Development of algorithm for temperature sensor based on the commercial MOSFETs behavior.

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***Abstract* — In this paper the MOSFET behavior operating in military temperature range was studied theoretically and experimentally. From this analysis, the gate bias range for better temperature sensing was determined and some SPICE simulations were used to generate a more robust database for the sensor. The algorithm was applied on inputted table (database) and an accurate temperature sensing was obtained.**

Keywords— MOSFET; High Temperature; Sensors;

I. INTRODUCTION

In the last century, the advent of integrated circuits (ICs) provided a great revolution in microelectronics. Nowadays the MOSFET technology is the main technology for ICs due to its high scaling capability [2]. Besides this, researchers have been engaged in the development of more complex ICs (analog and digital functions), based on CMOS transistors. [1]

However, with increasing integration density of devices into a single integrated circuit chip, the heating caused by the high number of transistor becomes critical to ensure the good performance of the ICs.

In this work, the study of a commercial MOSFET technology is performed as a function of temperature in order to obtain a database to the algorithm.

II. SENSOR DEVELOPMENT PROCEDURE

Some measurements were performed in a conventional bulk MOSFET transistors of a commercial CI. The CD 4007 consists of three transistors of each type (N and P). After the electrical characterization at room temperature some measurements of nMOSFET transistors were also performed from 25°C to 150°C, aiming to better understand the behavior of the MOS transistors at high temperatures. The nMOSFET measurements were used to supply the level 14 (BSIM3v3.3 model) of AIM-SPICE simulator with experimental parameters.

Both experimental and simulated transfer curves at room temperature are presented in Figure 1. From this figure it is possible to see a good agreement between the experimental and simulated drain currents. Besides the room temperature adjustment, the degradation factor was also used in the simulations as a function of temperature using the experimental curves obtained at 50ºC, 100ºC and 150ºC.

The drain current curves were extracted with the transistor operating in the linear region (triode) with the following polarization conditions: V_{DS}= 50mV and V_{GS} ranging from 0 to 5V.

After adjusting the parameters of level 14 of SPICE simulator, curves of the drain current were extracted as a function of the gate voltage, under the same polarization conditions, varying the temperatures in a military range (from -40ºC to 150ºC) with a temperature step of 10ºC.

The obtained drain current values were imported into MatLab software in order to obtain a database for the sensor.

The developed algorithm operates from a fixed gate voltage bias value (V_{GS}) and the drain current response (I_{DS}), determining the temperature of the environment in which the transistor is operating. In order to obtain higher accuracy, a linear interpolation of input values is done, resulting in a sensor with a precision of 0.1ºC.

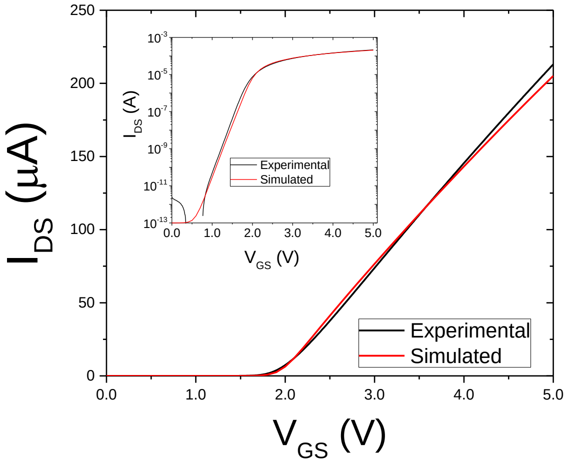

Figure 1 – Experimental and simulated drain current characterist as a function of gate voltage ate room temperature.

III. RESULTS AND DISCUSSION

The drain current (I_{DS}) of nMOSFET transistor when operating in the triode region, can be represented by the following equation:

$$I_{DS} = \mu_N . C_{OX} . \frac{W}{L} . \left[(V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right] \quad (1)$$

Figure 2 shows the experimental characteristic of three nMOS transistors (Fig.2A) and three pMOS (Fig.2B) ones. From these measurements it is possible to observe the uniform behavior among the three I_{DS} transistors and the subthreshold slope is almost the same for both types of transistors (approximately 100mV/déc)

Comparing the threshold voltages of the transistors, figure 3 shows that there is a slight variation between the Vth values, so that the mean threshold voltages of nMOS and pMOS are 1.903V and -1.6V, with a standard deviation of $4{,}73 \times 10^{-3}$ and $63{,}77 \times 10^{-3}$ and maximum deviation of 0.52% and 8.75%, respectively.

In recent years, the electrical characterization of CMOS technology operating under a wide temperature range has become increasingly important [2] [3]. For circuits designed to operate at different temperatures, it may be desirable for the circuit to operate at a bias point where the drain current does not vary with temperature.

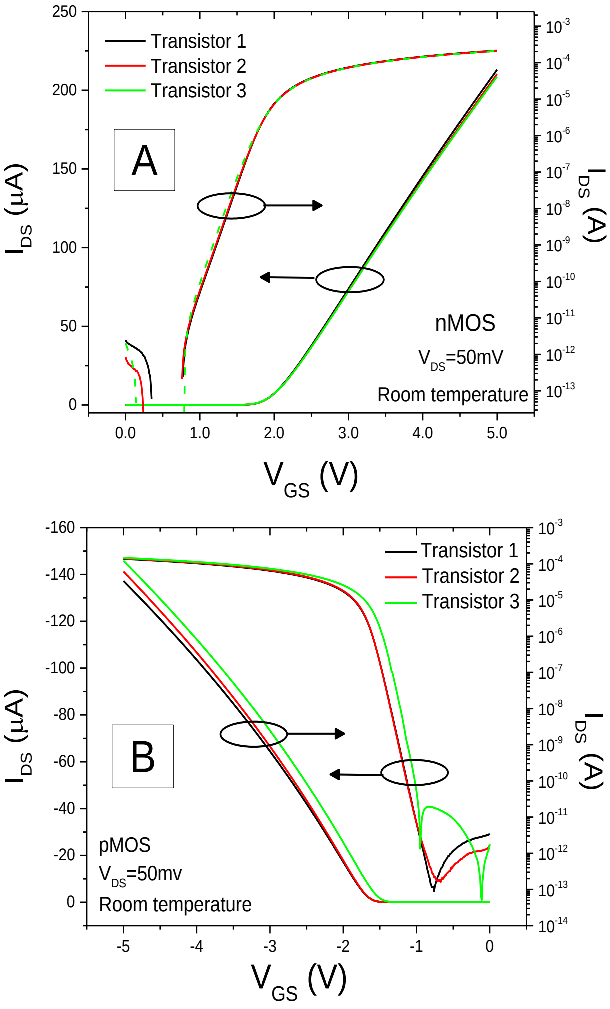

Figure 2 - Experimental I_{DS} curves as a function of V_{GS} for n-type (A) and p-channel devices (B).

Figure 4 shows the transfer curve ($I_{DS} x V_{GS}$) for $V_{DS} = 50mV$ for n-type MOSFET transistor for temperature varying from 25ºC to 150ºC. It is possible to see that there is a gate bias in which the drain current does not change with temperature. This point is called Zero Temperature Coefficient (V_{ZTC}).

This inflection point occurs because for $V_{GS} > V_T$, when the temperature increases the carriers mobility decrease and consequently there is a reduction in a drain current. However, for $V_{GS} < V_T$, the increase in temperature reduces the Fermi potential, where the variation of intrinsic carrier concentration, Ni, is the predominant factor (this increases exponentially with temperature). The reduction of ϕ_F reduces the value of V_T, thereby increasing the drain current.

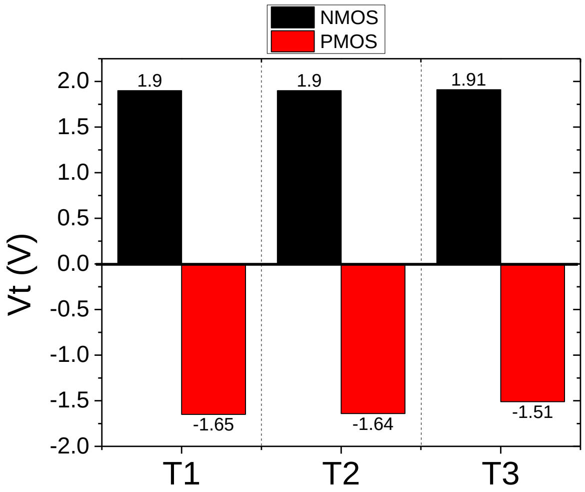

Figure 3 - Comparison of MOS transistor threshold voltages at room temperature

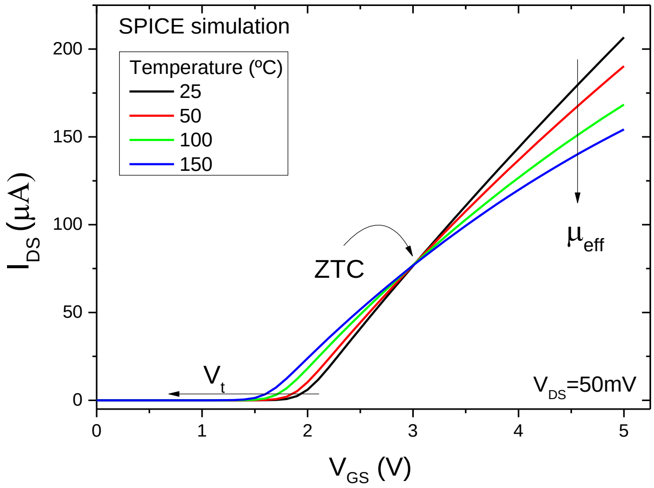

Figure 4 - $I_{DS} x V_{GS}$ characteristic curve for various operating temperatures

From Figure 4, it is observed that by varying the operating temperature, the characteristic curve of the nMOS transistor has an operating point (ZTC) in which no variation of I_{DS} occurs with the temperature due to compensation of the effects described above. For this gate voltage bias point (V_{ZTC}), the drain current is called I_{ZTC}. This operating point is of great importance for the stability of a circuit operating over a wide temperature range, considering the threshold voltage dependency (V_T) and the effective mobility (μ_{eff}) with the temperature.

In figure 5, the behavior of threshold voltage of transistors in two chips, operating at different temperatures is plotted as a function of temperature. It was possible to observe the threshold voltage reduction with the temperature increase due to the fermi potential reduction. All the transistors in both dies present the same behavior and through a graphical analysis. From the VT behavior it was extracted the threshold voltage degradation factor, which is also used in the simulation.

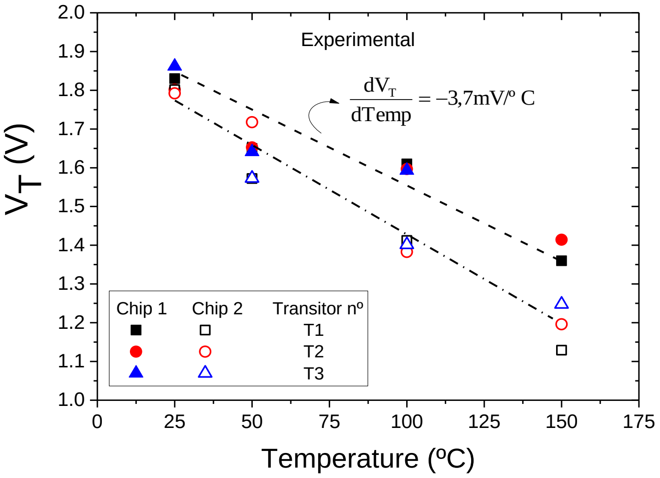

Figure 5- Variation of threshold voltage by temperature.

The sensor will not operate properly in V_{ZTC} (3.0V ~ 3.1V), since there is no variation of drain current as a function of temperature for this gate bias, as explained earlier. For better application as a sensor, the transistor must be polarized for gate voltages higher than V_{ZTC} (between 3.2V and 5V in this case), since for this gate bias there is the greater drain current variation as a function of temperature, as can be seen in Figure 6. In order to create a more robust database for the algorithm, the MOSFET transfer characteristic (I_{DS}xV_{GS}) was simulated for temperature from -40ºC up to 150ºC with step of 10ºC.

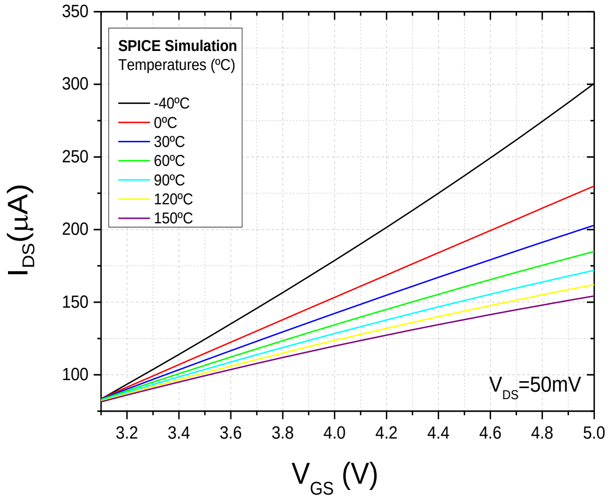

Figure 6 – The drain current as a function of gate voltage for temperature ranging from -40ºC up to 150ºC.

The temperature sensor was implemented following the algorithm flow, present in figure 7. Considering the commercial MOSFET (CD4007) working on a printed circuit board, when the MOSFET is biased with V_{DS}=50mV and V_{GS}=4.5V, the monitoring drain current changes with the local temperature. Some results of the temperature sensor is presented in table I.

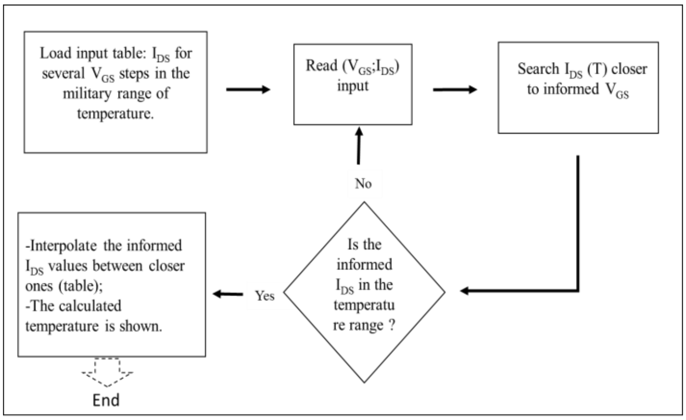

Figure 7 – Schematic algorithm flow.

Table I- Example of temperature sensor results

	Temperature (°C)	
I_{DS}(µA)	**Input table**	**Software output**
157.104	70	70
155.000	-	76.8
153.994	80	80

When entering a gate voltage value (within range from 3.2V to 5V) and drain current, the algorithm will search for this current and inform the respective temperature, for example that can be seen in lines 3 and 5 of Table I. However, when the informed current value does not correspond to the exact values of the table, the algorithm will look for closer values, making the linear interpolation between the currents, providing the temperature, with precision of 0.1 ° C. As example the value of 155µA was measured from MOSFET, and a linear interpolation was needed, resulting in a T=76.8ºC.

IV. CONCLUSION

In this work the effects of temperature on behavior of MOSFET transistors was studied for application as a temperature sensor. Initially, the Zero Temperature Coefficient and threshold voltage were analyzed and the better gate bias range was determined to optimize the current sensing.

The better sensing occurs at region on the mobility degradation dominates the drain current behavior when the temperature is changed. The higher is the applied gate voltage, the higher is the drain current variation and therefore the higher is the sensitivity of the transistor to detect this temperature variation. After to determine the optimal gate voltage range for the application of the sensor (from 3.2V to 5V), the table containing the collected data was inputted and a program was developed to MOSFET operates as a temperature sensor. The refining process (linear interpolation) allowed to obtain a very good precision (0.1ºC) for the sensor.

ACKNOWLEDGMENT

The authors would like to thank the CNPq for the financial support and Prof. Dr. João Antonio Martino for making feasible the experimental measurements using the LSI/USP laboratory

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