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Original Article

Temperature Effect on the Performance Stability of Power RF Transistor Based on Advanced Electrothermal Modelling

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Abstract *- This paper presents the investigation results of the electrothermal performance degradation of the RF power transistor. A comparative study of these degradations was conducted using 2D numerical modeling (ADS) for different temperature conditions. The MET model used is based on the wide signal equivalent circuit. This complex electric circuit comprises elements having a precise physical meaning acting on the component performance. Thus, any change in the value of these elements impacts performance. It makes it possible to estimate the device's dependability and lifetime more accurately. It can also be utilized to establish a link between the sorts of current failures and the electrical parameter drifts. The proposed model performs better than average in terms of accuracy and adaptability, and the results show that they are in accordance with the operational conditions.*

Keywords *- Characterization, Modulation, Power RF, Temperature effect, Self-heating.*

1. Introduction

Thermal phenomena remain the main cause of degradation [1,2]. Therefore, thermal testing becomes important for power RF components in many applications, which can lead to device failure. Our objective consists of refining the characterization and modelling, considering the thermal effects and the temperature evolution inside the component. This will make it possible to understand the degradation phenomena to anticipate the failures caused by aging in the thermal aspect.

Deal with variations of different electrical parameters, depending on the temperature, and the main aspects of the electrical-thermal analogy [3,4]. A new electrothermal model of power RF transistor which was implemented as a "black box" SDD (Symbolic Defined Device) in an ADS circuit page which was used as a reliability tool. One of the most important steps in a reliability study is modelling [5,6]. It consists of replacing the component with an electrical network made up of elements such as inductors, resistors, capacitors, and current and voltage generators. Each element or element set of this network reflects a physical phenomenon. The model must represent the component's behaviour with respect to its environment with certain approximations. Increasing the number of phenomena to be predicted increases the complexity of the model, and therefore all stages of design, extraction and validation will be more time-consuming [7,8]. It is always more interesting to have a model that is versatile, efficient and as general as possible.

2. Electrothermal Modulation

A new electrothermal model of power RF transistors has been implemented in the SDD form "black box" in an ADS (Advanced Design System) circuit page. This model takes into account the thermal effects and the evolution of the temperature inside the component. It uses a thermal network representing heat dissipation from the silicon chip to the ambient air. It is used to extract a set of relevant electrical parameters from measurements made on the component (characterization) that can be used to predict its reliability and lifetime.

The MET LDMOS model [9] is commercialized, and its library includes recently developed LDMOS devices. The equivalent circuit of the MET LDMOS empirical model is shown in Fig. 1. The model has a non-linear current source dependent on voltage and temperature. It also has a forward-biased diode as a voltage function and a reverse-biased diode as a function of temperature and voltage. The model also has nonlinear capabilities that are voltage and temperature dependent. It also has two internal gate conductances and temperature-dependent parasitic resistances. The second thermal circuit calculates the instantaneous temperature rise.

Itherm is the total instantaneous power absorbed in the transistor, Rth is the thermal resistance, Cth is the thermal capacity, and Vtsnk is the voltage source representing the heatsink temperature of the transistor.

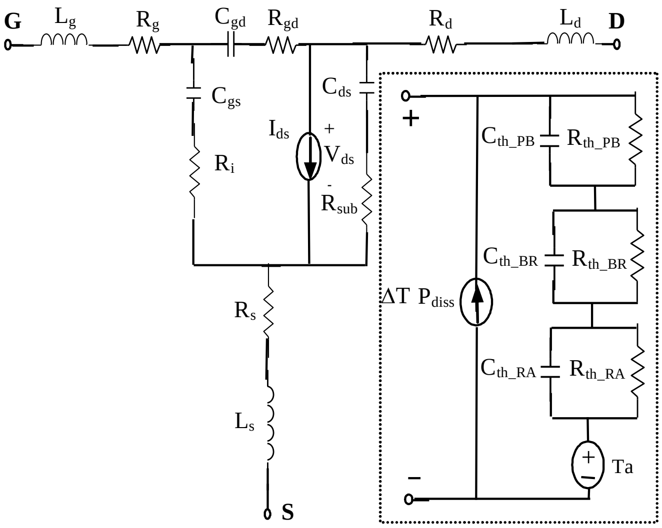

Fig. 1 Equivalent circuit of the MET LDMOS model

The simple power amplifier circuits were designed under ADS with an SDD black box associated with a program which is shown in Fig. 2. This SDD box is represented by a diagram in the form of a transistor with four nodes: gate, drain, source and a fourth thermal node.

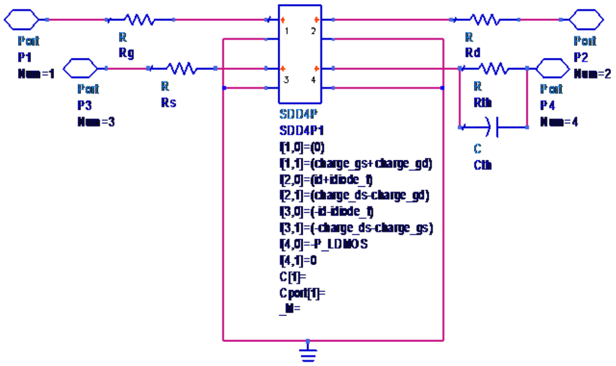

Fig. 2 LDMOS transistor diagram of a four-node SDD

The theoretical equations relating to thermal and electrical phenomena are very similar. It is possible to study heat transfer by electrical analogy. This is the reason why thermal resistances and capacities are defined in order to model the thermal behaviour of a device. The modelling replaces the component with an electrical network composed of elements (resistances and capacities) that translate a physical, electrical or thermal phenomenon. In heat flux propagation, thermal resistance and thermal capacity can be defined, making it possible to constitute a transmission line analogous to that encountered in the electrical field. The element model is built by equations describing its physical properties. The simulator must solve all these equations at all the excitation points required by the designer. Therefore, a circuit's calculation and resolution time directly depends on the equations and, therefore, on the models used for the components [10]. The component modeling must meet a set of requirements defined by the application domain and the designer's demands in terms of simulation results [12]. There is no model that can meet all of these requirements [9, 12]. However, the approach and the modeling type show various advantages and disadvantages [14]. Thus, the model choice or modeling approach must be made according to the needs. In our case, we first implement the model. We adapt it to our study component and improve it to obtain more precision and flexibility in adjusting terms and extraction of parameters.

3. Results and Discussion

To validate the model of preliminary results is necessary before studying the temperature effect on the performance stability of the power RF transistor. Figures 3 and 4 show the results of measurements and simulations. We obtained a good superposition between the simulation and the experiment for the different I_{ds} versus V_{gs} (threshold voltage) and I_{ds} versus V_{ds} (output) characteristics for different drain and gate bias values. The measurements are designated in symbols, and the simulations are in solid lines.

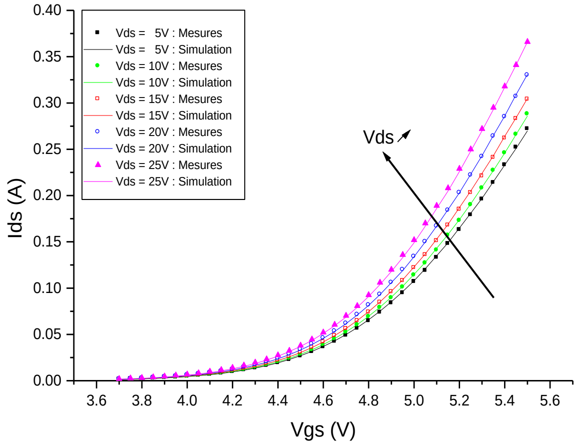

Fig. 3 threshold voltage for different drain biases, simulation (solid lines) and experimentation (symbols)

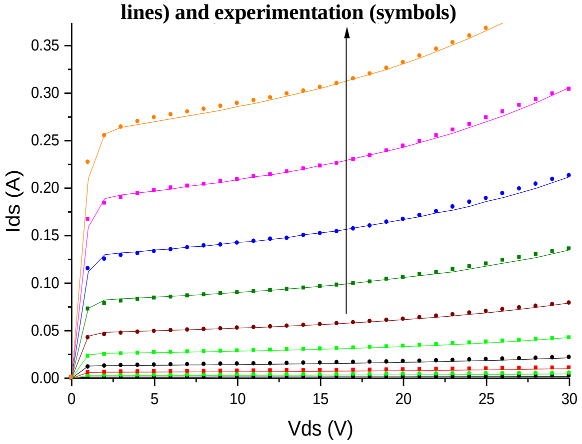

Fig. 4 Output characteristic for different gate biases [3.7V - 5.5V], simulation (solid lines) and experimentation (symbols).

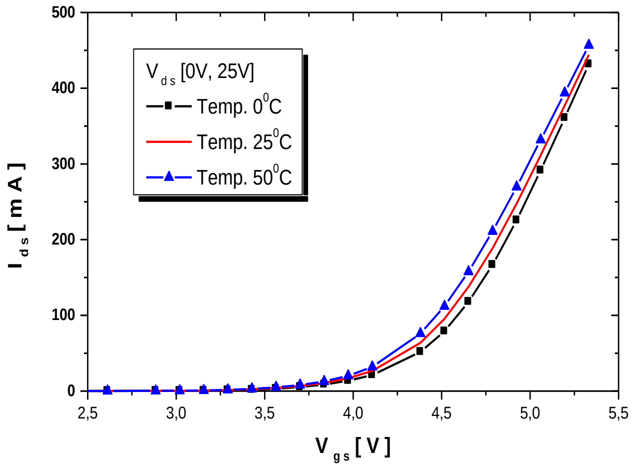

Fig. 5 Influence of temperature on threshold voltage Vt characteristic

It is advisable to be interested in how the temperature influences the electric characteristics of the transistor to establish a model allowing the coupling between the electric and the thermal behavior of the transistor. A more detailed study of the relation Eq.1, giving the expression of the threshold voltage as a function of the MOS physical and technological parameters, shows that this decreases with the temperature (figure 5). This variation is linear with temperature and can be represented as follows [13]:

$$G_m = \left.\frac{\partial I_{ds}}{\partial V_{gs}}\right|_{V_{ds}=cste} \tag{1}$$

$$V_t = V_{T0} + (V_{tT} \cdot T_j) \tag{2}$$

where T_0 is the ambient temperature, V_{T0} is the threshold voltage at T_0, V_{tT} equation coefficient, and T_j is the junction temperature.

The current channel Ids vary linearly with temperature for low current levels (Figure 6). This is due to the reduction of the threshold voltage [14,15,16].

Indeed, for an LDMOS, the current dependence with respect to the temperature is linked to the two phenomena having contradictory effects. The current I_{ds} is proportional to the mobility µ and the electrons concentration in the n channel [17]. When the temperature increases, n increases while µ decreases. For low current values, the effect of reduction in mobility is negligible compared to that of the increase in the carriers' number; therefore, the current value increases [18]. On the other hand, when the current value is high (high level of current), the mobility effect becomes preponderant and subsequently, the current decreases with temperature [19,20].

The On-state resistance is defined by the drain voltage ratio on the linear drain current (see Eq.3) and is inversely proportional to the latter. This resistance decreases when the source gate voltage increases.

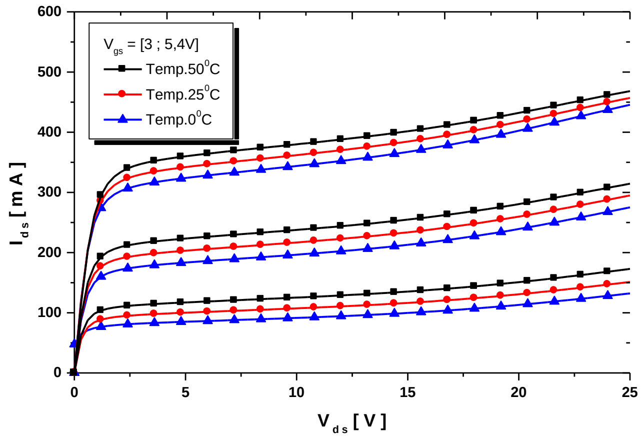

Fig. 6 Channel current variation measured at different temperatures

$$R_{ds\_on} = (V_{ds}/I_{ds})_{\ V_{ds\to 0}} \tag{3}$$

The on-state parameter depends on the heat distribution and dissipation (chip, package, radiator), which represents the flow of heat inside the transistor [21,22]; it also reflects different values of the junction temperature. The on-state resistance is inversely proportional to the electron's concentration in the channel with their mobility. When the temperature increases, the electron's concentration in the channel increases while their mobility decreases. For low applied voltage values, the electron concentration effect on resistance is significant (decrease in R_{dson}), whereas the mobility degradation effect becomes dominant in the case of a high voltage value polarization (an increase of R_{dson}) [21,22].

Power RF applications require reliable operation under high-temperature conditions. This implies the need to understand the thermal aspect of the MOSFET behavior in isothermal conditions (threshold voltage, conductance, etc.) and non-isothermal internal conditions (self-heating, non-homogeneous temperature in the component and diffusion heat). The heat given off by the components reaches the housing via the substrate. This heat transfer takes place by conduction, convection and/or radiation from the housing to the ambient.

Heat transfer by conduction is the special case where the non-uniformity of temperature leads to an energy transfer from one point to another in the system without the macroscopic transport of matter. Heat transfer by convection occurs at the separation limit in two phases of different natures. The transfer takes place in two stages. The first phase consists of heat exchange by conduction between the solid surface molecules and those of the film. The second phase results from the molecules displacement of the film with the heat transferred at the film level. The last mode of heat transfer is radiation transfer. There are two theories to explain energy transfer by radiation. One supposes the energy displacement by photons packets, the other by electromagnetic wave propagation. It is possible to associate a wavelength with thermal radiation, which extends from the visible to the infrared.

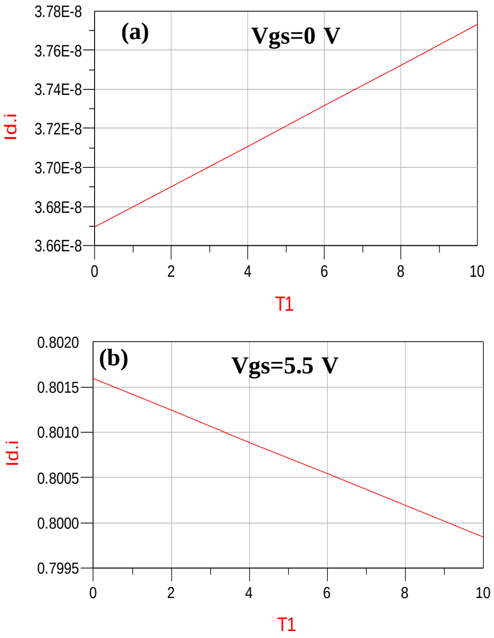

Fig. 7 Variation of I_{ds} vs temperatures: (a) V_{gs} = 0V, (b) V_{gs} = 5.5V

The drain current increases with temperature for low current levels and decreases for high levels [17]. We also observe a transformation of the output characteristics shapes due to the self-heating effect caused by the thermal resistance variation of the component. We vary the gate voltage to obtain low or high drain current levels. Figure 7 highlights the variation of I_{ds} as a function of temperature.

The threshold voltage is a highly temperature-dependent parameter, as shown in Figure 8. Affects the MOSFET transistor performance. We notice that the threshold voltage decreases with the temperature. The change in this voltage is caused mainly by the change in the Fermi potential Φ_F with temperature. A physical simulation verified this decay on a basic LDMOS [2,6,18].

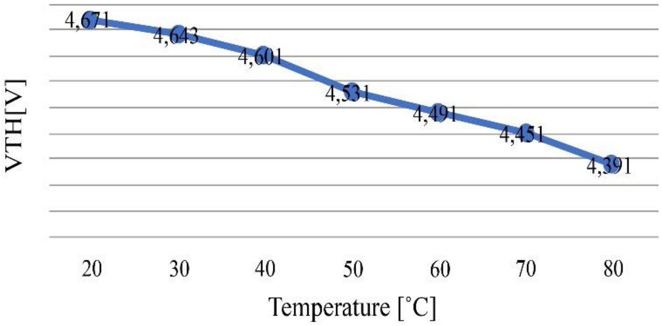

Fig. 8 Variation of threshold voltage V_{th} vs temperature

Different methods make it possible to measure the junction temperature of a transistor and thus to deduce its thermal impedance [3,6,7]. However, the major drawback of these experimental determinations is that only the static regime (or steady state) can be measured accurately. From the thermal impedance Z_{th}, only the thermal resistance R_{th} can be determined. The determination of the heat capacity C_{th} requires temperature measurement in a dynamic regime (or transitory regime). The influence of temperature is very important on the electrical parameters without forgetting the electrical-thermal analogy aspects. On the other hand, the developed electrothermal model of power RF transistor has been obtained, which will be used as a reliability tool facilitating the establishment of a link between the electrical parameters change of the transistor (after the accelerated aging tests), with any degradation phenomenon.

4. Conclusion

The electrothermal modelling of the power RF component was presented, which allows a good understanding of the identification methods of temperature-dependent parameters. The power RF transistor's electric behaviour is temperature-dependent. Temperature increases alter transistor performance and inevitably reduce their dependability. Self-heating and the effects of temperature have been accounted for in an electrothermal model. The model has been applied to comprehend the physical dynamics of the degradation. Thus, it is crucial to manage cooling systems and advance temperature measurement methods to assess the thermal consequences more accurately.

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