On the extraction methods for MOSFET series resistance and mobility degradation using a single test device


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***Abstract*—Parasitic series resistances and mobility degradation are limiting the development of advanced MOSFETs. We review, scrutinize, and critically compare five parameter extraction methods that use DC data measured from a single test device. The use of a single device facilitates individual characterization and avoids the impact of device-to-device model parameter variation that affects other common methods that require using measurements from arrays of transistors with several different geometries.**

***Index Terms*— MOSFET, parameter extraction, Mobility degradation, Parasitic series resistance.**

I. INTRODUCTION

THE presence of source-and-drain series resistance and mobility degradation in MOSFETs produce similar effects on their drain current-gate voltage $I_D(V_{GS})$ transfer characteristics. Various specialized books and review articles have explained and analyzed this topic [1-10], and several procedures have been proposed and reported to extract the values of the parameters that correspond to these two effects in MOSFET compact models [11-35]. We recently published a novel method that allows extracting the total series resistance and the mobility degradation of a single test device from DC measurements [34]. We have also described and critically reviewed several of the diverse methods that exist for extracting the values of these two important model parameters for MOSFET functional description [4,10].

We will examine here five methods for extracting the values of the series resistance and the mobility degradation parameters of MOSFET models that use drain current-gate voltage $I_D(V_{GS})$ transfer characteristics and drain current-drain voltage $I_D(V_{DS})$ output characteristics measured from a single test device.

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II. PARAMETER EXTRACTION METHODS

The above-threshold drain current of MOSFETs operating in the so-called triode region may be essentially modeled in general by a simple equation of the form [22]:

$$I_D = \frac{W}{L_{eff}} \mu_{eff} C_{ox} \left(V_{gs} - V_T - \frac{V_{ds}}{2} \right) V_{ds} \quad , \tag{1}$$

where W is the channel width, L_{eff} is the effective channel length, μ_{eff} is the V_{gs}-dependent effective mobility, C_{OX} is the gate dielectric capacitance, V_T is the threshold voltage, and the device's intrinsic gate-to-source, V_{gs}, and drain-to-source, V_{ds}, voltages are related to their external counterparts by:

$$V_{gs} = V_{GS} - I_D \frac{R}{2} \quad , \tag{2}$$

$$V_{ds} = V_{DS} - R\, I_D \quad , \tag{3}$$

where V_{GS} is the externally applied gate voltage, V_{DS} is the externally applied drain voltage, R is the total source-and-drain series resistance. In writing (2) and (3), the drain and source resistances are assumed equal ($R/2$). Possible asymmetry between the drain and the source, giving rise to different values of drain and source resistances, can be an important aspect to consider in modern devices and it has been recently studied in [10].

The V_{gs}-dependent degradation of the effective mobility is frequently modeled by an expression of the form [36]:

$$\mu_{eff} = \frac{\mu_o}{1+\theta_1 \left(V_{gs} - V_T\right) + \theta_2 \left(V_{gs} - V_T\right)^2} \tag{4}$$

where μ_o is the low-field mobility, θ_1 and θ_2 are the first and second order gate field (V_{gs}) mobility degradation factors. A commonly used first order (θ_2=0) simplified version of (4) is:

$$\mu_{eff} = \frac{\mu_o}{1+\theta_1 \left(V_{gs} - V_T\right)} \quad . \tag{5}$$

Substitution of (4) into (1) yields:

$$I_D = \frac{K_o \left(V_{gs} - V_T - \frac{V_{ds}}{2} \right) V_{ds}}{\left(1+\theta_1 \left(V_{gs} - V_T\right) + \theta_2 \left(V_{gs} - V_T\right)^2 \right)} \quad , \tag{6}$$

where

$$K_o \equiv \frac{W}{L_{eff}} \mu_o C_{ox} \tag{7}$$

is the so called "low-field transconductance parameter" and L_{eff} is the effective channel length.

III. METHODS BASED ON A SINGLE DEVICE WITH DIFFERENT DRAIN AND GATE BIASES

To illustrate these methods we will use recently published $I_D(V_{DS},V_{GS})$ data [34], measured from an experimental L=80 nm, W=192 µm, 8-fingered MOSFET intended for RF applications, that was fabricated at Imec, Leuven, Belgium [37,38].

To avoid possible inconsistencies among separately measured transfer and output characteristics, the drain current was measured once as a function of both bias variables V_{DS} and $V_{GS.}$ The resulting $I_D(V_{DS},V_{GS})$ characteristics are illustrated in Fig. 1. This was done by measuring a sequence of $I_D(V_{DS})$ at V_{DS} varying from 0 to 1.2 V with increments of 2mV (601 points), while V_{GS} was varied from 0V to 1V in 5 mV steps (201 points). Any 2-D transfer or output characteristics may be plotted in the usual 2-D representation by selecting the appropriate data set, as shown in Fig. 2.

To get $V_{DS}(V_{GS})$ contour plots at constant I_D we applied a simple linear interpolation algorithm to the previously measured $I_D(V_{DS},V_{GS})$ data. Fig. 3 shows $V_{DS}(V_{GS})$ contour plots for several values of I_D of the already described experimental MOSFET. The threshold voltage for small values of drain bias in this case is 0.42 V.

A. Direct fitting of the drain current

Several procedures, based on nonlinear optimization techniques, have been proposed to directly extract the series resistance [15,16,22]. Inserting the bulk-charge factor, α, which accounts for threshold voltage dependence on channel potential due to depletion thickness nonuniformity along the channel [39], into the model described by equations (1) to (3) and (5) yields:

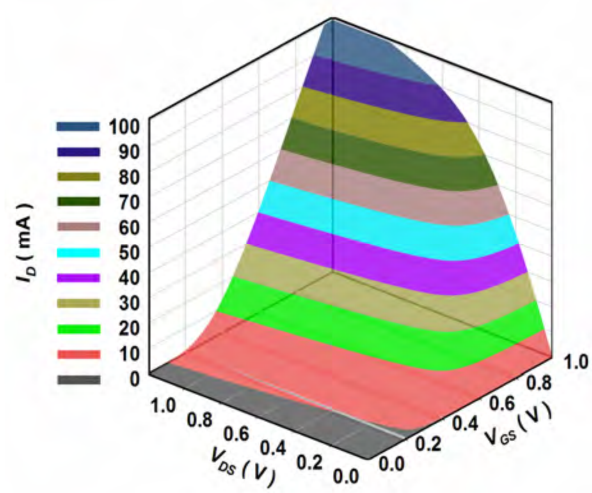

Fig. 1. Tridimensional plot of the measured $I_D(V_{DS},V_{GS})$ characteristics.

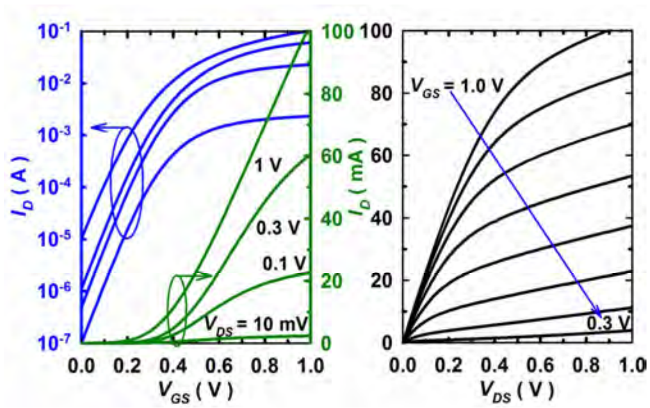

Fig. 2. The traditional presentation of the transfer characteristics, in logarithmic and linear scales, and the output characteristic for the

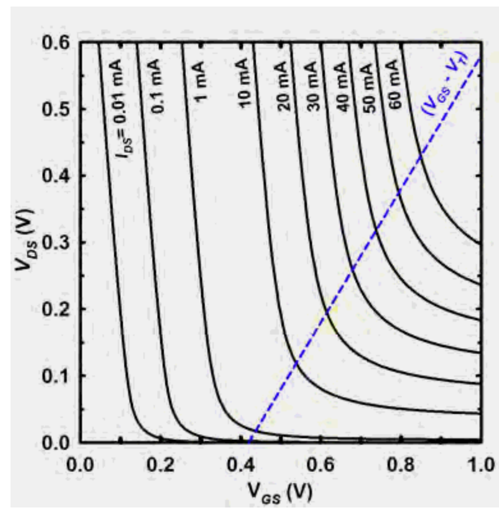

Fig. 3. Contour plots of drain voltage (V_{DS}) versus gate voltage (V_{GS}) for several values of drain current (I_D), as interpolated from measurements of the experimental device. The blue dashed straight line, corresponds to V_{DS}= (V_{GS} - V_T) and thus represents the border between triode and saturation.

$$I_D = \frac{K_o}{1+\theta_1 V_{gsT}} \left(V_{gsT} - \alpha \frac{V_{ds}}{2} \right) V_{ds} \tag{8}$$

where we have used $V_{gsT}=V_{GS}-V_T$ for brevity's sake.

Instead of trying to fit the implicit model represented by equations (2), (3) and (8) directly to the measured *I-V* characteristics, the equations are transformed into an explicit equation [22]. Substituting (2) and (3) into (8), and solving for the drain current, after some algebraic manipulations, an explicit expression for $I_D(V_{GS},V_{DS})$ is obtained [22]:

$$I_D = \frac{V_{DS}}{R_{ON} + \sqrt{R_{ON}^{\ 2} - R_0^{\ 2}}} \tag{9}$$

where

$$R_{ON} \equiv R + \frac{1+\theta_1 V_{GST}}{2K_o \left(V_{GST} - \alpha \frac{V_{DS}}{2} \right)} - \frac{R\left(V_{GST} - \frac{V_{DS}}{2} \right)}{2\left(V_{GST} - \alpha \frac{V_{DS}}{2} \right)} \tag{10}$$

and

$$R_0^{\ 2} \equiv \frac{V_{DS}\, R \left[K_o R\, (1-\alpha) + \theta_1 \right]}{2 K_o \left(V_{GST} - \alpha \frac{V_{DS}}{2} \right)} \quad . \tag{11}$$

Subscripts "0" and "ON" have been chosen because R_0^2=0 for the particular case of V_{DS}=0, and therefore equation (9) implies that R_{ON} represents half of the measured source-to-drain resistance (R_m=V_{DS}/I_D). Please note that R_0^2 in (11) could be either a positive or a negative quantity and it has units of squared resistance. Using this direct fit method, the values of the model parameters extracted from the measured data of the experimental MOSFET are: α=1 and V_T=0.42 V, K_o=1.48 A/V^2, θ_1=2.02 V^{-1}, and R=1.66 Ω.

B. Indirect fitting of the drain current

Instead of directly fitting the drain current, it has been suggested to use indirect bidimensional (V_{GS},V_{DS}) fitting of the source-to-drain resistance to enhance numerical calculation efficiency [22]. The source-to-drain resistance is defined as R_m=V_{DS}/I_D, as measured at low values of V_{DS}.

When the variable I_D in (9) to (11) is substituted by V_{DS}/R_m, after some algebraic manipulations one gets:

$$a_{VD}V_{DS} + a_{VG}\left(V_{GS} - V_T\right) - 2R_m = 0 \quad , \tag{12}$$

where the two coefficients are:

$$a_{VD} = R_m R K_o(2\alpha - 1) - R_m{}^2 K_o \alpha + R^2 K_o(1-\alpha) + R\theta_1 \tag{13}$$

and

$$a_{VG} = 2R_m{}^2 K_o - 2R_m\theta_1 - 2R_m R K_o \quad . \tag{14}$$

The parameter extraction process is as follows: First $I_D(V_{GS})$ is measured at low values of V_{DS} and the value of the threshold voltage V_T is extracted. With the known value of V_T and the measured $I_D(V_{GS},V_{DS})$ data, proceed to extract R, K_0, θ_1 and α by bidimensional (V_{GS},V_{DS}) fitting of Eq. (12). It is worthwhile noting that Eqs. (12) to (14) are much simpler than Eqs. (9) to (11) that would be used for direct fitting. Observe the straightforward functional dependence that Eq. (12) has on the independent variables (V_{GS},V_{DS}), as compared to the more complex dependence of Eqs. (9) to (11) on these variables. Consequently, this indirect fitting procedure results to be more computationally efficient than the direct fitting method.

For the experimental test device described before, the values of the parameters extracted using this indirect method with values of α=1 and V_T=0.42 V, are: K_o =1.48 A/V^2, θ_1=2.03 V^{-1} and R=1.66 Ω.

C. Constant mobility at two small drain biases

Campbell *et al* published a very interesting idea in 2011 for extracting the series resistance of MOSFETs [28]. They proposed to calculate the ratio of two $I_D(V_{GS})$ transfer characteristics, measured at two different but small values of drain bias (V_{DS1} and V_{DS2}), and assume that the mobility may be considered to be constant at such low drain biases. The derivation of their method may be systematically summarized as follows:

First, the effective mobility is obtained from (1) to (3) as:

$$\mu_{eff} = \frac{I_D}{\dfrac{W}{L_{eff}} C_{ox}\left(V_{GS} - I_D\dfrac{R}{2} - V_T - \dfrac{V_{DS} - RI_D}{2}\right)\left(V_{DS} - RI_D\right)} \, . \tag{15}$$

Second, the above equation is evaluated at V_{DS1} and V_{DS2} yielding two different currents (I_{D1} and I_{D2}).

Third, assuming that μ_{eff} is constant with respect to the small variations of V_{DS}, the following relation is obtained:

$$\frac{I_{D1}}{\left(V_{GS} - V_{T1} - I_{D1}\dfrac{R}{2} - \dfrac{V_{DS1} - RI_{D1}}{2}\right)\left(V_{DS1} - RI_{D1}\right)} = \frac{I_{D2}}{\left(V_{GS} - V_{T2} - I_{D2}\dfrac{R}{2} - \dfrac{V_{DS2} - RI_{D2}}{2}\right)\left(V_{DS2} - RI_{D2}\right)} \, , \tag{16}$$

where the terms (WC_{ox}/L_{eff}) have been cancelled.

Fourth, the terms (V_{DS1}− RI_{D1})/2 and (V_{DS2}− RI_{D2})/2 inside the long parentheses are neglected:

$$\frac{I_{D1}}{\left(V_{GS} - V_{T1} - I_{D1}\dfrac{R}{2}\right)\left(V_{DS1} - RI_{D1}\right)} \approx \frac{I_{D2}}{\left(V_{GS} - V_{T2} - I_{D2}\dfrac{R}{2}\right)\left(V_{DS2} - RI_{D2}\right)} \, . \tag{17}$$

Finally, the above relation is solved for R, yielding a quadratic equation.

A suggestion to improve the original method is: Follow the previously described steps up to equation (16), and solve it without ignoring the terms (V_{DS1}− $R\,I_{D1}$)/2 and (V_{DS2}− $R\,I_{D1}$)/2 to obtain the following expression for R:

$$R = \frac{2I_{D1}V_{DS2}\left(V_{GST} - \dfrac{V_{DS2}}{2}\right) - 2I_{D2}V_{DS1}\left(V_{GST} - \dfrac{V_{DS1}}{2}\right)}{I_{D1}I_{D2}\left(V_{DS1} - V_{DS2}\right)} \quad , \tag{18}$$

where again we have written the gate overdrive as V_{GST} = (V_{GS} − V_T) for brevity's sake.

Although there will be two slightly different values of threshold voltage in the two transfer characteristics at the two different drain biases, we have assumed that $V_{T1} \approx V_{T2} \approx V_T$ in writing (18), because the difference would be insignificant for the small and very close values of V_{DS} that would be used during actual extraction.

The model parameter values extracted by this method from measurements of the previously described test device with V_T=0.42V, are: K_o =1.37 A/V^2, θ_1=0.184 V^{-1}, and R=2.80 Ω.

A still better version of this method is described in the next section.

D. Constant mobility degradation factor at two small drain biases

Following the idea of the previous section, but instead of assuming that the mobility is constant at two small drain biases, we will now assume that it is the mobility degradation factor θ_1, in (5), which is constant [10]. The procedure is as follows:

First, use Eqs. (1) to (3) and (5), to write the expression for the mobility degradation factor:

$$\theta_1 = \frac{K_o\left(V_{DS}-RI_D\right)\left(V_{GST}-\frac{V_{DS}}{2}\right)\text{-}I_D}{I_D\left(V_{GST}-\frac{R}{2}I_D\right)} \quad . \qquad (19)$$

Second, evaluate the above equation at two different small values drain voltage, V_{DS1} and V_{DS2}, yielding two different currents (I_{D1} and I_{D2}).

Third, assuming mobility degradation is constant with respect to a small variation of V_{DS}, the following equation is obtained:

$$\frac{K_o\left(V_{DS1}-RI_{D1}\right)\left(V_{GST}-\frac{V_{DS1}}{2}\right)-I_{D1}}{I_{D1}\left(V_{GST}-\frac{R}{2}I_{D1}\right)} = \frac{K_o\left(V_{DS2}-RI_{D2}\right)\left(V_{GST}-\frac{V_{DS2}}{2}\right)-I_{D2}}{I_{D2}\left(V_{GST}-\frac{R}{2}I_{D2}\right)} \quad . \qquad (20)$$

Fourth, after some algebraic manipulations a second order equation is obtained:

$$aR^2+bR+c=0 \quad , \qquad (21)$$

where

$$a = 2K_oI_{D1}I_{D2}\left[I_{D1}\left(V_{GST}-\frac{V_{DS2}}{2}\right)\text{-}I_{D2}\left(V_{GST}-\frac{V_{DS1}}{2}\right)\right] \qquad (22)$$

$$\begin{aligned} b = &-2KI_{D1}^2V_{DS2}\left(V_{GST}-\frac{V_{DS2}}{2}\right) \\ &+2K_oI_{D1}I_{D2}V_{GST}\left(V_{DS2}-V_{DS1}\right) \\ &+2K_oI_{D2}^2V_{DS1}\left(V_{GST}-\frac{V_{DS1}}{2}\right)+2I_{D1}I_{D2}\left(I_{D1}-I_{D2}\right) \end{aligned} \qquad (23)$$

$$\begin{aligned} c = &\,4K_oI_{D1}V_{GST}V_{DS2}\left(V_{GST}-\frac{V_{DS2}}{2}\right) \\ &\text{-}4K_oI_{D2}V_{DS1}V_{GST}\left(V_{GST}-\frac{V_{DS1}}{2}\right) \end{aligned} \quad . \qquad (24)$$

The physically meaningful solution of the above quadratic equation to be used is the one with the negative sign of the square root. The values of the parameters extracted using this method from the measured data of the same test device, with α=1 and V_T=0.42 V, are: K_o =1.37 A/V^2, θ_1=0.595 V^{-1}, and R=2.50Ω.

E. Drain voltage versus gate voltage at constant current

This is a recently proposed method [34] based on plotting V_{DS} versus V_{GS} at I_D. Substituting (2) and (3) into (6), yields an analytic expression for V_{DS}:

$$\begin{aligned} V_{DS} = V_{GST} + \frac{RI_D}{2} - \Bigg[& V_{GST}^2 + \frac{\left(RI_D\right)^2}{4}\left(1+\frac{8V_{GST}\theta_2}{K_oR}+\frac{4\theta_1}{K_oR}\right) \\ & -\frac{I_D^3R^2\theta_2}{2K_o} - RI_DV_{GST}\left(1+\frac{2V_{GST}\theta_2}{K_oR}+\frac{2\theta_1}{K_oR}+\frac{2}{K_oRV_{GST}}\right)\Bigg]^{1/2} \end{aligned} \quad . \qquad (25)$$

The above equation could be directly used for nonlinear optimization. However, we recommend to previously obtain an estimation of the value of R by using a procedure based on two drain currents (I_{D1} and I_{D2}) for a given gate voltage (V_{GS}), corresponding to two drain voltages (V_{DS1} and V_{DS2}). Therefore, let us write the ratio of two known currents using (2), (3) and (6):

$$\frac{I_{D2}}{I_{D1}} = \frac{\left(1+\theta_1\left(V_{GST}-I_{D1}\frac{R}{2}\right)+\theta_2\left(V_{GST}-I_{D1}\frac{R}{2}\right)^2\right)}{\left(1+\theta_1\left(V_{GST}-I_{D2}\frac{R}{2}\right)+\theta_2\left(V_{GST}-I_{D2}\frac{R}{2}\right)^2\right)} \cdot \frac{\left(V_{GST}-\frac{V_{DS2}}{2}\right)\left(V_{DS2}-RI_{D2}\right)}{\left(V_{GST}-\frac{V_{DS1}}{2}\right)\left(V_{DS1}-RI_{D1}\right)} \quad . \qquad (26)$$

Now, assuming that at strong inversion the gate overdrive V_{GST}>>$I_DR/2$, the above equation may be simplified to:

$$\frac{I_{D2}}{I_{D1}} \approx \frac{\left(V_{GST}-\frac{V_{DS2}}{2}\right)\left(V_{DS2}-RI_{D2}\right)}{\left(V_{GST}-\frac{V_{DS1}}{2}\right)\left(V_{DS1}-RI_{D1}\right)} \quad . \qquad (27)$$

Solving (27) for R yields:

$$R = \frac{I_{D1}V_{DS2}\left(V_{GST}-\frac{V_{DS2}}{2}\right)-I_{D2}V_{DS1}\left(V_{GST}-\frac{V_{DS1}}{2}\right)}{2I_{D1}I_{D2}\left(V_{DS1}-V_{DS2}\right)} \quad . \qquad (28)$$

This quick procedure provides a decent estimation of R if the value of the threshold voltage is previously extracted, and the mentioned approximation is allowed by the fulfillment of the necessary assumption: V_{GST} >>$I_D\,R/2$.

We have calculated estimated values of R as a function of V_{GS} using Eq. (28), with V_T = 0.42 V and plots of $V_{DS}(V_{GS})$ for two pairs of I_D values. They are shown in Fig. 4. As can be observed in that figure, the resulting value of the resistance is weakly dependent on the selected pair of currents. This statement is consistence with the fact that the resistance could be a weakly dependent function of gate bias.

The values for I_D are to be selected so that the device is biased in strong inversion and triode region. Additionally, for a given V_{DS} and V_{GS} combination, the difference between I_{D1} and I_{D2} must be so small that there is no considerable variation in the extracted parameters.

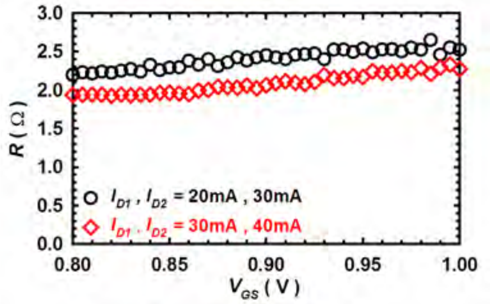

Fig. 4. The resulting value of series resistance R as a function of gate-to-source voltage, as calculated with (28), using two pairs of drain current measured from the same experimental test MOSFET.

However, it has to be large enough that dependence of the corresponding equations can be avoided (no redundancy). For the present test case, we have used a difference between I_{D1} and I_{D2} of 10 mA. For this voltage range, R is nearly constant at a value of about 2.1Ω. With this estimated value of R we can now check if the necessary assumption $V_{GST}>>I_D R/2$ is indeed valid. Substituting numerical values we find that $V_{GST}=1V-0.42V=0.58\ V > I_D\ R/2=0.042$V, which means that it is satisfied only within one order of magnitude. Therefore, we need to do an additional nonlinear optimization step using (25) and this estimated value of R. The new extracted values now are: R=1.65 Ω , θ_1=2.03 V^{-1} and K_o =1.48 A/V^2.

F. Comparison of extracted parameter values

Parameter values extracted from the measured data of the already described experimental test device, using the five described extraction methods are shown in Table 1. They are series resistance, first order mobility degradation factor, and transconductance parameter. They are presented alongside the calculated mean-squared error of the resulting drain current playback relative to the originally measured values.

We observe that essentially equal results and smallest mean-squared errors are produced by three methods: direct fitting, indirect fitting and drain voltage versus gate voltage at constant current. On the other hand, the other two methods, constant mobility and constant mobility degradation factor, produce different results and larger errors.

The larger errors of these two methods seem to originate from the fact that they require the assumption of small drain bias. The table also indicates that the error of the constant mobility method is the largest, and thus larger than that of the constant mobility degradation factor method, which in this respect is superior to the constant mobility method.

Fig. 5 presents measurements from the test device and results calculated with the extracted parameters from the methods of drain voltage versus gate voltage at constant current and constant mobility degradation factor. We observe that there is a fair correspondence, in strong inversion and in the triode region, between the experimental and the simulated curves with the method of drain voltage versus gate voltage at constant current. This figure also illustrates how the constant mobility degradation method can produce good results for small values of drain bias, but it is not very good at larger drain biases.

Table 1 Series resistance, mobility degradation coefficient, and transconductance parameters, as well as mean-squared error of the modeled current for five extraction methods, using a simple mobility model (θ_2=0).

Method	R (Ω)	θ_1 (V^{-1})	K_o (A/V^2)	Mean-squared error (mV)
Direct fitting	1.66	2.02	1.48	0.143
Indirect fitting	1.66	2.03	1.48	0.142
Constant μ_{eff} for two small values of V_{DS}	2.80	0.184	1.37	3.194
Constant θ_1 for two small V_{DS}	2.50	0.595	1.37	0.726
$V_{DS}(V_{GS})$ at constant I_D	1.65	2.03	1.48	0.141

IV. Conclusion

We have presented, examined, assessed and critically compared five extraction methods used to determine the values of the series resistance and the mobility degradation model parameters of MOSFETs from the measured drain current characteristics of a single device under various drain and gate biases.

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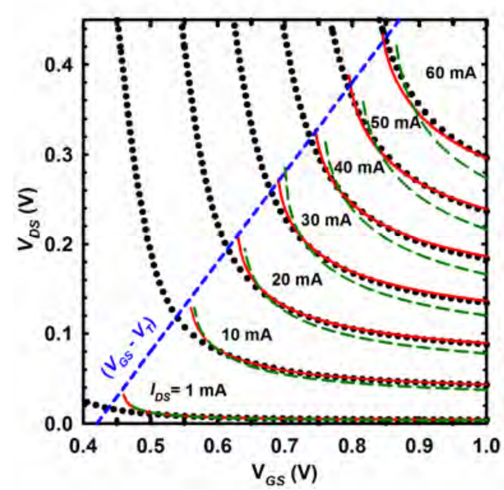

Fig. 5. Interpolated values from measurements (black dots), and results calculated with model parameters extracted using (a) the method of drain voltage versus gate voltage at constant current (red lines), and (b) the method of constant mobility degradation factor for two small drain bias (green dashed lines). The blue dashed line, corresponding to V_{DS}= (V_{GS} -V_T), represents the borderline between triode and saturation regions.

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