A New Approach for the Extraction of Threshold Voltage for MOSFET's

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ABSTRACT

A new approach for the extraction of threshold voltage (V_{th}) is proposed, namely, the "Third Derivative of Drain-Source Current" method or simply "TD" method. This method extracts the V_{th} by finding the V_{gs} where the third derivative of I_{ds} is maximal. It meets the threshold condition requirement, which is the onset of the inversion channel creation. The method has been tested on transistors down to 0.25μm channel length and is found to be fast, accurate and simple to implement using standard measurement equipment.

Keywords: Semiconductor, MOSFET's, Threshold Voltage, Extraction Method

1 INTRODUCTION

The voltage between the gate and source, $V_{gs,}$ of a MOS device determines the concentration of the carriers in the channel; the gate voltage for which the channel current becomes significant is called the threshold voltage, V_{th}. Since the threshold voltage defines the start of MOS transistor's operation, an accurate extraction of this parameter is crucial.

There are a number of threshold voltage extraction methods, however, the extracted values for the V_{th} vary from methods to methods [1-5]. Hence, a universal, easy to implement and accurate V_{th} extraction method is necessary. The Constant Current (CC) method defines the threshold voltage as the V_{gs} when $I_{ds} = I_{do} \times (W_{eff} / L_{eff})$ [1]. However, it has an ambiguous definition on the critical drain current, I_{do}. Although the Linear Extrapolation (LE) method [2] is widely used, the extracted V_{th} value may change significantly because of variations in the extrinsic resistance. The Second-Derivative-of-the-Logarithm-of-drain-current (SDL) method and Tranconductance Change (TC) method [3,4] define the threshold voltage as where the drift current contribution in I_{ds} is equal to the diffusion current contribution. However, it is not the threshold condition. The Match-Point (MP) method defines the threshold voltage as the gate voltage for which the exponential extrapolation of sub-threshold current deviates by 5% from the measured current [5]. Its extracted values meet the threshold condition, i.e. the onset of the inversion channel formation. Nonetheless, more time is consumed as extrapolation of the exponential component need to be done first.

A new approach for the extraction of V_{th} is proposed, namely, the "Third Derivative of Drain-Source Current" method or simply "TD" method. This method extracts the V_{th} by finding the V_{gs} where the third derivative of I_{ds} is maximal. This method meets the threshold condition requirement, which is the onset of the inversion channel creation.

2 THE NEW METHOD, THEORY

To illustrate the new method, understanding of the MOSFET's operation is necessary. In this section, we will first concentrate on the study of the transistor's operation using a nMOSFET's as an example. Later of this section, we will then focus on the new method.

2.1 MOSFET's Operation

Fig. 1 shows the MOSFET's channel inversion. With the drain and source grounded, the gate controls the charge in the channel. When a small positive biased voltage is applied to the gate of a nMOSFET, the conditions within the channel will change. For the condition of $V_{gs} > 0$, free holes that are present in the p-type silicon are repelled with the accumulation of positive charge at the gate, thus forming a depletion region. The depth of the depletion region from the silicon surface, W_D is given by

$$W_D = \sqrt{\frac{2\varepsilon_{Si}(\phi_S)}{qN_A}} \tag{1}$$

where ε_{Si} is the permitivity of silicon, ϕ_S is the surface potential and N_A is the substrate doping concentration. This depletion region is formed over both the length and width directions. Increasing the positive gate voltage further will eventually lead to the saturation of the depletion depth at,

$$W_{D\,max} = \sqrt{\frac{2\varepsilon_{Si}(2\phi_B)}{qN_A}} \tag{2}$$

where ϕ_B is the bulk potential. Once the saturation of the depletion region is reached, additional gate bias will attract negative mobile electrons to the surface. When enough electrons have accumulated in the channel area, the surface of the silicon changes from hole-dominated to electron-dominated material and is said to have inverted. Under this condition, a conducting n-channel or inversion layer is formed under the gate between the two n^+-diffusion, namely, source and drain, as shown in Fig. 1. Further increase in gate voltage will only increase the surface potential slowly beyond $2\phi_B$, whereby the increased gate voltage drops across the gate oxide. The minimum gate voltage, which is required to form the conducting channel or an inverted layer, is called the threshold voltage V_{th}. We can classify the above four stated operation regions as depletion region, weak inversion, moderate inversion, and strong inversion.

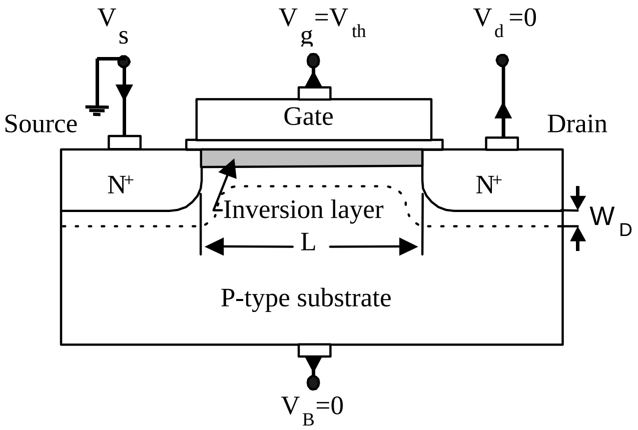

Fig.1 MOSFET's channel inversion

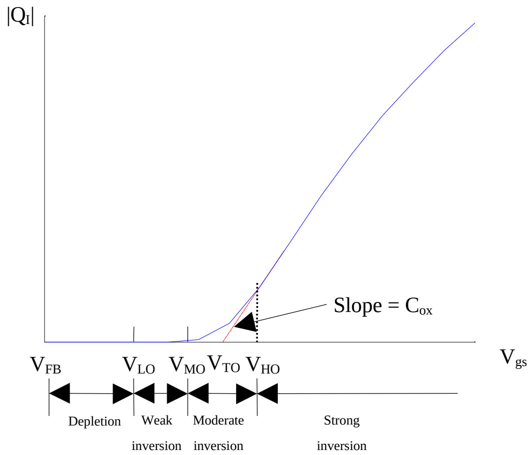

Fig.2 Magnitude of inversion layer charge per unit area vs. V_{gs}

Fig. 2 shows the magnitude of inversion layer charge per unit area versus the V_{gs}. The onsets of weak, moderate and strong inversion, V_{LO}, V_{MO}, V_{TO} can be expressed respectively as:

$$V_{LO} = V_{FB} + \phi_F + \gamma\sqrt{\phi_F - V_{bs}} \quad (3)$$

$$V_{MO} = V_{FB} + 2\phi_F + \gamma\sqrt{2\phi_F - V_{bs}} \quad (4)$$

$$V_{TO} = V_{FB} + \phi_S + \gamma\sqrt{\phi_S - V_{bs}} \quad (5)$$

where, V_{FB} is the flat-band voltage, ϕ_F is the Fermi potential, ϕ_S is the surface potential, and γ is the body factor. The theoretical definition of V_{th} is based on the "strong-inversion" condition at which the ϕ_S is twice of the ϕ_F. Therefore, from eqns. (4) and (5), It is clear that V_{TO} will be equal to V_{MO} if the transistor is biased in the "strong inversion" condition.

2.2 The New Method

It is clear that the V_{TO} and V_{MO} can be easily determined from Fig. 2. V_{TO} can be determined by finding the V_{gs} where the second derivative of the drain-source current is maximum which is the TC method. Whereas, V_{MO} is equal to the V_{gs} where the third derivative of I_{ds} is maximum which is the proposed method. The graphical representation of the proposed method is illustrated in Fig. 3. The transconductance (Gm) curve is obtained by differentiating the drain current (I_{ds}) with respect to the gate voltage (V_{gs}) and once again to give the curve Gm′ whereas the Gm" curve can be obtained by differentiating the Gm' curve again. The position of the peak of the Gm" curve on the V_{gs} axis is taken as the threshold voltage.

Fig. 4 shows that the extracted V_{th} using TD method coincides with the extracted V_{th} using MP. Since this approach is physically defined, it is valid for all kinds of technology variations and it is independent of tolerances in channel dimensions and extrinsic resistance.

3 RESULTS AND DISCUSSION

The new approach is verified with MOSFET's data down to 0.25μm. Fig. 5 compares the extracted results of different methods with V_{ds} biasing at (a) 0.5V and (b) 2.5V. As we can see, the extracted V_{th} values using TD method are very close to the V_{th} values extracted using MP method. While TC method over estimates the value of $V_{th.}$ The reason for this over-estimation is that, conventionally, we will treat the surface potential equal to $2\phi_F$, neglecting a additional term $\Delta\phi$ which has value of several thermal voltage.

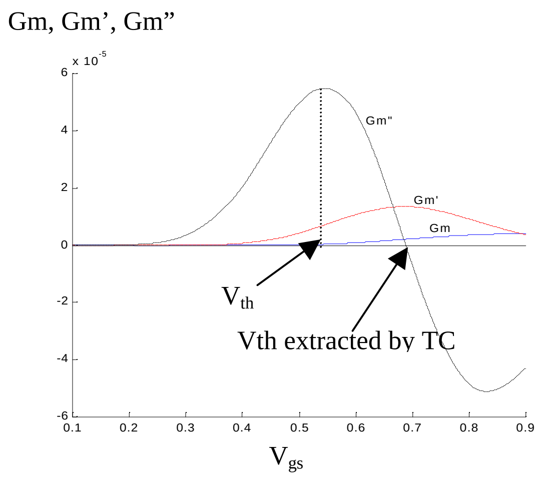

Fig.3 Threshold voltage extraction by TD method and TC method.

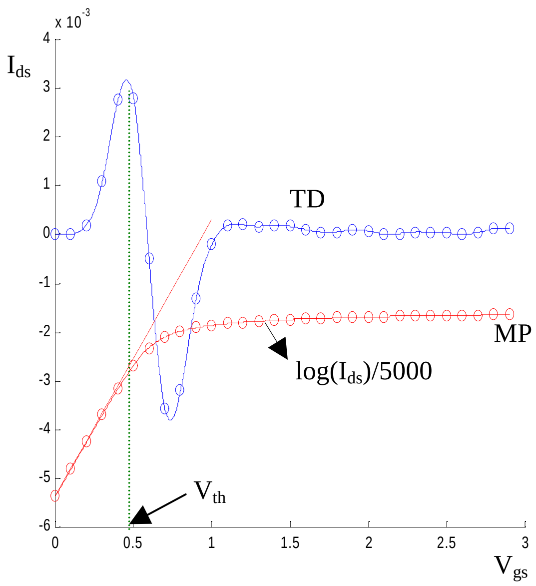

Fig.4 Comparison of extraction approaches between TD and MP methods

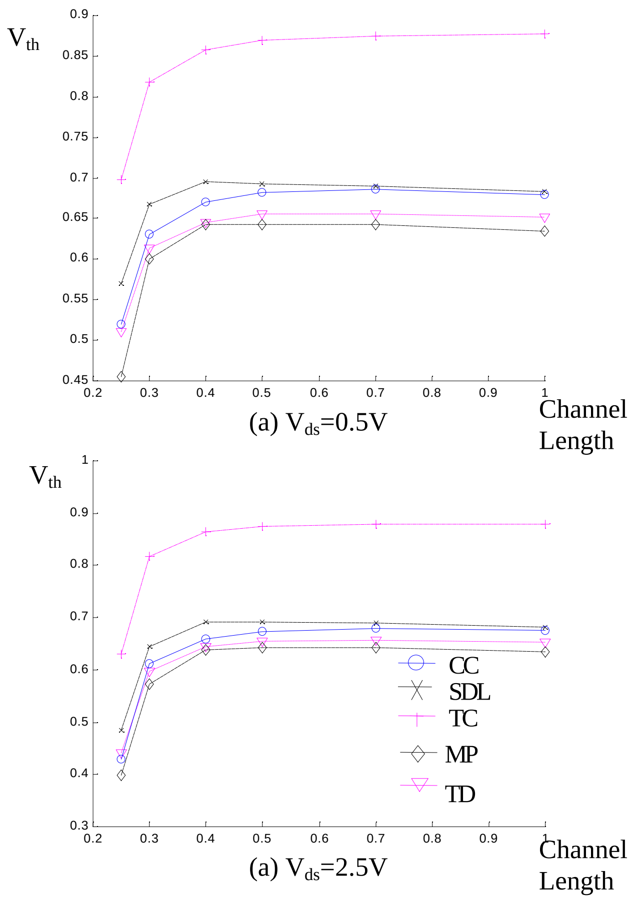

Fig.5 Extracted V_{th} by different methods versus channel lengths from 0.25 to 1µm at (a) V_{ds}=0.5V and (b) V_{ds}=2.5V

4 CONCLUSION

A new approach (TD method) for the extraction of V_{th} is proposed. It has been desmostrated with MOSFET's data with channel length down to 0.25µm. This method is physically reliable and is found to be fast, accurate and simple to implement.

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