THE DRIFT/DIFFUSION RATIO OF THE MOS TRANSISTOR DRAIN CURRENT

Sabin EFTIMIE[1], Adrian RUSU[2], Adrian - Mihai IONESCU[3]

Lucrarea prezintă o nouă metodă de evaluare a raportului dintre cele două componenete ale curentului de drenă ale unui tranzistor MOS: curentul de câmp şi cel de difuzie. Stabilind anumite limite pentru acest raport, se poate delimita regiunea de inversie moderată pe caracteristicile de transfer ale unui tranzistor. Cunoaşterea limitelor inversiei moderate oferă posibilitatea obţinerii unei precizii mai bune atunci când sunt folosite modele continue. Vor fi date şi exemple de stabilire a limitelor inversiei moderate în cazul unor tranzistoare submicronice, comparând aceste rezultate cu soluţiile oferite de alte modele.

The paper presents a new method to evaluate the ratio between the two components of drain current in MOS transistors: drift and diffusion. By setting certain limits for this ratio, the moderate inversion region can be delimited in transfer electrical characteristics. The limits of the moderate inversion give the possibility for a more accurate applying of the continuous models. Some examples are given by extracting the main model parameters for a sub-micron MOS transistor and the limits of moderate inversion are compared with the results obtained using other models.

Keywords: drift/diffusion ratio, MOS transistor

1. Introduction

The basic principles of the gate action on drain current in MOS transistor indicate two extreme domains:

- the strong inversion, modeled by parabolic laws, where the current is given by the drift component and
- the sub-threshold region, where the models use an exponential law and a diffusion component of the current is considered [1], [2].

Between the two regions, an intermediate one is considered. This region must take into account the both components of the current, drift and diffusion, and represents the test-key of any continuous model. The limits of the moderate inversion can be calculated using the Tsividis' model [2], where the ratio between

[1] Eng., ON SEMICONDUCTOR, Bucharest, Romania, sabin.eftimie@gmail.com
[2] Prof., University POLITEHNICA of Bucharest, Romania
[3] Prof., École Polytechnique Fédérale de Lausanne, Switzerland

the main capacitances of the MOS transistor is used. This paper presents a new way to determine the moderate inversion limits by compiling the drain currents's drift/diffusion ratios. The results of both methods are close, but the new proposed one offers the possibility to use even drain current to estimate the ratio between its components.

2. Previous Models

2.1. The definition of the drift and diffusion currents

The surface potential based models are recognized today as ones of the most precise in all operation regions, including moderate inversion. This is achieved by considering the drain current as the sum of diffusion current and drift current [3]. These two components have exact definitions if they are considered as local values along the MOS channel and they can be averaged on its entire length to obtain an analitical expression for them. Using the charge sheet model [1], [2], [4], these currents can be considered as functions of the inversion charge present under the gate:

$$I_{D,drift} = Z\mu(-Q_I)\frac{d\varphi_s}{dy} \tag{1}$$

$$I_{D,diffusion} = Z\mu\varphi_t\frac{dQ_I}{dy}, \tag{2}$$

where the notations are classically. The total current, I_D, represents the sum of these components:

$$I_D = I_{D,drift} + I_{D,diffusion} = Z\mu\left[-Q_I\frac{d\varphi_s}{dy} + \varphi_t\frac{dQ_I}{dy}\right] \tag{3}$$

and has a constant value in the whole channel. This observation permits to integrate it along the channel and to obtain the average values of the diffusion and drift currents, as follows:

- the average drift current (usually named only "drift current"):

$$I_{D1} = \frac{Z}{L}\mu\int_{\varphi_{s0}}^{\varphi_{sL}}(-Q_I)d\varphi_s \tag{4}$$

- the average diffusion current (usually named only "diffusion current"):

$$I_{D2} = \frac{Z}{L}\mu\varphi_t \int_{Q_{IS}}^{Q_{ID}} dQ_I \,, \tag{5}$$

where the integration limits represent the corresponding values of the source-end and drain-end of the channel.

In order to compute the values of the I_{D1} and I_{D2} current is necessarily to solve the equations:

$$Q_I = -C_{ox}\left(V_G - V_{FB} - \varphi_s - \gamma\sqrt{\varphi_s}\right) \tag{6}$$

$$\varphi_s = V_G - V_{FB} - \gamma\sqrt{\varphi_s + \varphi_t \exp\left(\frac{\varphi_s - 2\varphi_F - V}{\varphi_t}\right)} \,, \tag{7}$$

where V_G is the gate voltage and the potential V along the channel varies from V_S (source voltage) to V_D (drain voltage). These equations can't be solved analytically and, as consequence, any continuous exact model can't be developed starting from this point.

2.2. Tsividis' model

The limits of the moderate inversion are presented in figure 1. These are:

- V_M, the lower limit of the moderate inversion and
- V_H, the upper limit of this region.

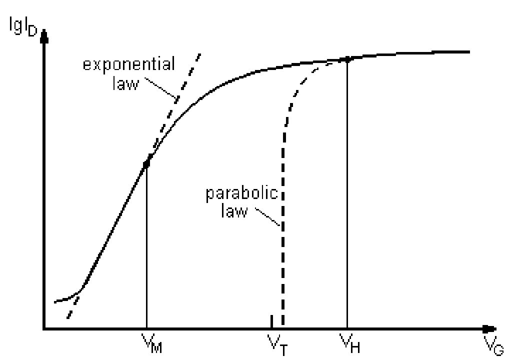

Fig. 1. Drain current dependence of the gate voltage,with the two aproximations for weak inversion and strong inversion

In other words, these limits can be considered as the maximum voltage (V_M) where the exponential law can be considered and the minimum voltage (V_H) from which the parabolic law can be used.

In order to evaluate the width of the moderate inversion region, Tsividis [2], [4] has considered the ratio of the inversion capacitance (C_i) and the sum of the oxide and bulk capacitance ($C_{ox} + C_b$) as these capacitances are presented in figure 2. Taking into consideration the continuous growth of the C_i capacitance with V_G voltage, these two limits are defined as:

$$V_G = V_M \quad \text{for} \quad \frac{C_i}{C_{ox} + C_b} = 0.1 \tag{8a}$$

$$V_G = V_H \quad \text{for} \quad \frac{C_i}{C_{ox} + C_b} = 10\,. \tag{8b}$$

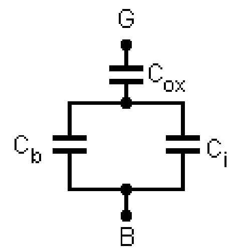

Fig. 2. The simplified capacitance network between gate and bulk of a MOS transistor

These limits will be considered for comparison with an alternative method presented in the next section.

3. The Proposed Model

3.1. The equivalent circuit of the MOS transistor

The MOS transistor function is considered as the injection of charge through the junctions source-channel (D_S) and channel-drain (D_D) (figure 3) [5].

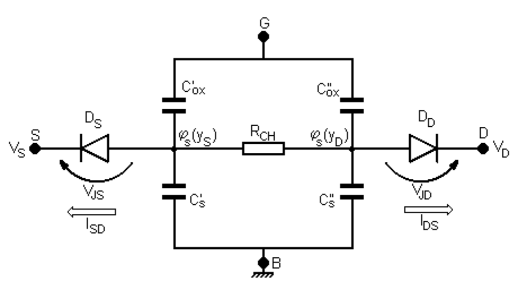

Fig. 3. Equivalent circuit of a MOS transistor

The equivalent circuit is based on the charge sheet model [4]. The corresponding biases of these junctions are V_{JS} and V_{JD}, respectively. The injected currents of each junction are I_{SD} – from the D_S junction – and I_{DS} – from the D_D junction. The total drain current is given by the difference of the two currents:

$$I_D = I_{SD} - I_{DS} . \tag{9}$$

The cathodes of the junctions D_S and D_D are biased by the voltages V_S, respectively V_D, while the anodes are biased by $\varphi_s(y_S)$ and $\varphi_s(y_D)$ which represent the potentials at the ends of the channel. These potentials, $\varphi_s(y_S)$ and $\varphi_s(y_D)$, are obtained *across* the distributed network of channel resistance (R_{CH}) and the oxide/substrate capacitances. In order to represent this network, in figure 3 only a simplified one was presented, where the capacitances are split between source (C'_{ox} and C'_s) and drain (C''_{ox} and C''_s). The drain current is dependent on the voltage V_{DS}, that has the following equation:

$$V_{DS} = \varphi_s(y_D) - \varphi_s(y_S) + V_{JS} - V_{JD} . \tag{10}$$

3.2. The potential method

In order to obtain the average values of the drift and diffusion currents along the channel, a new method is used, named the "potential method". Starting from equation (3), a variable changing is performed, substituting the coordinate y by the corresponding channel resistance, r_{CH}:

$$dr_{CH} = \frac{dy}{-\mu Z Q_I} . \tag{11}$$

As consequence, the differential equation in the channel becomes:

$$I_D dr_{CH} = d\varphi_s + \varphi_t \frac{dQ_I}{-Q_I} . \tag{12}$$

Integrating this equation along the channel:

$$I_D \int_0^{R_{CH}} dr_{CH} = \int_{\varphi_s(y_S)}^{\varphi_s(y_D)} d\varphi_s + \varphi_t \int_{Q_I(y_S)}^{Q_I(y_D)} \frac{dQ_I}{Q_I} \tag{13}$$

the average values of the drift and diffusion currents are:

- the drift current (I_{D3}), representing the first part of equation (13):

$$I_{D3} = \frac{\varphi_s(y_D) - \varphi_s(y_S)}{R_{CH}} \tag{14}$$

- the diffusion current (I_{D4}), representing the second part of equation (13):

$$I_{D4} = \frac{\varphi_t}{R_{CH}} \ln \frac{Q_I(y_S)}{Q_I(y_D)}. \tag{15}$$

Taking into consideration the exponential dependence of the injected inversion charge at the ends of the channel on the bias of source and drain junctions, the final equation of the diffusion current is:

$$I_{D4} = \frac{V_{JS} - V_{JD}}{R_{CH}}. \tag{16}$$

By adding the two components, I_{D3} and I_{D4}, the equation of the total drain current becomes:

$$I_D R_{CH} = [\varphi_s(y_D) - \varphi_s(y_S)] + (V_{JS} - V_{JD}) \tag{17}$$

As a physical interpretation of this "potential method" it can observe that the weight of the drift and diffusion currents is depending on a sharing of the drain-source voltage between the channel, $[\varphi_s(y_D) - \varphi_s(y_S)]$, and the two junctions, $(V_{JS} - V_{JD})$.

3.3. The drift/diffusion ratio

Taking into account the equations (14), (16) and (17), the following ratios can be defined:

- the weight of the drift current, r_c:

$$r_c = \frac{I_{D3}}{I_D} = \frac{\varphi_s(y_D) - \varphi_s(y_S)}{V_{DS}} \tag{18}$$

- the weight of the diffusion current, r_d:

$$r_d = 1 - r_c = \frac{I_{D4}}{I_D} = \frac{V_{JS} - V_{JD}}{V_{DS}}. \tag{19}$$

In order to obtain analytical solutions of these ratios dependent on applied voltages, the case of linear electrical characteristics is considered. For small V_{DS} voltages, the corresponding ratio r_c will be noted r_{c0} and will be given by:

$$r_{c0} = \lim_{V_{DS} \to 0} \frac{\varphi_s(y_D) - \varphi_s(y_S)}{V_{DS}} = \left. \frac{d\varphi_s(y_D)}{dV_{DS}} \right|_{V_{DS}=0}. \tag{20}$$

Using the equation (7), the ratio r_{c0} is calculated as:

$$r_{c0} = \frac{\dfrac{\gamma \exp[(\varphi_s(y_S) - 2\varphi_F)/\varphi_t]}{2\sqrt{\varphi_s(y_S) + \varphi_t \exp[(\varphi_s(y_S) - 2\varphi_F)/\varphi_t]}}}{1 + \dfrac{\gamma\{1 + \exp[(\varphi_s(y_S) - 2\varphi_F)/\varphi_t]\}}{2\sqrt{\varphi_s(y_S) + \varphi_t \exp[(\varphi_s(y_S) - 2\varphi_F)/\varphi_t]}}} \tag{21}$$

The above equation may be rewritten using the normal variables:

$$x_s = \frac{\varphi_s(y_S)}{\varphi_t} \tag{22a}$$

and:

$$x_F = \frac{\varphi_F}{\varphi_t}; \tag{22b}$$

the following form is obtained:

$$r_{c0} = \frac{\dfrac{(\gamma/\varphi_t)\exp(x_s - 2x_F)}{2\sqrt{x_s + \exp(x_s - 2x_F)}}}{1 + \dfrac{(\gamma/\varphi_t)[1 + \exp(x_s - 2x_F)]}{2\sqrt{x_s + \exp(x_s - 2x_F)}}}. \tag{23}$$

Figure 4 shows the curves of the drift current weight, r_{c0}, on the normalized surface potential, x_s, considering a large range for the body-effect coefficient γ, from 0.01 to 10 $V^{1/2}$. It can be observed that the weight of the drift current is approximately zero at the beginning of the inversion ($\varphi_s/\varphi_F = 1$) and

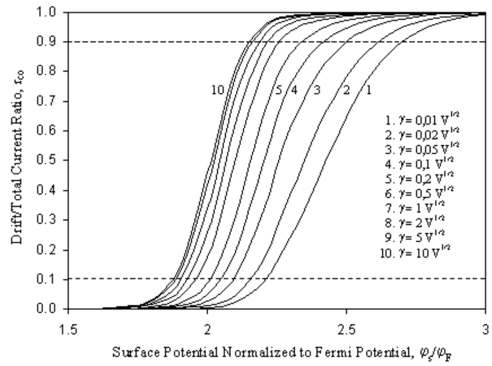

Fig. 4. Drift current ratio dependence of surface potential

grows to unity for deep strong inversion ($\varphi_s/\varphi_F > 3.5$). It is interesting to observe that the condition for starting strong inversion, $\varphi_s/\varphi_F = 2$, *lies* in the moderate inversion region, where r_{c0} has significant values.

4. The Moderate Inversion Limits

The limits of the moderate inversion region can be determined considering the conventional limits 0.1 and 0.9 for the r_{c0} ratio:

- the minimum (lower) limit:

$$\varphi_{sM} = \varphi_s\big|_{r_{c0}=0.1} \tag{24a}$$

- the maximum (upper) limit:

$$\varphi_{sH} = \varphi_s\big|_{r_{c0}=0.9}. \tag{24a}$$

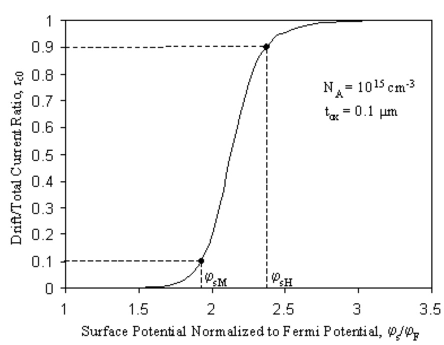

Fig. 5. Example for calculating the limits of moderate inversion region

An example is presented in figure 5 where a particular case with $N_A = 10^{15}$ cm^{-3} and $t_{ox} = 0.1\mu m$ is considered. The extracted values are: $\varphi_{sM} = 1.924\varphi_F$ and $\varphi_{sH} = 2.367\varphi_F$. For comparison with the Tsividis' model, figure 6 shows the ratio of capacitances:

$$r_T = \frac{C_i}{C_{ox} + C_b} \tag{25}$$

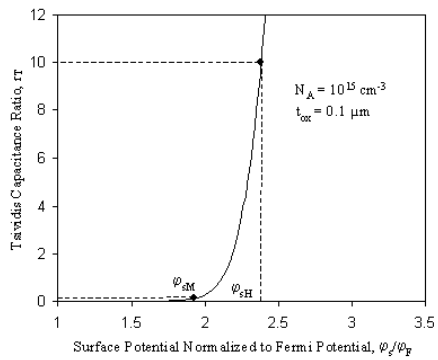

Fig. 6. Calculating moderate inversion limits using Tsividis model

as a function of the same relative surface potential (φ_s/φ_F). Considering the limits 0.1 and 10, given by equations (8a) and (8b), the following results are obtained: $\varphi_{sM} = 1.898\varphi_F$ and $\varphi_{sH} = 2.381\varphi_F$. One can see a good fit of the results obtained by the two methods. In order to extend the comparison, the width of moderate inversion region was represented on a graph indicated by Tsividis [6], as a

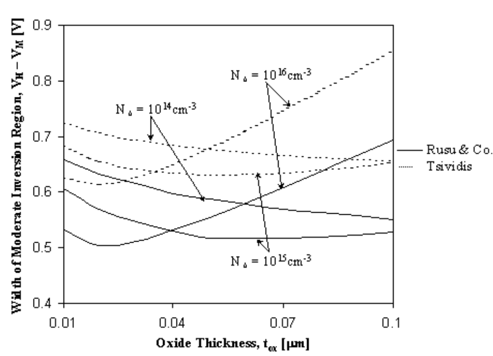

Fig. 7. Comparison between Tsividis and Rusu considering the width of moderate inversion region as a fucntion of oxide thickness

function of oxide thickness and substrate concentration (figure 7). The width of moderate region is defined as:

$$V_H - V_M = V_G\big|_{\varphi_s=\varphi_{sH}} - V_G\big|_{\varphi_s=\varphi_{sM}} . \tag{26}$$

In this figure, the Tsividis' results are indicated with dashed line, while the results of our paper (Rusu and Co.) are with solid lines. The two curves have the same shape, with the observation that the new results are systematically lower than the Tsividis' ones, but less than 20%. A correction can be made if the limits 0.1 and 0.9 used in equations (24a) and (24b) are slightly modified. In figure 8 a

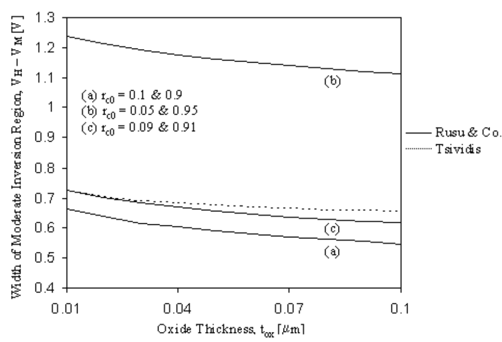

Fig. 8. Changing the moderate inversion limits for fitting Tsividis' results

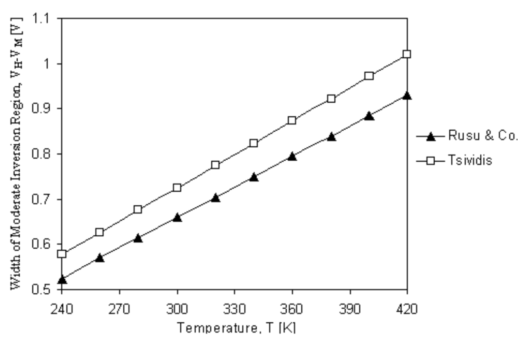

Fig. 9. The Dependence of the width of moderate inversion region.of temperature

comparison of the models was performed for $N_A = 10^{14}$ cm^{-3}. The limits 0.1 and 10 of Tsividis' model were kept unchanged – equations (8a) and (8b). Meanwhile, the limits of our model were modified as: (a) r_{c0} = 0.1 & 0.9 (as in figure 7), (b) r_{c0}

= 0.05 & 0.95 and (c) r_{c0} = 0.09 & 0.91. In case (b) the width of moderate inversion region is larger, but for the last case the fitting is quite good.

In the following, keeping the same conventional limits for the drift current weight, 0.1 and 0.9, another comparison was made to observe the dependence of moderate inversion width on temperature for both models. Figure 9 shows this dependence for temperatures between 240 and 420 K, considering a MOS transistor with $N_A = 10^{14}$ cm^{-3} and t_{ox} = 10 nm. It can observe the reduction of the width of moderate inversion region while the temperature is decreasing.

A final result is given in figure 10, where the limits of moderate inversion region are indicated on a transfer electrical characteristic for a sub-micron MOS transistor. These limits were calculated using the procedure indicated in this paper. The threshold voltage V_T was determined by using the third derivative of the characteristic [7]. The performing of these determinations does not need the existence of any information concerning the MOS capacitances.

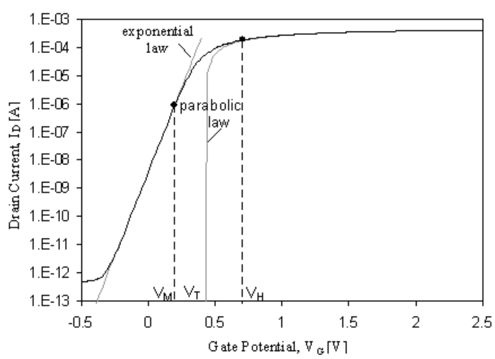

Fig. 10. Limits of the moderate inversion region on a real transfer electrical characteristic

5. Conclusions

The paper presented a new method to define the average currents for the drift and diffusion processes. The drift/diffusion ratio depends on the drain-source voltage sharing between the channel and the transition regions of source and drain junctions. The conventional limits for moderate inversion are given by the weight of the drift current in the total drain current; usually, the limits are 0.1 and 0.9. The results are in good agreements with the limits of Tsividis' model extracted from capacitance ratio. The advantage of the proposed model lies in the possibility to extract the limits of moderate inversion region directly from the electrical characteristics.

R E F E R E N C E S

[1] *S. M. Sze*, “Physics of Semiconductor Devices”, J. Wiley, New York 1981
[2] *Y. P. Tsividis*, “Operation and Modeling of the MOS Transistor”, McGraw – Hill, New York, 1987
[3] *R. Woltjer and Co.*, “An Industrial View on Compact Modeling”, Solid – State Electronics, 51, 1572, 2007
[4] *J. R. Brews*, “A Charge Sheet Model of the MOSFET”, Solid – State Electronics, 21, 345 1978
[5] *A. Rusu,* “Non-Linear Electrical Conduction in Semiconductor Structures”, Editura Academiei Române, Bucharest, (in Romanian), 2000
[6] *Y. P. Tsividis*, “Moderate Inversion in MOS Devices”, Solid – State Electronics, 25, 1099, 1982
[7] *A. Rusu*, “Toward a Demonstration of the Non-Linear Electrical Conduction Law”, Proceedings of the 2001 International Semiconductor Conference, Sinaia, Romania, 413 2001.