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Improvement of g_m/I_D Method for Detection of Self-Heating Effects

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This paper presents an improvement on the use of the transistor efficiency to verify the presence of self-heating effects using only DC measurements. Applying this improved method on FinFET devices allowed the establishment of a comparison of the self-heating effect among devices with different channel lengths, despite their different channel length modulation effects.

Introduction

The problem to identify the self-heating effect (SHE) through DC measurements occurs due to the superposition of this effect with the channel length modulation (λ). As presented in Figure 1, depending on the thermal resistance (R_{th}), the classical negative output conductance may not be observed at all if $\lambda > 0$, inducing one to wrongly believe that no SHE is present.

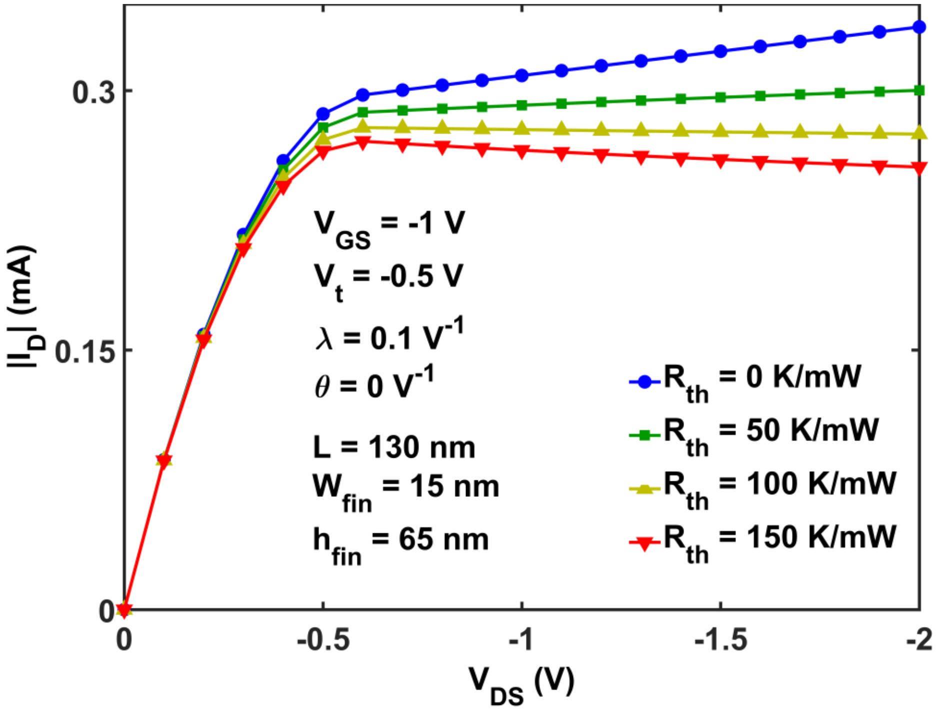


Figure 1. Simulated drain current as a function of drain voltage for different thermal resistances R_{th}.

Currently, most of the techniques available require special test structures or setups to assess the SHE through electrical characterizations (1). For instance, two of the most

popular methods are the AC conductance (2) and small-signal RF (3), since they are effective at high frequencies; on the other hand, both require RF transistors to be performed, which are not always available. A new method for SHE detection, which relies only on DC measurements, was recently proposed: the signature on the transistor efficiency (g_m/I_D) (4). However, it presents some problems due to the channel length modulation (λ) and electric field mobility degradation factor (θ).
The goal of this work is to propose an improvement to this g_m/I_D method for SHE detection taking into consideration different λ and θ parameters.

The signature on the transistor efficiency method

The g_m/I_D method allows to quickly verify whether the SHE is present in the device being studied, making the visualization and qualitative characterization of the SHE easier, as represented in Figure 2, in which the effect is separated in different regions of intensity.

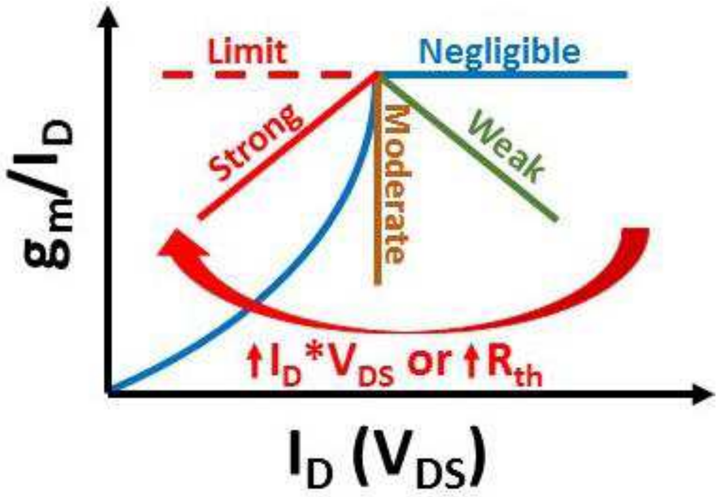
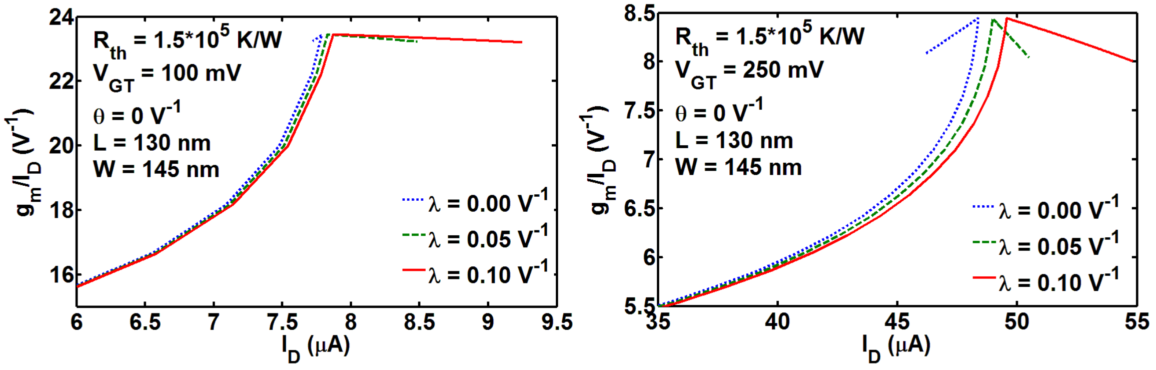


Figure 2. Influence of the SHE on the transistor efficiency versus drain current.

However, it would not be possible to use it to compare different devices. Since the method originally used the drain current (I_D) on the x-axis with fixed gate voltage (V_{GS}) and varying drain voltage (V_{DS}), imprecise comparisons would be performed if the devices being studied were differently affected by the λ, as shown in Figure 3.



(a) (b)

Figure 3. Simulated transistor efficiency for different λ as a function of drain current with varying drain voltage and fixed overdrive voltage of (a) 100 mV and (b) 250 mV.

Simple mathematical simulations were performed to obtain these results, in which the λ was considered through the model $I_D = I_{Dsat}*(1 + \lambda*V_{DS})$, where I_{Dsat} is the saturation current at low V_{DS}, and λ is a fitting parameter. From Figure 3, one might wrongly conclude that the devices with greater λ present a weaker SHE, when in fact the opposite should be truth, since I_D increases with λ, resulting in more heat being generated, thus stronger SHE.

Proposed improvement to the method

To achieve an improvement to the method, a new analysis of the expression for the influence of the SHE on the g_m/I_D in saturation must be conducted. Therefore, it is presented in [1], where P is the applied power ($P = I_D*V_{DS}$), T_0 is the room temperature, c-factor is the mobility degradation coefficient with temperature, V_{GT} is the overdrive voltage ($V_{GT} = V_{GS} - V_t$, V_t is the threshold voltage), and θ is the electric field mobility degradation factor.

$$g_m/I_D = \{(R_{th}*P + T_0)/[(1 + c)*R_{th}*P + T_0]\}*\{1/V_{GT} + 1/[V_{GT}*(1+\theta*V_{GT})]\} \qquad [1]$$

The terms multiplying the thermal resistance (and consequently relevant to the SHE) are both I_D and V_{DS}, thus, initially either of them could be used as a variable for the analysis. Nevertheless, as previously explored, the use of I_D with varying V_{DS} would be problematic due to λ influence. Considering that V_{GT} influences I_D, this voltage could be employed; however, given the degradation of the mobility due to the vertical electrical field, observed in [1] as the θ factor, the use of V_{GT} becomes less interesting. Hence, the only option remaining is the direct use of V_{DS} as the variable on the x-axis. To verify if the use of this option presents relevant results, Figure 4 was generated from simulations like those of Figure 1.

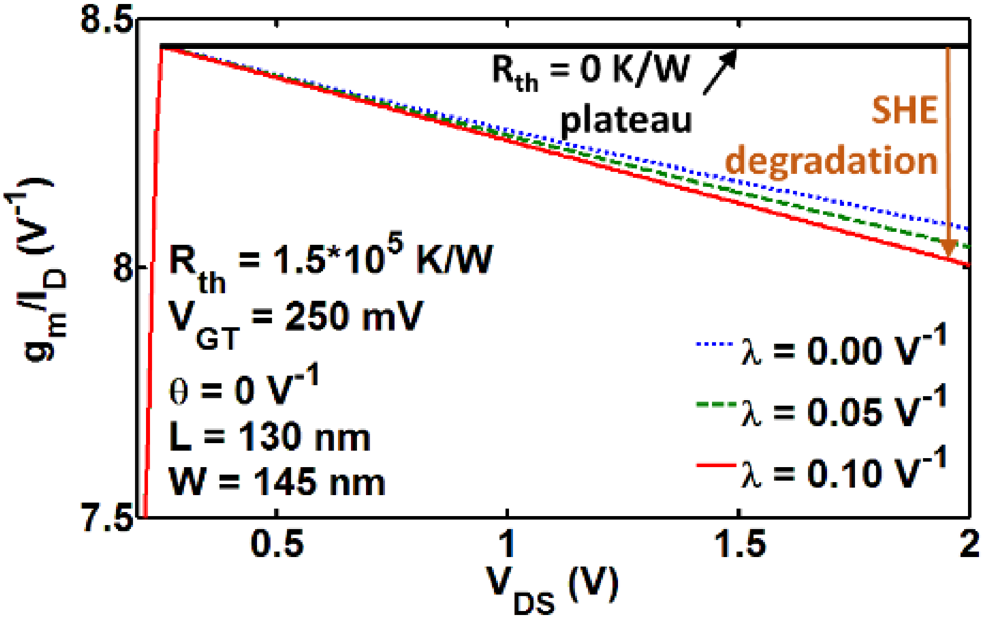


Figure 4. Simulated transistor efficiency for different λ as a function of drain voltage.

In this case, it is possible to observe that, the greater the g_m/I_D degradation from the expected plateau in the case where $R_{th} = 0$ K/W, the more significant is the SHE.

An important consideration that must be made concerning the use of this method for comparisons is that the θ factor could still add another undesired component to the SHE analysis on the g_m/I_D curves. Should the comparison be performed among devices fabricated in multiple dimensions or even distinct technologies, factors that might result in different θ, the g_m/I_D in saturation for each device will change, despite presenting a similar degradation, becoming lower for higher values of θ, even though the R_{th} is kept constant, as shown in Figure 5.

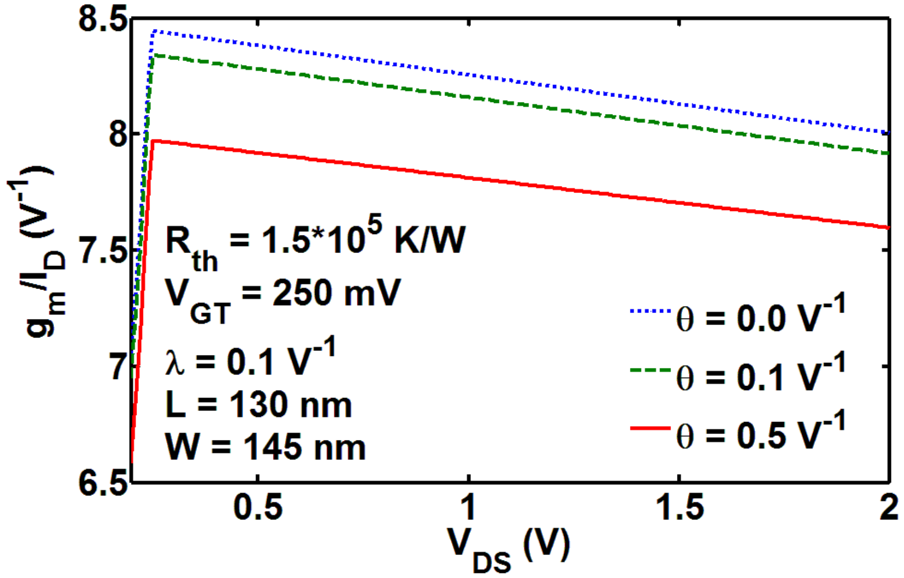


Figure 5. Simulated transistor efficiency for different θ as a function of drain voltage.

To improve the comparison, a simple mathematical fix is suggested, resulting on the curves present in Figure 6, where each is divided by the factor $F = [2/V_{GT} - \theta/(1+\theta*V_{GT})]$.

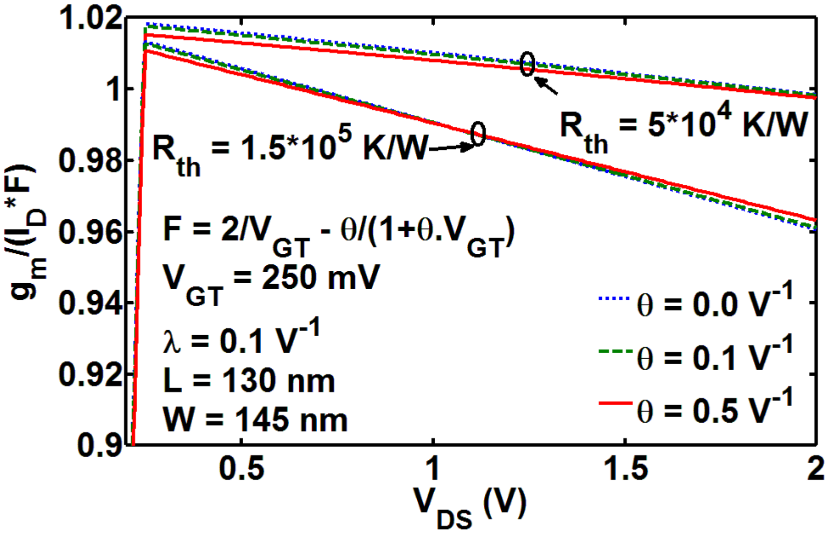


Figure 6. Simulated transistor efficiency divided by F for different θ and thermal resistances (R_{th}) as a function of drain voltage.

In this case, the agreement for the same R_{th} is much better, ensuring that the SHE becomes the main factor in the degradation of the g_m/I_D, as demonstrated by varying R_{th}. To verify these results, experimental pFinFET devices were measured and had their $g_m/(I_D{*}F)$ plotted as a function of V_{DS}, after applying the division by F, resulting in Figure 7.

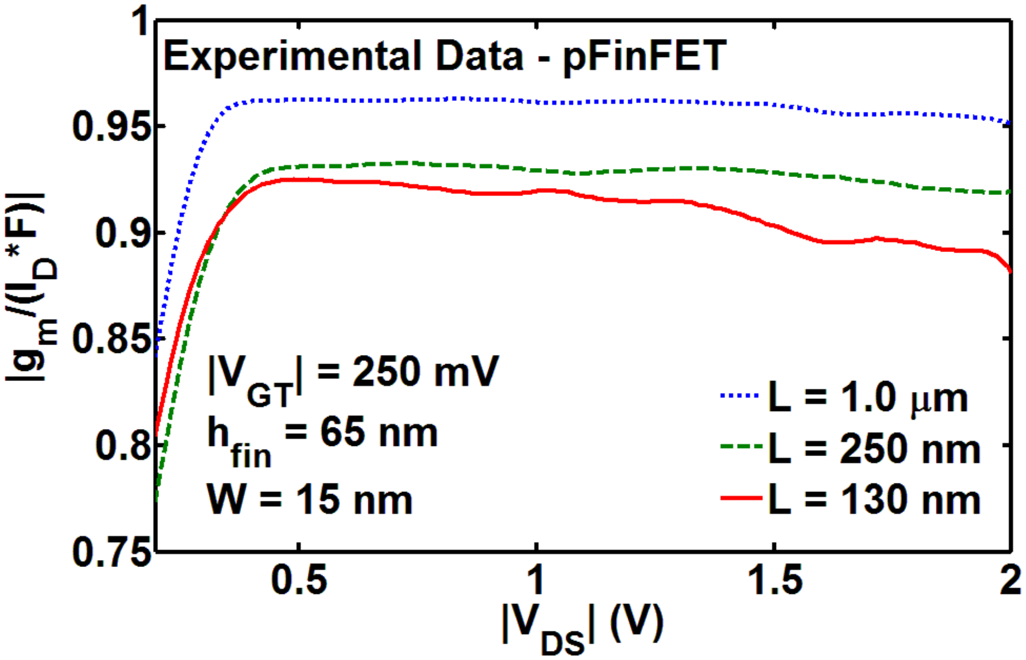


Figure 7. Experimental transistor efficiency of a pFinFET divided by F factor for different channel lengths.

To obtain such results, the threshold voltage was extracted using the extrapolation method in saturation (5), and θ was extracted through a new Y-function method (6).
As expected, the device with shorter channel presents a higher g_m/I_D degradation (i.e. a steeper slope) due to the SHE, since it has a higher current level than the other devices.

Conclusions

An improvement to the g_m/I_D method for detection of the self-heating effect was proposed and tested through mathematical simulations and experimental data in this paper. Based only on DC measurements, this improved method allows a better SHE comparison among devices that present different channel length modulation and electric field mobility degradation factor.

Acknowledgments

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