Undoped-body MOSFET Modeling: Explicit Analytic Solution of Surface Potential and a Definition of Threshold Voltage

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***Abstract*—In this work we present a highly accurate, single-piece, explicit analytic solution of the surface potential as a function of the gate voltage for the particular case of undoped (or lightly doped) body. This solution is continuously valid for all regions of operation. Considering that the widely accepted traditional definition of threshold voltage, based on the bulk Fermi potential, is totally meaningless for devices with undoped channel regions, and in view of the ambiguity that other definitions introduce, we propose here a new unambiguous analytic definition for the threshold voltage of undoped-body devices. This definition ensues from the mathematical description underlying the concept of the transition from the subthreshold region to the superthreshold region. The resulting surface potential equation and the threshold voltage definition are both expressed by means of the Lambert *W* function. An approximation for the -1 branch of the Lambert *W* is proposed and used to present an approximate logarithmic expression for the threshold voltage.**

***Index Terms*—MOSFET compact model, Surface potential, Undoped body, Intrinsic channel, Threshold voltage, Lambert function approximation.**

I. Introduction

THE effectiveness of integrated circuit design depends strongly on the accuracy and complexity of the models used for simulation [1]. Traditional regional compact MOSFET models present serious problems with their description precision around the transition from the subthreshold region to the superthreshold region [2]. This transition is becoming increasingly important in light of the continuing downscaling of the dimensions and downsizing of the terminal voltages. On the other hand, surface potential-based compact models, which continue to receive growing attention, contain increased physical descriptions and are among the most accurate models available. They offer the advantage over the regional modeling approach of being capable of producing single-piece continuous portrayals of the drain current and its derivatives, valid throughout all regions of operation. Precise description of at least up to the third order derivative with respect to the bias voltages is of paramount importance, among other reasons, for performing correct distortion analysis.

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A. Channel Surface Potential

Quasistatic surface potential-based models require that the channel surface potential be expressed in terms of the terminal voltages. Unfortunately, in the usual case of doped-body devices, the surface potential is related to the gate voltage by a well known transcendental equation that does not have a closed-form exact analytic solution. Therefore the surface potential is commonly obtained either by cumbersome numerical iteration, or by using some approximate solution [3],[4]. In either case, accuracy [5] or computational efficiency can be seriously compromised, making such an otherwise desirable model frequently unattractive from a practical point of view. However, for the particular case of undoped (or lightly doped) body, it is in fact possible to write a highly accurate analytic expression of the surface potential as an explicit function of the terminal voltages. Such solution will be deduced, presented and verified in the next section.

The solution uses the principal branch of the Lambert *W* function [6], a special function which cannot be expressed in terms of elementary functions, and is defined as the solution to the equation $W(x)\exp[W(x)]=x$. The Lambert *W* function has already proved its usefulness in numerous physics applications [7]. It has also been used recently for finding the solutions to several previously unsolved but basic diode [8] and bipolar transistor circuit analysis problems [9], and it can be found already incorporated into some circuit simulation tools. It is our hope that the explicit solution that is proposed here could result useful in the formulation of next generation surface potential-based compact models of advanced MOSFETs that take advantage of using an undoped-body.

B. Threshold Voltage

Although the threshold voltage is the most important device parameter for the design, modeling, simulation and utilization of MOSFETs [1],[2], its value is dependant upon its definition, which unfortunately is not always clearly stated when referring to this parameter. It is common in the literature to define the threshold voltage from a phenomenological point of view, as the gate voltage at which the surface potential at the Si-SiO_2 interface becomes twice the bulk Fermi potential of the semiconductor body [1],[2].

Attempts have been made in the past to improve this definition for doped devices [2],[10]. For example, a new definition was proposed [11] to improve the accuracy of the V_T model for long-channel devices, but its improvement is less significant for MOSFETs with a channel length in the sub-micron range. A general graphical definition of threshold for uniformly doped-body short-channel devices was proposed [12] as being the intersection of the two asymptotic equations of the surface potential versus gate voltage that dominate in the depletion and strong inversion regions. Other types of functional definitions exist for the threshold voltage [13], such as the *de facto* industry standard known as the "constant current definition" based on the flow of a given pre-established level of drain current, or another closely related "critical current at threshold" that has been recently proposed for deep-submicron MOSFETs [14].

C. Undoped-body MOSFETs

The level of miniaturization that is being reached in modern devices is causing the emergence of significant fluctuations of the devices characteristics, especially regarding the threshold voltage, due to the inherent randomness of dopant impurity locations within the reduced length of the channel [15]. A proposed solution to this problem consists on using an undoped (or lightly doped) body to sustain the channel. This idea, sometimes referred to as "intrinsic channel," has been implemented in V-groove [16], double-gate SOI [17], and several kinds of epitaxial channel [18],[19] MOSFETs. In this increasingly important situation of MOSFETs with undoped channel regions, it is obvious that the traditional and widely accepted definition of threshold voltage, based on the bulk Fermi potential, becomes meaningless [20].

It has been suggested [3] to define the threshold voltage of these devices as the gate voltage that produces a certain preestablished constant value of mobile charge in the channel. Although this definition is quite simple, it depends on the arbitrary choice of the predetermined value, as does the traditional constant-current definition. Considering the inherent ambiguity that these definitions introduce, we will propose in Section 3 a new unambiguous analytic definition for the threshold voltage of undoped-body long-channel devices. It follows a previously proposed graphical definition of the threshold voltage of doped body devices [12]. The novel definition is based on the mathematical description underlying the concept of the transition from the subthreshold region to the superthreshold region.

The resulting threshold voltage is expressed by means of the -1 branch of the Lambert W function, which is later simplified to a more familiar logarithmic approximate expression. Second order considerations, such as Fermi-Dirac carrier distribution and quantum-mechanical effects [21], are neglected in the present study for the sake of simplicity. Their exclusion however should not affect the general validity of the conclusions, and it is possible to incorporate them without loss of generality for applications where they are significant.

II. Expression for the Surface Potential

A. Gate Voltage in terms of the Surface Potential

Charge-sheet analysis indicates that the relationship between the potential at the channel's Si-SiO_2 interface of an enhancement MOSFET and the voltage at its gate, assuming zero drain-to-source and source-to-body voltages, can be expressed by the well known equation [1],[2]:

$$\left(V_{GS} - V_{FB} - \psi_S\right)^2 = \frac{\varepsilon_s^{\,2}}{C_o^{\,2}} F^2(\psi_S) \ , \qquad (1)$$

where V_{GS} is the gate-to-source voltage, V_{FB} is the flat-band voltage, determined mainly by the gate material-to-semiconductor work function difference if we neglect interface trap charges, ψ_S is the surface potential at the Si-SiO_2 interface, C_o is the gate-oxide capacitance per unit area, ε_s is the permittivity of the semiconductor, and F is the Kingston function defined by [1]:

$$F^2\left(\psi_S\right) \equiv \frac{2}{\beta^2 L_D^2}\left[e^{-\beta\psi_S} + \beta\psi_S - 1 + \frac{n_0}{p_0}\left(e^{\beta\psi_S} - \beta\psi_S - 1\right)\right] . \quad (2)$$

Here, $\beta = q/kT$ is the inverse of the thermal voltage, n_0 and p_0 are the equilibrium electron and hole concentrations, and L_D is the Debye length. Since we are considering the case of channel enhancement in an undoped body, the equilibrium electron and hole concentrations are equal to the intrinsic carrier density ni. In that case the intrinsic Debye length is

$$L_D^{\,2} = \frac{\varepsilon_s}{q\,\beta\,n_i} \ . \qquad (3)$$

Therefore, substituting $n_0 = p_0 = n_i$, (2) and (3) into (1) yields

$$\left(V_{GS} - V_{FB} - \psi_S\right)^2 = \frac{2q\,\varepsilon_s\,n_i}{\beta\,C_o^{\,2}}\left[e^{-\beta\psi_S} + e^{\beta\psi_S} - 2\right] . \quad (4)$$

Taking the square root of this equation and expressing the exponential functions in terms of hyperbolic functions yields the equation that describes the gate voltage as a function of the channel surface potential for all regions of operation of an undoped body device:

$$V_{GS} - V_{FB} - \psi_S = \mathrm{sgn}\left(\psi_S\right)\frac{2\sqrt{kT\,\varepsilon_s\,n_i}}{C_o}\sqrt{\cosh\left(\beta\psi_S\right) - 1} \ . \quad (5)$$

In this equation the $\mathrm{sgn}(\psi_S)$ indicates that a minus sign is used when the bands bend up and a plus sign when the bands bend down. If we wish to circumvent the burden of changing signs during the calculation, we may use the following half-angle trigonometric identity

$$\sinh\left(\frac{\alpha}{2}\right) \equiv \pm\sqrt{\frac{1}{2}\left[\cosh\left(\alpha\right)-1\right]} \ , \qquad (6)$$

to get a more convenient equation continuously valid for any band bending:

$$V_{GS} - V_{FB} = \psi_S + \frac{2\sqrt{kT\,\varepsilon_s\,n_i}}{C_o}\sqrt{2}\,\sinh\left(\frac{\beta\psi_S}{2}\right) \ . \qquad (7)$$

In the classical uniformly doped-body case, the presence of space charge from ionized dopant atoms in the depletion region introduces additional surface potential terms under the square root of the RHS of the analogous to equation (5), which prevents obtaining an analytical solution of the surface potential in terms of the gate voltage. Fortunately this is not the case when the body is undoped and such a solution is indeed possible.

B. *Surface Potential as an explicit function of Gate Voltage*

The general form of equation (7) may be represented as

$$x = y + c\sinh(b\,y) \ , \qquad (8)$$

which can be solved explicitly in terms of the Lambert *W* function to yield the following approximate expression:

$$y = \frac{1}{b}W\left[\frac{cb}{2}e^{-b\,x}\right] - \frac{1}{b}W\left[\frac{cb}{2}e^{b\,x}\right] + x \ , \qquad (9)$$

where *W* is the usual short-hand notation for the principal branch of the "Lambert-*W*" function. Equation (9) represents a novel analytic solution to equation (8), which although not exact, it is however highly accurate for the problem at hand.

We can apply (9) to solve for the surface potential in (7) and get:

$$\psi_S = -\frac{2}{\beta}W\left(\frac{1}{4}\beta\,V_o\sqrt{2}\ e^{\frac{\beta(V_{GS}-V_{FB})}{2}}\right) + \frac{2}{\beta}W\left(\frac{1}{4}\beta\,V_o\sqrt{2}\ e^{-\frac{\beta(V_{GS}-V_{FB})}{2}}\right) + V_{GS} - V_{FB} \qquad (10)$$

where

$$V_o = \frac{2\sqrt{kT\,\varepsilon_s\,n_i}}{C_o} \ . \qquad (11)$$

It should be emphasized that (10) constitutes a highly accurate and continuous solution of the surface potential in the full range of downward (enhancing an *n*-type channel) and upward band-bending (enhancing a *p*-type channel) for the case of an undoped (or lightly doped) body. If we are just interested in either an *n*-type or a *p*-type channel, we need only consider the corresponding positive or negative surface potentials. For example, for an *n*-type channel device, reverting (7) to exponential form and assuming $\psi_S >> 1/\beta$ we may ignore the exponential with the negative exponent and the implicit "-1" term to get

$$V_{GS} - V_{FB} = \psi_S + \frac{V_o}{\sqrt{2}}e^{\frac{\beta\psi_S}{2}} \ , \qquad (12)$$

which has the following exact analytic solution:

$$\psi_S = -\frac{2}{\beta}W\left(\frac{1}{4}\beta\,V_o\sqrt{2}\ e^{\frac{\beta(V_{GS}-V_{FB})}{2}}\right) + V_{GS} - V_{FB} \ . \qquad (13)$$

Strictly speaking (13) is not truly "exact" because of the simplifications that were made before attempting the solution. The "-1" term is added to the exponential only to ensure that $V_{GS} - V_{FB}$ becomes zero when the surface potential goes to zero, but neglecting it only introduces a small error around the origin. If an accurate solution is needed also around the origin, it is easy to see that the inclusion of the "-1" term modifies the solution to

$$\psi_S = -\frac{2}{\beta}W\left(\frac{1}{4}\beta\,V_o\sqrt{2}\ e^{\frac{\beta(V_{GS}-V_{FB})}{2}+\frac{V_o}{\sqrt{2}}}\right) + V_{GS} - V_{FB} + \frac{V_o}{\sqrt{2}} \ . \qquad (14)$$

Clearly the additional terms in (14) are insignificant, except when $V_{GS} - V_{FB}$ approaches zero. It might be then preferable to use (13) whenever not interested in getting exact values around the origin. This solution of the surface potential in the range of downward band-bending (*n*-type channel) has, of course, an analogous counterpart for upward band-bending (*p*-type channel).

III. A Definition for the Threshold Voltage of Undoped-body Devices

We propose here a definition for threshold that takes into consideration the asymptotic behavior of the two surface potential functions that describe both the subthreshold and superthreshold regions. In spite of the undoped-body, we will still refer to these two regions as the weak and strong "inversion" regions of operation, to maintain the analogy to classical doped-body devices.

Recalling (12) for the *n*-channel device and considering the corresponding dominant terms for each bias condition, we can obtain the following two asymptotic equations at the two distinct regions of operation:

$$V_{GS} - V_{FB} \approx \frac{V_o}{\sqrt{2}} e^{\frac{\beta\psi_S}{2}}, \tag{15}$$

for the superthreshold (strong inversion) region, and

$$V_{GS} - V_{FB} \approx \psi_S, \tag{16}$$

for the subthreshold (weak inversion) region. The same argument about the absence of the "-1" term in (15) could also be made here, but in this case it would be pointless to include it, since we are interested in the threshold voltage and not in values around the origin.

We propose that the onset of strong inversion, that we call the "threshold," lies at the transition point where strong inversion behavior, as described by asymptotic equation (15), begins to dominate over weak inversion behavior, as described by asymptotic equation (16). In other words, it is the point where the surface potential crosses over from linear-like to logarithmic-like behavior with respect to the gate voltage. Accordingly, the intersection of the two asymptotic equations, (15) and (16), gives a value of V_{GS} which is not only convenient but also physically meaningful for defining the threshold voltage, V_T, of the undoped body MOSFET.

Following the above idea, the new analytic definition for the threshold voltage (henceforth referred to as "the asymptotic V_T") of undoped-body long-channel MOSFETs is obtained by solving equations (15) and (16) :

$$V_T = V_{FB} - \frac{2}{\beta} W_{-}\left(-\frac{\beta V_o \sqrt{2}}{4}\right), \tag{17}$$

where the symbol W_{-} represents the -1 branch of the Lambert W function. It might be noted that there is another solution, corresponding to the principal branch of the Lambert W function, given by:

$$V_T = V_{FB} - \frac{2}{\beta} W\left(-\frac{\beta V_o \sqrt{2}}{4}\right), \tag{18}$$

which must be discarded as physically unreasonable. The corresponding value of surface potential at threshold may be found if needed by substituting (17) into (13).

Although (17) is a sufficiently simple expression, it might be desirable for quick hand calculations to be able to use an approximate expression in terms of elementary analytic functions. Several approximations have been proposed for the branches of the Lambert W function [7], [9]. We propose to use the following convenient approximation for the negative branch of the Lambert W valid at very small negative values of the argument:

$$W_{-}(x) \approx \ln\left[\frac{x}{\ln(-x)}\right]. \tag{19}$$

Replacing (19) for the negative branch of the Lambert W function in (17) we obtain an approximate logarithmic expression for the threshold voltage:

$$V_T = V_{FB} - \frac{2}{\beta} \ln\left[\frac{-\frac{\beta V_0 \sqrt{2}}{4}}{\ln\left(\frac{\beta V_0 \sqrt{2}}{4}\right)}\right]. \tag{20}$$

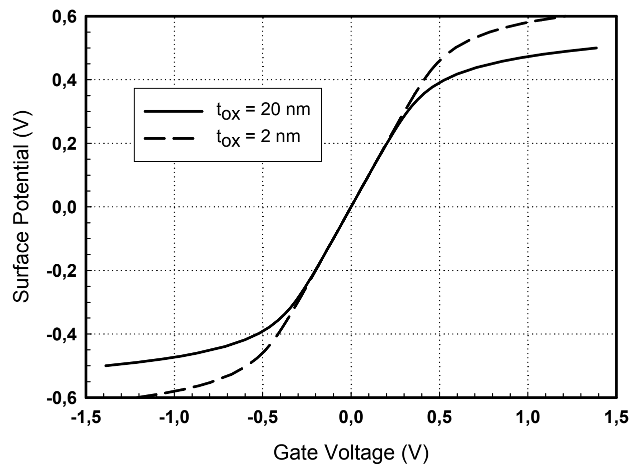

Fig. 1 - Surface potential as a function of gate voltage calculated with (10) for an undoped-body long channel MOSFET, for two gate-oxide thicknesses, assuming zero flat-band and drain-to-source voltages.

IV. Discussion

Figure 1 presents the surface potential, ψ_S , versus gate voltage, V_{GS} , characteristics obtained from equation (10) for an undoped-body long n-channel MOSFET, with two gate-oxide thickness of 2 and 20 nm, assuming zero flat-band and drain-to-source voltages. Figure 2 shows the surface potential, ψ_S , versus positive gate voltage, V_{GS} , as obtained with equations (13) or (14) for a gate-oxide thickness of 2 nm. Also presented are the two superthreshold and subthreshold asymptotic equations of ψ_S, (15) and (16), corresponding to the strong and weak inversion regions. The projection of the intersection to the V_{GS}-axis graphically describes the threshold voltage of the device (denoted as "Asymptotic V_T" in the figure).

The value of V_T graphically indicated here by this asymptotic definition coincides with the value of 0.599V calculated using (17). The corresponding value of the surface potential at threshold is 0.504V found by substituting the calculated V_T into (13).

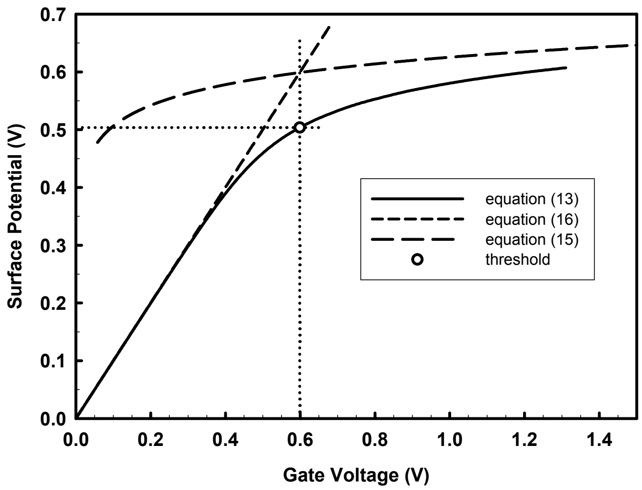

Fig. 2 Surface potential versus positive gate voltage, V_{GS} , as obtained with equations (13) for a gate-oxide thickness of 2 nm. Also presented are the two superthreshold and subthreshold asymptotic behaviors, (15) and (16). The projection of the intersection to the horizontal axis graphically defines the "Asymptotic Threshold Voltage" with a value of 0.599V for this device.

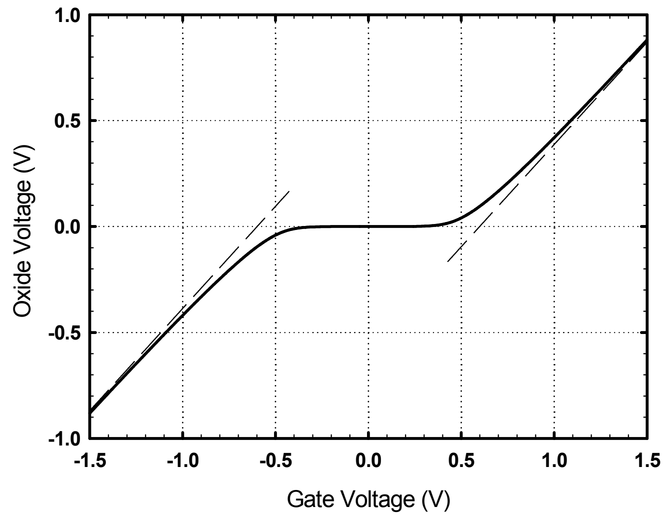

Fig. 3 Voltage drop across the gate-oxide as a function of negative and positive applied gate voltage for an oxide thickness of 2 nm, assuming zero flat-band and drain-to-source voltages, as calculated using (10). Also shown are the linear extrapolations whose intersections with the gate voltage axis indicate positive and negative threshold voltages of $\pm$ 0.599V.

The carrier charge per unit area induced in the channel is the total charge in the semiconductor, Q_S , which can be obtained from (10), if interface trap charges are neglected:

$$\frac{Q_S}{C_0} \equiv V_{ox} = \left(\psi_S - V_{GS} + V_{FB}\right) = \\ -\frac{2}{\beta} W\left(\frac{1}{4}\beta V_o \sqrt{2}\ e^{\frac{\beta(V_{GS}-V_{FB})}{2}}\right) + \\ \frac{2}{\beta} W\left(\frac{1}{4}\beta V_o \sqrt{2}\ e^{-\frac{\beta(V_{GS}-V_{FB})}{2}}\right) \quad . \qquad (21)$$

It should be remembered that, for simplicity's sake, the original formulation is based on Maxwell-Boltzmann, not on Fermi-Dirac, charge distribution statistics. Thus, calculated surface potential values near $E_g/2q$ are not exactly accurate, but this consideration should not greatly affect the validity of the present results for gate oxide thicknesses > 2nm.

Figure 3 presents the gate-oxide voltage, V_{ox}, versus the applied gate voltage, for an oxide thickness of 2 nm, assuming zero flat-band voltage, zero drain-to-source voltage, and zero oxide charge, as calculated by (21). When multiplied by the gate capacitance per unit area, C_0, this plot also represents the carrier charge per unit area, Q_S , induced in the channel.

The curves of Figs. 1 and 3 evidence the symmetric nature of the channel (*n* or *p*) enhancement mechanism. The expected linear increase of the carrier charge-sheet density with gate voltage is clearly seen in Fig. 3, at values well above the threshold voltage.

Figure 3 indicates that the intersections of the linear extrapolations with the gate voltage axis, indeed produce the same threshold voltage value of 0,599V, for the 2nm oxide thickness device. This is equivalent to the traditional conceptual definition of threshold voltage as the gate voltage at which the inversion charge goes to zero. The values shown match very well the value calculated by the asymptotic-V_T definition of (17). Furthermore, the linear extrapolation of the drain current versus gate bias characteristic, simulated with a 2D device simulator, produces [22] an almost identical value of threshold voltage as calculated with (17).

The dependence of the threshold voltage on gate-oxide thickness, as calculated using (17) is presented in Fig. 4. The resulting plot confirms that the threshold voltage of undoped-body devices, as described by this asymptotic-V_T definition, decreases essentially as a linear function of the logarithm of oxide thickness.

This behavior, although atypical in highly doped body devices, is what should be expected for undoped-bodies. We have also confirmed that it occurs even for lightly doped bodies, for doping concentrations of less than about 10^{15}cm^{-3}, above which level the conventional behavior is again exhibited.

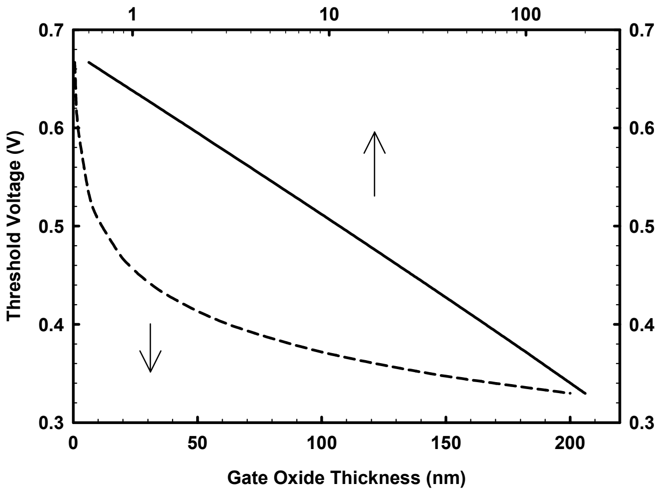

Fig. 4 Logarithmic and linear representations of the Threshold Voltage dependence on Gate Oxide Thickness, as calculated using (17).

V. Conclusions

Short channel SOI MOSFETs with undoped body have received great attention recently. As a first step in studying these devices, we have developed a highly accurate analytic solution of the surface potential as an explicit function of the gate voltage for bulk MOSFETs with undoped body. This solution is continuously valid for all regions of operation and is based on Lambert *W* functions.

We have also presented a new approach for defining the threshold voltage, which is based on finding the intersection of the surface potential versus gate voltage asymptotic equations for the so-called weak and strong inversion regions. The resulting new definition is also expressed in terms of the Lambert *W* function.

It has been shown that this threshold voltage defined by such intersection matches the values of V_T determined by extrapolating the carrier charge-sheet density to zero. This definition of V_T results in general a better one than the values predicted by conventional or other modified definitions. The proposed asymptotic approach therefore promises a more dependable means to define the threshold voltage of modern undoped-body MOSFET devices.

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