Briefs

The Pseudo-Two-Dimensional Approach to Model the Drain Section in SOI MOSFETs

M. Youssef Hammad and Dieter K. Schroder

***Abstract*—The pseudo-two-dimensional (2-D) approach is extended from traditional bulk-Si devices to silicon-on-insulator (SOI) ones. All the possible scenarios associated with partially- and fully-depleted devices are included in the analysis. The benefits of the pseudo-2-D approach in saturation-region modeling are briefly discussed.**

***Index Terms*—Drain section, pseudo-2-D, SOI MOSFET model.**

I. Introduction

As in traditional bulk-Si MOSFETs, the channel in SOI MOSFETs consists of a source section and a drain section when the device is in saturation [1], [2]. Because of the transfer of charge control from the oxide field to the lateral field, channel electrons in the drain section are not confined to the Si surface as they are in the source section. Rather, they spread deeper into the Si film, and the channel becomes two dimensional, since it has depth as well as length. The most successful analytical approach to model the drain section in bulk-Si MOSFETs has been the "pseudo-2-D" approach. This approach was introduced by El-Mansy and Boothroyd [3], and it was subsequently expanded by Ko [1], [4]. Previous work in SOI MOSFETs has utilized Ko's final results either as is [5] or with minor modification [6]. Veerarghavan and Fossum [7] presented a derivation based on the pseudo-2-D approach. However, their derivation is specific to fully-depleted (FD) devices only. Furthermore, their work does not show how the traditional analysis by Ko [1] can be extended to SOI. In this brief, we show how Kos analysis can be extended to SOI MOSFETs, both FD and partially-depleted (PD).

II. Formulation the Pseudo-2 D Approach

The first step in the analysis is to set up a Gaussian box in the drain section. There are two possibilities as far as setting up the Gaussian box is concerned. 1) The boundary between the source and drain sections is located at a point where the Si film is not fully depleted. This possibility occurs in PD devices when the device is bulk-like over the entire channel length. Possibility 1) also includes the scenario where the boundary is located at a point where the film *is* fully depleted except for a back accumulation layer. This scenario occurs in FD devices with a back accumulation layer extending over the entire channel length, and in PD devices where the latter part of the channel is FD-SOI-like with a back accumulation layer. 2) The boundary is located at a point where the film is fully depleted. This possibility occurs in FD devices when the latter part of the channel is without a back accumulation layer, and in PD devices when the latter part of the channel FD-SOI-like without a back accumulation layer. The reader is referred to our publication [8] for a description of the possible scenarios in SOI MOSFETs. The two possibilities are identical as far as the top, left, and right sides of the Gaussian box are concerned. The top side is located at the front Si/SiO_2 interface, the left side is located at the boundary between the source and drain sections, and the right side is located at the drain end of the channel. The two possibilities differ, however, as far as the placement of the bottom side is concerned. In the first possibility, the bottom side is placed at a depth $x = x_1$, where x_1 is the depletion region depth at the boundary between the source and drain sections. x_1 is obtained using the electrostatic analysis of the source section except in the scenario where a back accumulation layer exists in a fully- depleted film. In this scenario, x_1 is simply the Si film thickness, $t_{\rm si}$, since the back accumulation layer is assumed to be much thinner than the Si film. In the second possibility, the bottom side of the Gaussian box is placed at the back Si/SiO_2 interface.

Let us discuss each of the possibilities described above in detail. Fig. 1 illustrates the Gaussian box in the first possibility. The n^+ drain region is assumed to be perfectly conducting, i.e., the electric field is identically zero everywhere in that region. Furthermore, the n^+/p junction is assumed to be perfectly vertical and perfectly abrupt. The electric field crossing the bottom side (Side 4) of the Gaussian box is assumed to be identically zero.

We apply Gauss' law to the Gaussian box with sides 1, 2, 3$'$, and 4, where Side 3$'$ is a vertical side located at an arbitrary position y' between $y' = 0$ and $y' = \Delta L$ (see Fig. 1). This yields

$$\begin{aligned}\varepsilon_{\rm si}\int_0^{x_1} E_y(x,\, y'=0\,dx &- \varepsilon_{\rm si}\int_0^{x_1} E_y(x,\, y')\,dx \\ &- \varepsilon_{\rm ox}\int_0^{y'} E_{\rm ox}(0,\, k)\,dk \\ &= -qN_A x_1 y' - qN_m x_1 y' \end{aligned} \tag{1}$$

where N_m is the channel electron density. Differentiating equation (1) with respect to y', we have

$$\begin{aligned}-\varepsilon_{si}\frac{d}{dy'}\int_0^{x_1} E_y(x,\, y')\,dx &- \varepsilon_{\rm ox}E_{\rm ox}(0,\, y') \\ &= -qN_A x_1 - qN_m x_1. \end{aligned} \tag{2}$$

To proceed further in the analysis, expressions for $\int_0^{x_1} E_y(x,\, y')\,dx$ and $E_{\rm ox}(0,\, y')$ are needed. $E_{\rm ox}(0,\, y')$ is given by

$$E_{\rm ox}(0,\,{\rm y}') = \frac{V_{\rm GS} - V_{\rm FB} - 2\phi_{\rm F} - V_{\rm CS}(y')}{t_{\rm ox}} \tag{3}$$

where $V_{\rm CS}(y')$ is the channel voltage at y'. The integral $\int_0^{x_1} E_y(x,\, y')\,dx$ depends on how E_y changes with depth x at a given lateral position y'. If we let $E_s(y')$ be the lateral field at the surface ($x = 0$) for a lateral position y', then the integral can be written as follows:

$$\int_0^{x_1} E_y(x,\, y')\,dx = \frac{E_s(y')x_1}{\eta_{\rm sp}} \tag{4}$$

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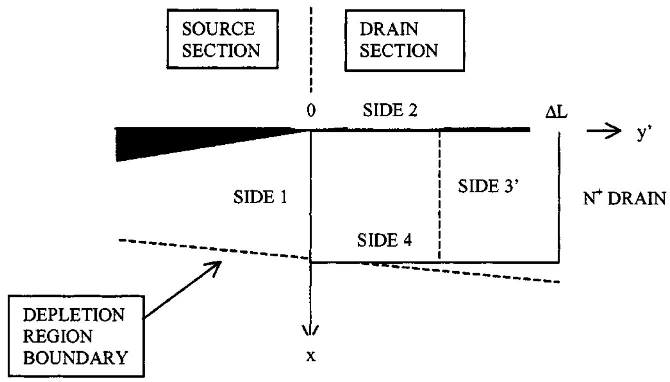

Fig. 1. Gaussian box for first possibility.

where $\eta_{\rm sp}$ (known as the "lateral channel field spreading parameter") is a positive number that characterizes the dependence of E_y on x at a given y'. According to equation (4), a larger value of $\eta_{\rm sp}$ means that the lateral field at a given y' decreases faster from its value at the surface ($E_s(y')$) to its value at x_1 (zero). For example, if $\eta_{\rm sp}$ is equal to 1, then the lateral field does not decrease at all with depth. And if $\eta_{\rm sp}$ is equal to 2, then the lateral field decreases linearly with depth. According to El-Mansy and Boothroyd [3] a value of about three is suitable for $\eta_{\rm sp}$ in the present situation.

Equations (3) and (4) are substituted in equation (2), and then the analysis proceeds in an identical fashion to that by Ko [1]. The analysis results in the following differential equation

$$\frac{dE_s(y')}{dy'} = \frac{(V_{\rm CS}(y') - V_{\rm D1})}{\lambda^2} \tag{5}$$

where $\lambda^2 = \varepsilon_{\rm si} t_{\rm ox} x_1 / \varepsilon_{\rm ox} \eta_{\rm sp}$ and $V_{\rm D1}$ is the channel voltage at the boundary between the source and drain sections. Applying the boundary conditions, $E_s(y' = 0)$ = the critical field, E_c, and $V_{\rm CS}(y' = 0) = V_{\rm D1}$, equation (5) can be solved producing a set of equations identical to the ones presented by Ko [1] except for the expression for λ (in [1], $\lambda^2 = \varepsilon_{\rm si} t_{\rm ox} x_j / \varepsilon_{\rm ox} \eta_{\rm sp}$, where x_j is the junction depth and $\eta_{\rm sp} \cong 1$). The equations express the field and potential distribution in the drain section and thus can be used to model hot electron effects. The equations also provide a relationship between $V_{\rm D1}$ and ΔL needed in the calculation of the drain current in saturation.

Let us now consider the second possibility. The assumptions stated before Fig. 1 still apply, except for the one associated with Side 4 of the Gaussian box. We apply Gauss' law to the Gaussian box with sides 1, 2, 3′, and 4. Sides 1, 2, 3′ are as shown in Fig. 1; however, side four is located at the back Si/$\rm SiO_2$ interface now. Gauss' law yields

$$\begin{aligned} &\varepsilon_{\rm si} \int_0^{t_{\rm si}} E_y(x, y'=0)\, dx - \varepsilon_{\rm si} \int_0^{t_{\rm si}} E_y(x, y')\, dx \\ &\quad - \varepsilon_{\rm ox} \left\{ \int_0^{y'} E_{\rm ox}(0, k)\, dk + \int_0^{y'} E_{\rm BOX}(t_{\rm si}, k)\, dk \right\} \\ &= -qN_A t_{\rm si} y' - qN_m t_{\rm si} y' \end{aligned} \tag{6}$$

where $E_{\rm BOX}$ is the buried oxide (BOX) field. Differentiating equation (6) with respect to y', we have

$$\begin{aligned} &- \varepsilon_{\rm si} \frac{d}{dy'} \int_0^{t_{\rm si}} E_y(x, y')\, dx - \varepsilon_{\rm ox} \\ &\quad \cdot \left[E_{\rm ox}(0, y') + E_{\rm BOX}(t_{\rm si}, y') \right] \\ &= -qN_A t_{\rm si} - qN_m t_{\rm si}. \end{aligned} \tag{7}$$

To proceed further in the analysis, expressions for $\int_0^{t_{\rm si}} E_y(x, y')\, dx$, $E_{\rm ox}(0, y')$, and $E_{\rm BOX}(t_{\rm si}, y')$ are needed. $E_{\rm ox}(0, y')$ is given by equation (3). $E_{\rm BOX}(t_{si}, y')$ is given by

$$E_{\rm BOX}(t_{\rm si}, y') = \frac{V_{\rm GSb} - V_{\rm FBb} - \phi_{\rm sb}(y')}{t_{\rm BOX}} \tag{8}$$

where the b subscript in $V_{\rm GSb}$, $V_{\rm FBb}$, and $\phi_{\rm sb}$ signifies back gate voltage, flatband voltage, and surface potential, respectively. To simplify (8), $\phi_{\rm sb}(y')$ needs to be written in terms of the front surface potential, $\phi_s(y')$. This can be done by realizing that the perfectly vertical $\rm n^+$/p junction coupled with the thick (compared to the Si film), charge-free BOX causes the field in the drain section to be very lateral and uniformly distributed from $x = 0$ to $x = t_{\rm si}$. We verified this using MEDICI simulations, which showed that the equipotential contours are practically vertical in the drain section. Thus, $\phi_{\rm sb}(y') = \phi_s(y') = 2\phi_F + V_{\rm CS}(y')$ is substituted in equation (8).

The expression for $\int_0^{t_{\rm si}} E_y(x, y')\, dx$ is analogous to (4) except for the replacement of x_1 with $t_{\rm si}$. Since as explained above the lateral field is uniform with depth, a value of one suitable for $\eta_{\rm sp}$. The expressions for $\int_0^{t_{\rm si}} E_y(x, y')\, dx$, $E_{\rm ox}(0, y')$, and $E_{\rm BOX}(t_{\rm si}, y')$ are substituted in (7), and then the analysis proceeds in an identical fashion to that by Ko [1]. The analysis results in a differential equation identical to (5) except for the expression for λ. λ^2 is now given by $\lambda^2 = \varepsilon_{\rm si} t_{\rm si} / \eta_{\rm sp} \varepsilon_{\rm ox} (1/t_{\rm ox} + 1/t_{\rm box})$.

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