanche breakdown region caused by a sinusoid signal at the 1dB compression point is equivalent to a 3.8 dB input backed off multi-carrier signal. When operating with modulated carriers (e.g. filtered BPSK) the presented procedure can easily be applied to estimate the stress in reference to the CW case.

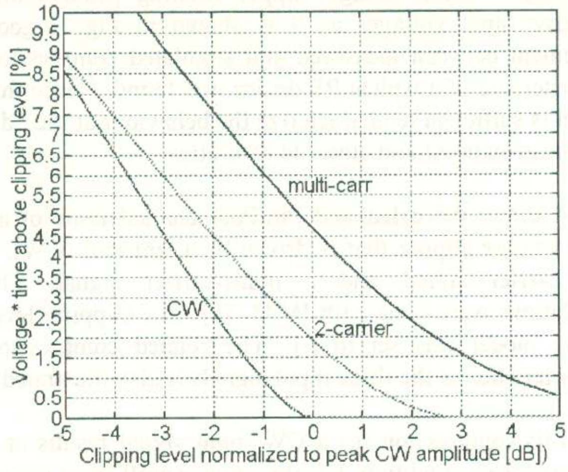

Figure 7 Measure of stress to the device vs. clipping level for CW, 2-carrier and multicarrier signals.

References

[1] S. H. Wemple, 'Control of Gate-Drain Avalanche in GaAs Mesfet's', IEEE Trans. on Electron Devices, Vol. ED-27, No. 6, pp. 1013- 1018 June 1980.

[2] S. M. Sze, 'Physics of Semiconductor Devices', John Wiley & Sons, 1976

[3] H.Hasegawa, et.al. 'High reliability power GaAs Mesfet under RF overdrive condition', IEEE MTT-S digest, vol. 1, pp 289- 292, June 1993

[4] J. M. Golio, 'Microwave Mesfets & Hemts', Artech House, 1991.

[5] W. Bösch, G. Gatti, IMAL, software to simulate intermodulation generated by nonlinear systems under multi-carrier operation., ESTEC internal memo.

[6] J. Spilker, 'Digital Communications by Satellite', Prentice Hall Inc. 1977.