Threshold Voltage Extraction Methods Applied to ^{BE}SOI (Back Enhanced) MOSFET

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***Abstract* - This paper presents a comparative study of four threshold voltage extraction methods applied to a new transistor fabricated at LSI/PSI/USP, called ^{BE}SOI (Back Enhanced) MOSFET. The selected methods are: constant current, linear extrapolation, second derivative and transition method. The proposal is to compare the results and understand which methods best fit this new technology. A long channel device was chosen for this analysis and multiple curves were extracted by varying the back gate voltage. Among the methods studied in this paper, the transition method (integration approach) presented better results.**

Keywords - Threshold voltage, ^{BE}SOI MOSFET, electrical characterization

I. INTRODUCTION

The present work studies and applies an array of mathematical methods for extracting the threshold voltages of ^{BE}SOI MOSFET (Back-Enhanced Silicon on Insulator Metal-Oxide-Semiconductor Field Effect Transistor) devices. These transistors were developed by the Integrated Systems Laboratory (LSI) of the Polytechnic School of the University of Sao Paulo (EP-USP) in 2015 [1].

The ^{BE}SOI is an evolution of the SOI MOSFET technology that was developed by LSI/PSI/USP [1]. This transistor eliminates the need for drain and source doping, making it possible for the device to behave as an n-MOSFET or a p-MOSFET, depending on the back gate voltage. This happens because, when a voltage with high enough absolute value is applied to the back gate (substrate), the buried oxide exerts a capacitive effect on the back interface (buried oxide/substrate), attracting holes or electrons in the back channel. This way, the transistor can assume the role of an n- or p-MOSFET, for positive or negative back gate voltages, respectively. Figure 1 shows a schematic view of the device.

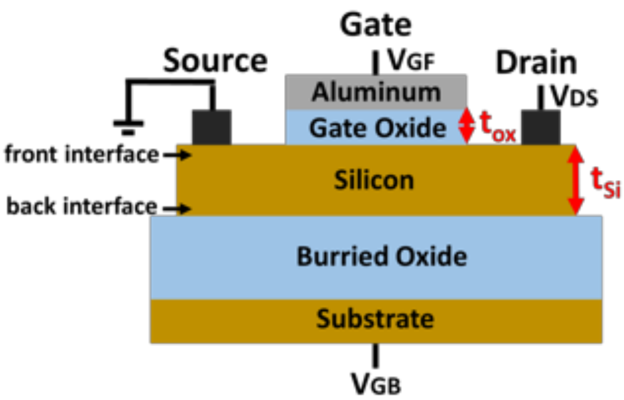

Figure 1. Schematic profile of the ^{BE}SOI MOSFET.

The threshold voltage V_t is the transistor parameter that indicates the gate-source voltage at which there appears a significant flow of electrons between the drain and source terminals, conducting electricity [2]. The applications of the threshold voltage for the ^{BE}SOI are twofold: modeling and reliability. V_t can be used, for example, in SPICE models to obtain voltage simulations for the transistor. Additionally, in terms of reliability, the rate of change of V_t over time can be a good measure of the working conditions of a given transistor [3].

Nowadays, as described in [4], the threshold voltage for the ^{BE}SOI is typically obtained through the second derivative method, where the voltage is the maximum value of the second derivative of the I_D x V_G curve. This method has the advantage of being less dependent on the circuit's series resistance; however it presents high sensitivity to noise [3]. Another problem is that this method was not selected through an exhaustive study of other methods, but simply for convenience.

For these reasons, it is very important to study different V_t extraction methods and compare them to the other existing methods for a more thorough and scientific evaluation on what are the most appropriate and accurate methods for the extraction in this new device. This paper selected the four main applied methods described in [5] for characterizing the V_t of the ^{BE}SOI MOSFET.

II. METHODOLOGY

For characterizing the transistor, an adequate value of V_D = 0.1V was chosen. In sequence, the HP4156C, a precision semiconductor parameter analyzer was used for extraction procedure. The measurements were taken for channel dimensions (W, L) of 10 and 40 µm, respectively. This device was fabricated by LSI/PSI/USP in earlier work [1] and was manufactured with aluminum contacts. The back gate voltage applied varied from -30V to -15V, with a 2.5V step size.

Using the provided curve extraction software, the curves were extracted and saved to CSV files. The measured curves can be seen on Figure 2. Afterwards, computer scripts that calculate V_t for each method were developed using the Python programming language.

Out of the eleven methods presented in [5], four of them were selected as listed below:

- constant current (M1);
- linear extrapolation (M3);
- second derivative (M4);
- transition (M7).

The constant current method (M1) is one of the most popular threshold voltage extraction methods, and it specifies that the value of V_t is equal to the value of V_G for a predetermined I_D. The usual constant used for MOSFETs is $I_D = 10^{-7}$ W/L.

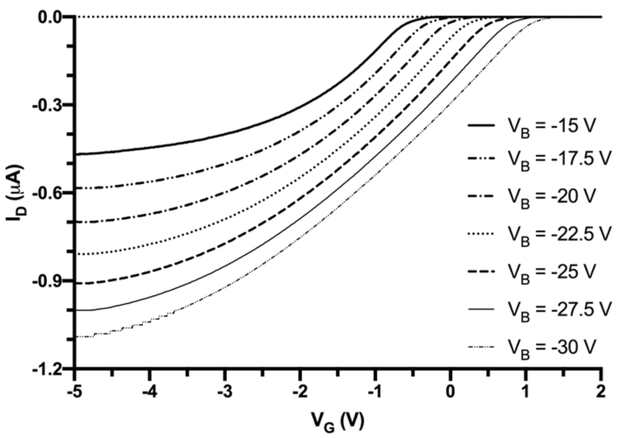

Figure 2. Extracted I_D x V_G curves for the transistor.

The linear extrapolation method (M3) is also very popular. Its first step is to find the maximum point of the first derivative of the I_D x V_G curve (maximum slope point). Afterwards, this point and its derivative are used to linearly extrapolate the I_D x V_G curve. From the extrapolated line, the value of V_t equals the value of V_G when $I_D = 0$.

The second derivative method (M4) consists of differentiating the I_D x V_G curve twice and determining V_t as the maximum point of the obtained curve. It is a widely used method, but it has the disadvantage of being very sensitive to noise.

The least popular of these four methods, the transition method (M7) calculates V_t by obtaining the maximum point of the G1 curve, which is defined by Equation 1.

$$G1(V_{GS}, I_D) = V_{GS} - 2 * (\int_{V_{GSb}}^{V_{GSa}} I_D \, dV_{GS})/I_D \quad (1)$$

To deal with noise issues, a couple different filters had to be applied to the data, according to the method's demands. For M1, due to its simplicity, no filtering was needed. However, when you begin differentiating the signal, noise increases rapidly, so that for M3, a rolling mean filter had to be applied to the differentiated curve. As for M4, the noise was even higher, so there were two filters used: a rolling mean filter and a median filter. When analyzing M7, there was also noise, since there has to be a lot of calculation with the data, so a median filter was applied to the G1 function.

Since the ^{BE}SOI transistor with aluminum source/drain electrodes contacts works better as a pMOS, it will be the focus of this work.

III. RESULTS AND ANALYSIS

The Python scripts were ran for the I_D x V_G curves of the transistor and V_t was obtained for each back gate voltage (V_B) value. All methods executed in less than 5s in total, so execution time was not an important factor for choosing an adequate method. For this work, the reason for choosing M1, M3, and M4 is that they are the most widely used for the scientific people and industry, while M7 has shown consistently good values that are close to the overall mean. All of these results are presented in Table 1, with all measurements in Volts.

Table 1. Threshold voltages (V_t) obtained for different back gate voltages for a devices dimension of 10 μm/40 μm (W/L).

V_B [V]	M1	M3	M4	M7	Mean
-30	1.06	1.06	1.00	1.13	1.17
-27.5	0.78	0.80	0.71	0.85	0.94
-25	0.50	0.52	0.44	0.57	0.66
-22.5	0.23	0.24	0.13	0.30	0.38
-20	-0.05	-0.03	-0.12	0.03	0.08
-17.5	-0.33	-0.30	-0.39	-0.24	-0.18
-15	-0.60	-0.56	-0.68	-0.49	-0.46

In order to compare how the values trend with regards to the average, they were normalized for each V_B by subtracting the least-squares linear fit of the average values from the curve. This way, it is possible to detect whether the outputs for each method are predominantly above or below the mean. The average considered was obtained using all of the 11 methods described in [5]. Figure 3 shows a comparative graph of these results.

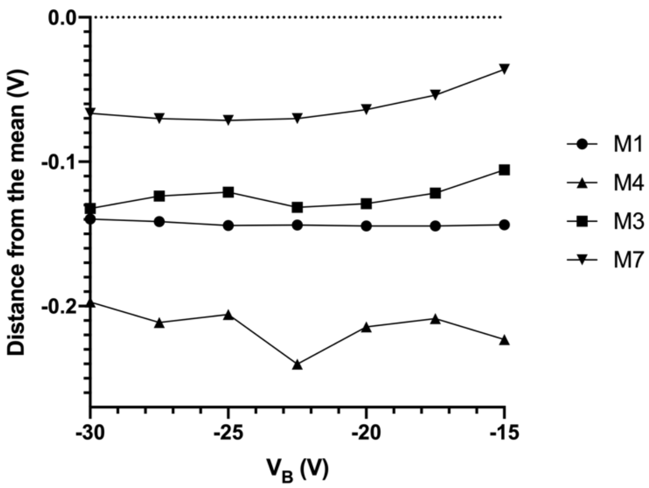

Figure 3. Difference of V_t against the average using selected methods for various substrate voltages in the 10 μm/40 μm (W/L) transistor.

Method 1, the constant current method, has remarkably consistent differences from the mean in all data points, though it undershoots it by about 0.15V. This is likely due to the chosen constant mentioned earlier, which is arbitrary and could be improved for the ^{BE}SOI.

Method 4, the second derivative method, shows the largest variation between data points, which indicates that there is still a lot of influence of noise in the measurements.

Method 3, the linear extrapolation method, and Method 7, the transition method, both give results that are smoother and closer to the mean, with M7 being the closest.

IV. CONCLUSION

The currently used method (second derivative) has presented difficulties due to its low tolerance to noise, meaning it isn't the best choice, specially when compared to methods, like M1 or M3, which are just as simple to implement and require less signal processing.

For modeling purposes, the transition method (M7) shows itself to be a good fit since it is the closest to the average value of all the methods presented in the original paper. The main advantage of this method is that is based on an integral approach, which is not noise dependent.

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