# The impact of MOSFET's physical parameters on its threshold voltage

MILAIM ZABELI, NEBI CAKA, MYZAFERE LIMANI, QAMIL KABASHI
Faculty of Electrical and Computer Engineering
University of Prishtina
10110 Prishtina, Fakulteti Teknik, Kodra e Diellit, p.n.
KOSOVA

*Abstract:* The aim of this paper is to research the impact of physical parameters which characterize the MOSFET transistors structure on the threshold voltage value. It is also analysed the role of substrate (the body effect) on the threshold voltage. The MOSFET threshold voltage value will have influence in the dynamic and static work regime (mode) of device. Based on the results obtained we can further see impact of each single physical parameter on the total value of threshold voltage. Moreover we can see which of these parameters will have significant and small impact on the threshold voltage. Hence, considering we can adjust the values of MOSFET physical parameters to reach the accepted threshold voltage.

*Key words:* MOSFET parameters, threshold voltage, body effect, enhancement-type NMOS, doped density, short-channel, narrow-channel.

## 1 Introduction

An important value which characterizes the MOSFET transistors is the value of threshold voltage. According to the MOSFET type the value of threshold voltage can take positive and negative value. This value can be controlled during the fabrication process of MOSFET transistors. The physical structure of n-channel enhancement-type MOSFET (or NMOS) is represented in Fig.1. Because the enhancement-type NMOS have advantage over other type of MOSFET transistors, hence in following we will analyze this. Terminals of MOSFET transistors are indicate with S (source), D (drain), G (gate) and B (body).

The value of the gate-to-source voltage $V_{GS}$ needed to create (induced) the conducting channel (to cause surface inversion) is called the threshold voltage and denoted with $V_{th}$ or $V_t$ [1, 2, 3, 4]. The value of the threshold voltage is dependent from some physical parameters which characterize the MOSFET structure such as: the gate material, the thickness of oxide layer $t_{ox}$, substrate doping concentrations (density) $N_A$, oxide –interface fixed charge concentrations (density) $N_{ox}$, channel length L, channel width W and the bias voltage $V_{SB}$ [2, 5].

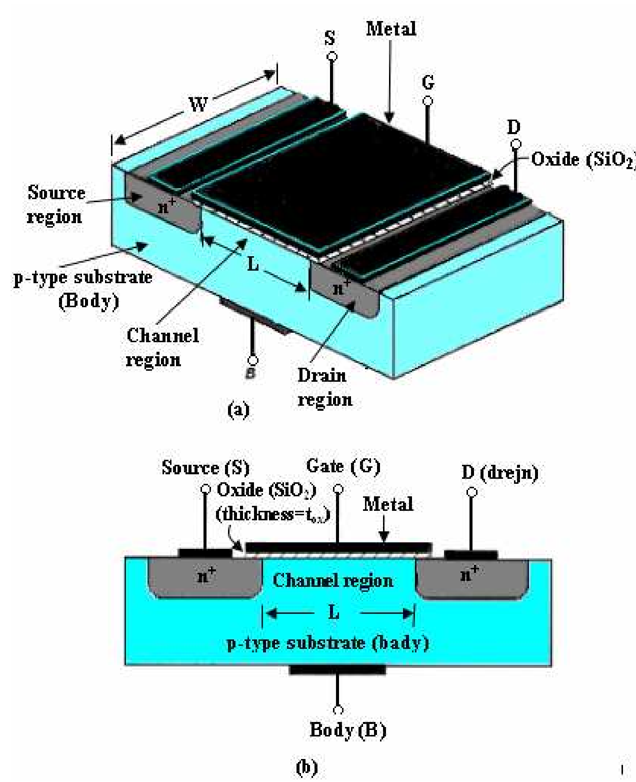


Fig.1 The physical structure of an n-channel enhancement-type MOSFET: (a) perspective view; (b) cross-section.

# 2 Calculation the threshold voltage

## 2.1 Calculation the threshold voltage of NMOS with long-channel

To calculate the threshold voltage we must consider physical parameters of MOSFET structure which have the impact in value of the threshold voltage by considering the various components of $V_t$ (when $V_{SB}$ = 0V, the threshold voltage will indicate $V_{t0}$). For practical purposes, we can identify four physical components of the threshold voltage: the work function difference between the gate and channel ($\Phi_{GC}$), the gate voltage component to change the surface potential ($-2\phi_F$), the gate voltage component to offset the deletion region charge of the fixed acceptor ions near surface ($-Q_B/C_{Ox}$) and gate voltage component to offset the fixed charges in the gate oxide and in silicon –oxide interface ($-Q_{ox}/C_{ox}$) [2, 5]. Now, we combine all of these voltage components to find the threshold voltage. For zero substrate, bias voltage ($V_{SB}$ = 0V) will have this expression [2]:

$$V_{t0} = \Phi_{GC} - 2\phi - \frac{Q_{B0}}{C_{ox}} - \frac{Q_{ox}}{C_{ox}} \quad (1)$$

Where:

$$\Phi_{GC} = \phi_F(substrate) - \phi_F(gate) \quad (2)$$

$$Q_{B0} = -\sqrt{2qN_A\varepsilon_{Si}\left|-2\phi_F\right|} \quad (3)$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \quad (4)$$

For nonzero substrate bias voltage ($V_{SB} > 0$), the depletion charge density term must be modified [2, 5] as:

$$Q_B = -\sqrt{2qN_A\varepsilon_{Si}\left|-2\phi_F + V_{SB}\right|} \quad (5)$$

Now the generalized form of threshold voltage will be:

$$V_t = \Phi_{GC} - 2\phi - \frac{Q_B}{C_{ox}} - \frac{Q_{ox}}{C_{ox}} \quad (6)$$

$$V_t = V_{t0} + \gamma\left(\sqrt{\left|-2\phi_F + V_{SB}\right|} - \sqrt{\left|2\phi_F\right|}\right) \quad (7)$$

γ- is the body-effect parameter.

$$\gamma = \frac{\sqrt{2qN_A\varepsilon_{Si}}}{C_{ox}} \quad (8)$$

where:

$\phi_F$ - the substrate Fermi potential, $q$- electron charge,

$\varepsilon_{Si}$ – dielectric constant of silicon ($S_i$),

$Q_B$ – the depletion region charge density at surface inversion ($\phi_S = -\phi_F$),

$C_{ox}$ – the gate oxide capacitance per unit area.

Based in acquired values at Fig.2 and Fig.3 is represented dependence of the threshold voltage $V_{t0}$ (when source and body have same potential) on thickness of oxide layer $t_{ox}$, for parametric values of substrate doping density $N_A$ and oxide-interface fixed charge density $N_{ox}$.

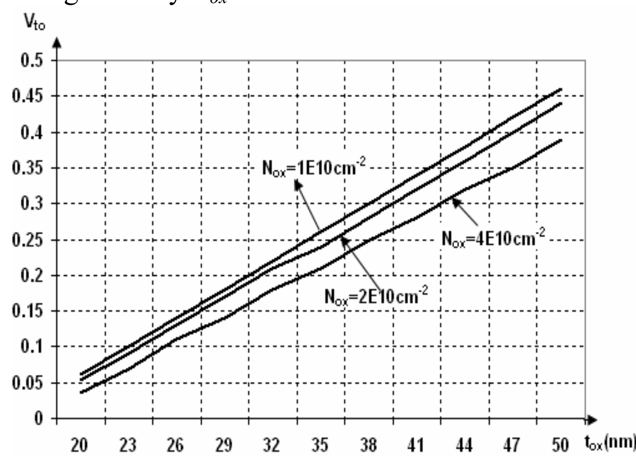


Fig.2. The dependence of the threshold voltage $V_{t0}$ on thickness of oxide layer $t_{ox}$ for parametric values of oxide-interface fixed charge density $N_{ox}$, when $N_A = 10^{16}cm^{-3}$.

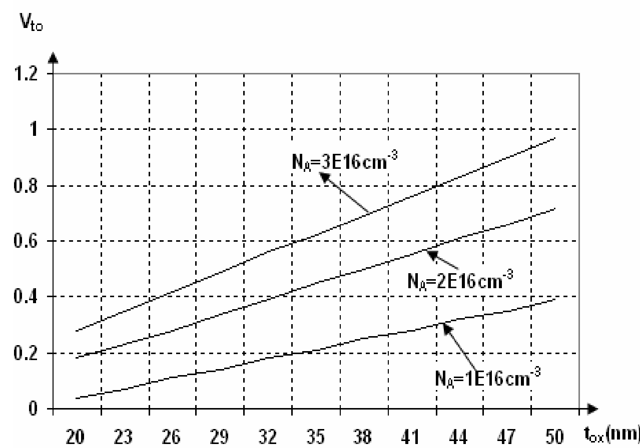


Fig.3. The dependence of the threshold voltage $V_{t0}$ on thickness of oxide layer $t_{ox}$ for parametric values of substrate doping density $N_A$, when $N_{ox} = 10^{10}cm^{-2}$.

From Fig.2 and Fig.3, based on acquired values we can see influence of $t_{ox}$, $N_A$ and $N_{ox}$ in values of threshold voltage. For larger value of each parameter: $t_{ox}$, or $N_A$ the value of threshold voltage will increase.

But, for larger value of $N_{ox}$ the value of threshold voltage will decrease, which is not significant.

Influence of substrate bias voltage (the body effect) on the threshold voltage is shown in Fig.4.

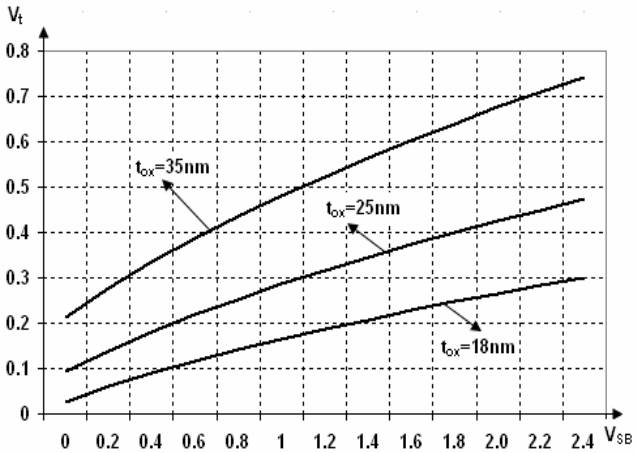


Fig.4. Variation of the threshold voltage $V_t$ as a function of the source-to-substrate ($V_{SB}$) voltage for parametric values of thickness oxide layers $t_{ox}$, when $N_A = 10^{16}$ cm$^{-3}$ and $N_{ox} = 4*10^{10}$ cm$^{-3}$.

Fig. 4 shows dependence of threshold voltage on the polarization voltage $V_{SB}$, for which results the higher values of the threshold voltage for higher value of $V_{SB}$ in comparison with $V_{t0}$ (as in case of integrated circuits).

## 2.2 Calculation the threshold voltage of NMOS with short-channel

A MOSFET transistor is defined as a short-channel device if its channel length is on the same order of magnitude as the depletion regions thicknesses of source and drain junction. Otherwise MOSFET can be defined as a short-channel device if effective channel length $L_{eef}$ is approximately equal to the S and D junction depth $x_j$, Fig.5. When NMOS is defined as a short-channel device the length of channel will have impact on the threshold voltage. A short-channel will reduce the threshold voltage of $\Delta V_t$ compare with long-channel device [2, 5, 8, 9].

$$V_{t0}(\text{short-channel}) = V_{t0} - \Delta V_{t0} \quad (9)$$

Let $\Delta L_S$ and $\Delta L_D$ represent the lateral extend of the depletion regions associated with the source junction and the drain junction, as in Fig 5. Then, the bulk depletion region charge contained within the trapezoidal region is:

$$Q_{B0} = -(1 - \frac{\Delta L_S + \Delta L_D}{2 \cdot L})\sqrt{2qN_A\varepsilon_{Si}|-2\phi_F|} \quad (10)$$

After calculation the $\Delta L_S$ and $\Delta L_D$, the amount of threshold voltage reduction $\Delta V_{t0}$ can be found as [2, 5]:

$$\Delta V_{t0} = \frac{1}{C_{ox}}\sqrt{2q\varepsilon_{Si}N_A|-2\phi_f|}\,\frac{x_j}{2L}\left[\left(\sqrt{1+\frac{2x_{dS}}{x_j}}-1\right)+\left(\sqrt{1+\frac{2x_{dD}}{x_j}}-1\right)\right] \quad (11)$$

-$x_{dS}$, $x_{dD}$ represent the depth of depletion regions at source and drain as results of pn junction, respectively.

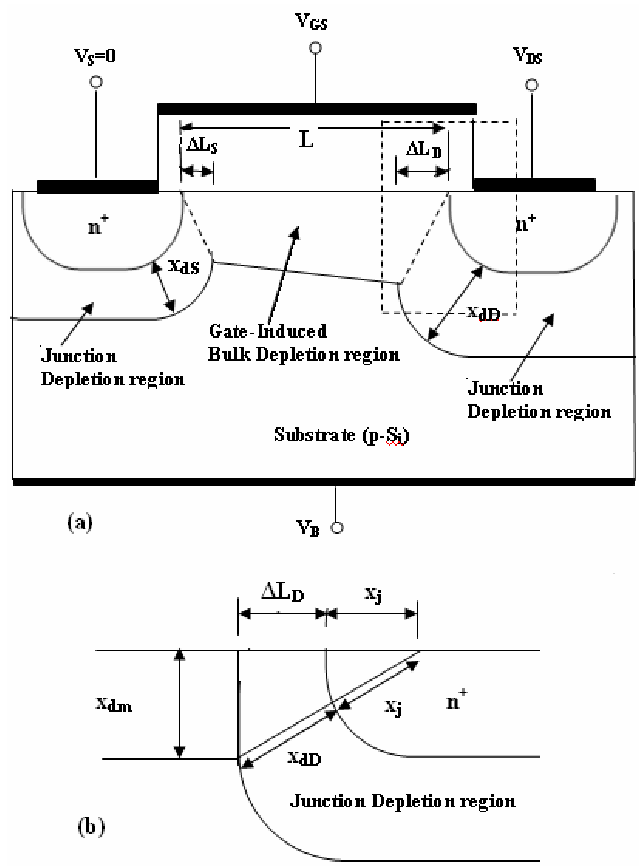


Fig.5 (a) Simplified geometry of the MOSFET channel region, with gate-induced bulk depletion region and the pn-junction depletion regions.
(b) Close-up view of the drain diffusion edge.

Influence of the length channel L, the depth $x_j$ of drain (source) regions and drain-to-source voltage ($V_{DS}$) on the voltage term $\Delta V_{t0}$, are shown in Fig.6, Fig.7 and Fig.8.

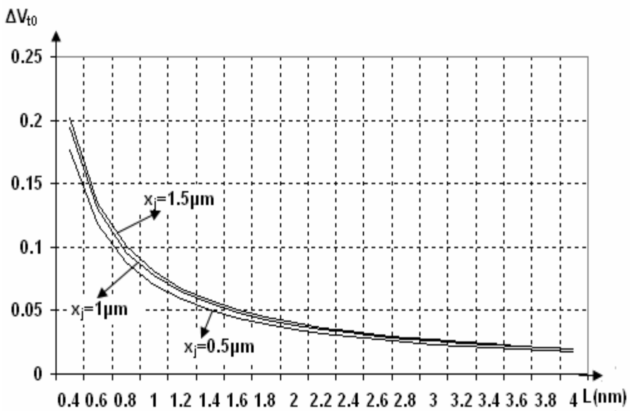


Fig.6 The dependence of the $\Delta V_{t0}$ on the length $L$ for parametric values of depth $x_j$, when $N_A = 10^{16}$ cm$^{-3}$, $N_D = 10^{18}$ cm$^{-3}$, $t_{ox} = 20$ nm and $V_{DS} = 0$V.

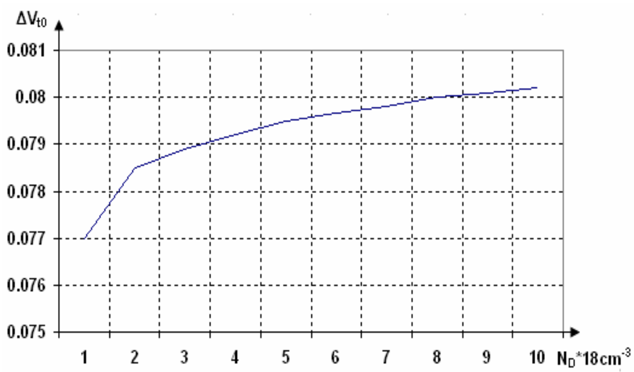


Fig.7 The dependence of the $\Delta V_{t0}$ on $N_D$ (source and drain doping density), when $N_A=10^{16}$cm$^{-3}$, L=1µm, $t_{ox}$=20nm, $x_j$=1µm and $V_{DS}$=0V.

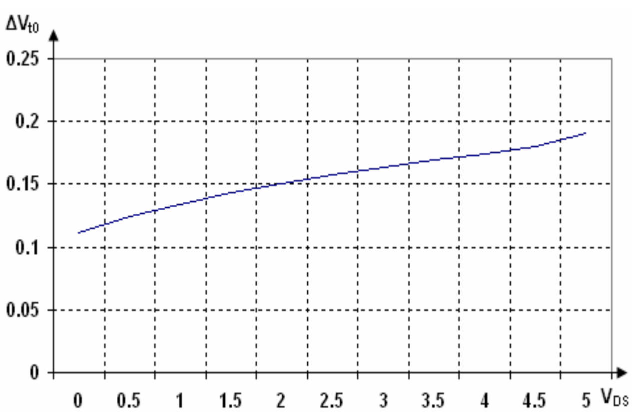


Fig.8 The dependence of $\Delta V_{t0}$ on $V_{DS}$ voltage, when $N_A = 10^{16}$ cm$^{-3}$, $N_D = 10^{18}$ cm$^{-3}$, $t_{ox} = 20$ nm, $x_j = 1$ µm and $L = 0.7$ µm.

Based in acquired values which are represented in Fig.6, Fig.7 and Fig.8, for $L \approx x_j$ the $\Delta V_{t0}$ will have influence in reduction of the threshold voltage $V_{t0}$. While if $L >> x_j$ the $\Delta V_{t0}$ is not significant, the NMOS is defined as long-channel device. The increase the value of parameters $N_A$ and $x_j$ will have small influence in term of the threshold voltage $\Delta V_{t0}$. The $V_{DS}$ voltage will have significant influence in the term $\Delta V_{t0}$, which results in larger value for higher value of $V_{DS}$.

## 2.3 Calculation the threshold voltage of NMOS with narrow-channel

A MOSFET transistor is defined as a narrow-channel device if its channel width is on the same order of magnitude as the maximum depletion regions thickness into the substrate ($x_{dm}$). This effect will have influence in the threshold voltage and results in higher value for $\Delta V_{t0}$ if compared with long-channel device [2, 5].

$$V_{t0(\text{narrow-channel})} = V_{t0} + \Delta V_{t0} \tag{12}$$

The voltage term $\Delta V_{t0}$ as results of narrow-effects if shapes of the depletion region edges are modeled by quarter-circular arcs can be found as [2]:

$$\Delta V_{t0} = \frac{1}{C_{ox}} \sqrt{2q\varepsilon_{Si} N_A \left|-2\phi_f\right|} \frac{\pi \cdot x_{dm}}{2W} \tag{13}$$

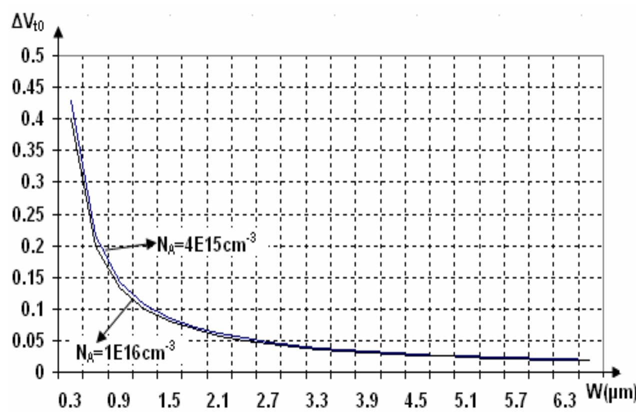


Fig.9 The dependence of $\Delta V_{t0}$ on channel width (W) for parametric values of $N_A$, when $N_D = 10^{18}$ cm$^{-3}$ and $t_{ox} = 20$ nm.

In Fig.9 is shown the dependence of voltage term $\Delta V_t$ on the channel width and we can say: when $W \approx x_{dm}$ the $\Delta V_t$ term will have influence in the increase of the total threshold voltage, while $W >> x_{dm}$ the $\Delta V_t$ term is not significant.

# 3 Conclusion

Based on the results obtained, as shown in figures (2-9), we have seen impact of several physical parameters which characterize the MOSFET transistors (NMOS) on the threshold voltage. Therefore, we can conclude that for long-channel device the threshold voltage will decreases when: the substrate doping decreases ($N_A$), the oxide thickness decreases ($t_{ox}$), the oxide-interface charge increases (will have little effect; $N_{ox}$). For short-channel device we will have reduction of the threshold voltage by $\Delta V_t$ term compared with the long-channel device, which depends of: the length of channel ($L$), the junction depth ($x_j$), drain diffusion doping (small effect) and drain-to-source voltage ($V_{DS}$). For narrow-channel device we will increase the threshold voltage by $\Delta V_t$ term compared with the long-channel device, which is dependent of: the width channel ($W$), the maximal depletion region thickness ($x_{dm}$). The positive source-to-substrate voltage $V_{SB}$ (body effect, as in IC) will cause the increment on total value of threshold voltage. Finally, for MOSFETs which have a small channel length and a small channel width, the threshold voltage variations due to short- and narrow-channel effects may tend to cancel each other out.

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