



A procedure for the extraction of the bulk-charge effect parameter in MOSFET models

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Abstract

A technique is proposed to extract the bulk-charge effect parameter from the triode region of operation of the MOSFET characteristics. The method involves making two measurements of drain current as a function of gate voltage at two small values of the drain voltage. The procedure was tested on synthetic I_d - V_{gs} characteristics modeled with SPICE and simulated by a 2D device simulator. It was also applied to measured I_d - V_{gs} characteristics of real devices. Both constant and normal field dependent mobilities were considered for comparison. Very good agreement is obtained between the parameters used in modeling and simulation and the extracted values. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Channel depletion thickness in strong inversion is not uniform along the channel of MOSFETs causing the threshold voltage to vary and become dependent on the channel potential. This is what is known as the bulk-charge effect [1]. Accordingly, compact models that are used with SPICE-like circuit simulators frequently portray the intrinsic I - V characteristics of a MOSFET, at zero substrate bias, in strong inversion within the linear (triode) region by an expression of the form [2].

$$I_d = K \left(V_{GS} - V_{th} - \frac{\alpha}{2} V_{DS} \right) V_{DS} \quad (1)$$

where K is a function of the normal and longitudinal fields that includes the gate capacitance per unit area,

the effective (W/L) size and the effective mobility of the channel, V_{th} is the intrinsic threshold voltage and V_{GS} and V_{DS} are the intrinsic gate and drain to source voltages, respectively, defined in terms of their extrinsic (external) counterparts, V_{gs} and V_{ds} , by

$$V_{GS} = V_{gs} - I_d R_S, \quad (2)$$

and

$$V_{DS} = V_{ds} - I_d (R_S + R_D), \quad (3)$$

where R_S and R_D are the source and the drain series resistances. Parameter α accounts for the bulk-charge effect, which depends on the channel length and width and on substrate bias and has a value close to unity,

$$\alpha = 1 + \gamma \delta, \quad (4)$$

where γ is the body factor and δ is the square-root approximation factor in the bulk charge [3,4]. Parameter α is termed 'ALPHA' in AIM-SPICE models [5], ' α ' in

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BSIM1 and BSIM2 models [6] and A_{bulk} in the newer BSIM3v3 model [1].

2. Methodology

In order to extract the parameter α , two threshold characteristics [7] of the MOSFET, I_{d1} and I_{d2} , are measured versus gate voltage V_{gs} , in the linear region with zero substrate bias, at two small constant values of applied drain voltage, V_{ds1} and V_{ds2} , respectively. The relationship between the two applied drain voltages is set such that the second drain voltage is equal to some multiple value of the first,

$$V_{ds2} = mV_{ds1}. \quad (5)$$

Substituting Eqs. (2) and (3) into Eq. (1) and evaluating at the two drain voltages, V_{ds1} and V_{ds2} , yields the two expressions, I_{d1} and I_{d2} , as a function of voltage V_{gs} :

$$I_{d1} =$$

$$K \left\{ [V_{gs} - I_{d1}R_S] - V_{th} - \frac{\alpha}{2}[V_{ds1} - I_{d1}(R_S + R_D)] \right. \\ \left. \times [V_{ds1} - I_{d1}(R_S + R_D)] \right\}, \quad (6)$$

$$I_{d2} =$$

$$K \left\{ [V_{gs} - I_{d2}R_S] - V_{th} - \frac{\alpha}{2}[mV_{ds1} - I_{d2}(R_S + R_D)] \right\} \\ \times [mV_{ds1} - I_{d2}(R_S + R_D)]. \quad (7)$$

Let V_{gs1} and V_{gs2} be the respective gate voltage values that make $I_{d1} = I_{d2}/m$. Then, equating Eq. (6) to Eq. (7) divided by the factor m yields

$$\frac{K_1}{K_2} = \frac{\{[V_{gs2} - mI_{d1}R_S] - V_{th} - (\alpha/2)[mV_{ds1} - mI_{d1}(R_S + R_D)]\}}{\{[V_{gs1} - I_{d1}R_S] - V_{th} - (\alpha/2)[V_{ds1} - I_{d1}(R_S + R_D)]\}}, \quad (8)$$

where V_{gs1} and V_{gs2} are the gate voltages corresponding to the same $I_{d1} = I_{d2}/m$ and K_1 and K_2 are the values of K at V_{gs1} and V_{gs2} . Assuming for the time being that the variation of K can be neglected by letting $K_1 = K_2$ and solving Eq. (8) for parameter α results in the expression

$$\alpha = 2 \frac{(V_{gs2} - V_{gs1})}{(m-1)V_{ds1}} - 2 \frac{I_{d1}}{V_{ds1}} \left[\left(1 - \frac{\alpha}{2}\right)R_S - \frac{\alpha}{2}R_D \right]. \quad (9)$$

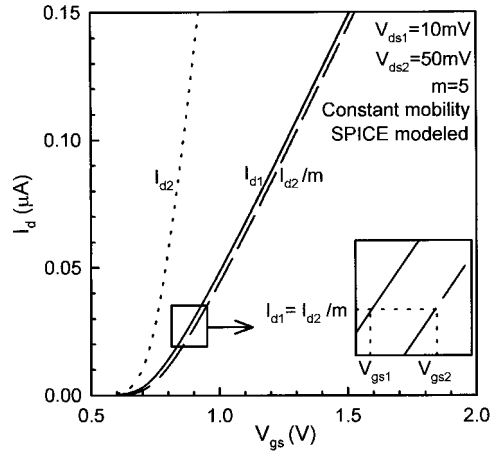


Fig. 1. Threshold characteristics of an AIM-SPICE modeled constant mobility n-channel MOSFET at $V_{ds1} = 10$ mV and $V_{ds2} = 50$ mV ($m = 5$). Also shown is the I_{d2}/m curve.

Since α is close to one, Eq. (9) can be approximated by

$$\alpha \approx \frac{2(V_{gs2} - V_{gs1})}{(m-1)V_{ds1}} - \frac{I_{d1}}{V_{ds1}}[R_S - R_D]. \quad (10)$$

The second term becomes zero for symmetric devices and it is in general negligible in comparison to the first for non-symmetric devices. Therefore, the bulk-charge effect parameter α can be obtained from

$$\alpha \approx \frac{2(V_{gs2} - V_{gs1})}{(m-1)V_{ds1}}. \quad (11)$$

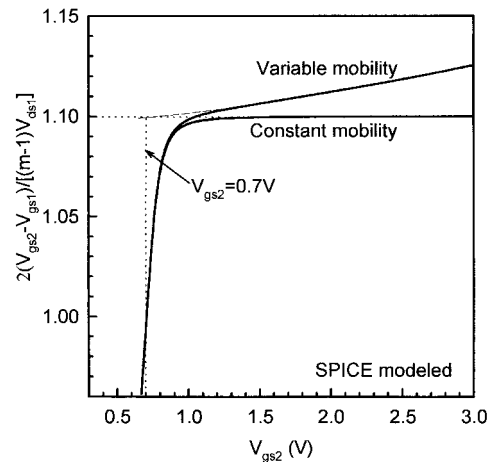


Fig. 2. Plot of Eq. (11) for two n-channel MOSFETs modeled with AIM-SPICE using constant and variable linearly decreasing mobility models [5]. The vertical dotted line represents the value of $V_{gs2} = V_{th} = 0.7$ V, whose intersection with the extrapolation of the linear operation region gives the extracted value of $\alpha = 1.1$, equal to the one used in the model.

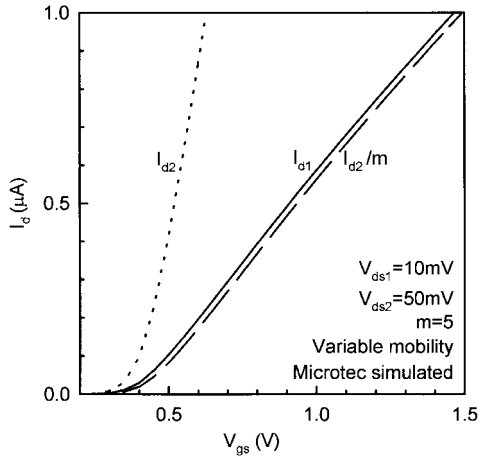


Fig. 3. Threshold characteristics of a variable mobility n-channel MOSFET simulated with a 2D device simulator MICROTEC at $V_{ds1} = 10$ mV and $V_{ds2} = 50$ mV ($m = 5$). Also shown is the I_{d2}/m curve.

This formula is independent of the threshold voltage. Its applicability when the variation of K can not be assumed negligible will be determined later by testing it on variable mobility devices.

3. Procedure validation and discussion

In order to test the effectiveness of the method, synthetic $I_d - V_{gs}$ characteristics were calculated at two small drain voltages, $V_{ds1} = 0.01$ V and $V_{ds2} = 0.05$ V ($m = 5$), in the linear region of a long n-channel MOSFET using an AIM-SPICE Level-8 model, with a threshold voltage of 0.7 V and a bulk-charge effect parameter of 1.1. Both constant and variable mobility models were used in the simulation to test the sensitivity of using Eq. (11) in the procedure, when K varies significantly with V_{GS} . The variable mobility was simulated using a variable linearly decreasing model [5]. Fig. 1 shows for illustration only the $I_d - V_{gs}$ characteristics of the constant mobility device at the two drain voltages, together with the I_{d2}/m curve. Fig. 2 presents the result obtained in both cases by subtracting V_{gs1} from V_{gs2} at equal values of $I_{d1} = I_{d2}/m$ and dividing by 0.04 V, as required by Eq. (11).

The constant mobility curve in Fig. 2 shows a flat portion corresponding to the linear region of operation throughout which $K_1 = K_2$. It clearly indicates a value of $\alpha = 1.1$. In the case of variable mobility, the curve is not flat in the linear region of operation. Fig. 2 illustrates how the value of $\alpha = 1.1$ can be accurately extracted for the variable mobility device by extrapolating the linear operation portion of the plot of Eq. (11) and finding its intersection with the vertical line

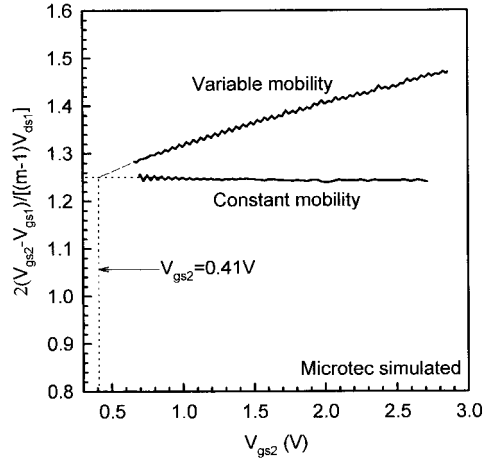


Fig. 4. Plot of Eq. (11) for two n-channel MOSFETs simulated with a 2D device simulator MICROTEC using constant mobility and Yamaguchi's [9] variable mobility model. The vertical dotted line represents the value of $V_{gs2} = V_{th} = 0.41$ V, whose intersection with the extrapolation of the linear operation region gives the extracted value of $\alpha = 1.25$, equal for both constant and variable mobility devices.

corresponding to a value of $V_{gs2} = V_{th} = 0.7$ V, where mobility degradation is negligible.

We next extracted the parameter α of a long n-channel MOSFET simulated with 2D device simulator MICROTEC [8]. We again ran two simulations, one with constant mobility and another with a variable mobility defined by Yamaguchi's model [9]. The resulting $I_d - V_{gs}$ characteristics at the same two drain voltages as before, together with the I_{d2}/m curve, are shown in Fig. 3, only for the variable mobility case.

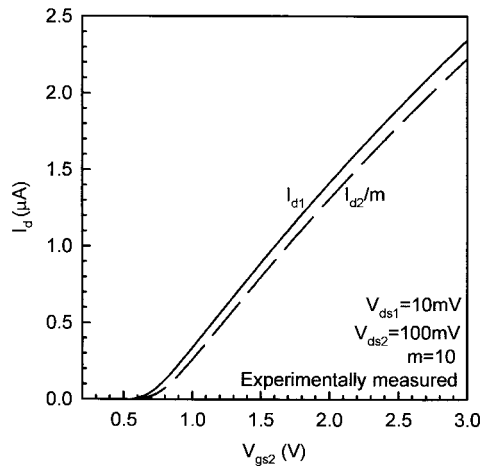


Fig. 5. Experimental threshold characteristics of a 20/20 μm n-channel MOSFET measured at $V_{ds1} = 10$ mV and the I_{d2}/m curve measured at $V_{ds2} = 100$ mV ($m = 10$).

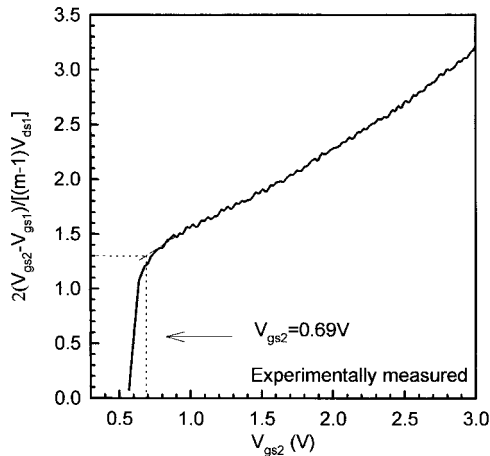


Fig. 6. Plot of Eq. (11) for the device of Fig. 5. The vertical dotted line represents the value of $V_{gs2} = V_{th} = 0.69$ V, whose intersection with the extrapolation of the linear operation region gives the extracted value of $\alpha = 1.3$.

Fig. 4 shows that a value of α of about 1.25 is obtained readily for the constant mobility device from the flat portion of the plot of Eq. (11). In the case of the device simulated with variable mobility, an almost exact value for α is extracted from Fig. 4, as before, from the intersection of the extrapolated linear operation portion of the curve and the vertical line corresponding to a value of $V_{gs2} = V_{th} = 0.41$ V, which was previously extracted for this device using standard methods [10].

As a final test, the extraction procedure was applied to real devices fabricated at Harris Semiconductor. Fig. 5 presents the I_d - V_{gs} characteristics of a 20 μm wide, 20 μm long n-channel MOSFET, measured at drain voltages of 10 and 100 mV. The second current has been already divided by the factor of $m = 10$. The result of Eq. (11) is presented in Fig. 6. Following an analogous procedure as before, a value of $\alpha = 1.3$ is extracted from the intersection of the extrapolated linear operation portion of the curve and the vertical line corresponding to a value of $V_{gs2} = V_{th} = 0.69$ V, previously extracted using standard methods [10].

4. Conclusion

The proposed procedure represents a simple way to extract the bulk-charge effect parameter of MOSFET models from the device's I_d - V_{gs} threshold characteristics in the linear region of operation. The procedure was positively validated by comparing the values extracted from I_d - V_{gs} characteristics modeled with SPICE to the known bulk-charge effect parameter used in the model. It was also shown that it is possible to extract the correct value of α when the channel mobility is significantly variable. Additionally, we have successfully tested the method using 2D simulations, with both constant and variable mobility models and by applying it to measured characteristics of real devices.

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