Extraction of Mobility Degradation and Source-and-Drain Resistance in MOSFETs

J. Muci1, A.D. Latorre Rey1, F.J. Garcia-Sánchez1, D.C. Lugo Muñoz1, A. Ortiz-Conde1, C.-S. Ho2, J.J. Liou3,4, M.A. Pavanello5, and R. T. Doria5

1Solid-State Electronics Laboratory, Simón Bolívar University, Caracas 1080, Venezuela.
2Powerchip Semicond. Corp., Hsinchu Science-Based Industrial Park, Hsinchu, Taiwan, ROC
3School of Electrical Engineering and Computer Science, University of Central Florida, Orlando, FL 32816-2450, USA.
4Department of ISEE, Zhejiang University, Hangzhou, China,
5Department of Electrical Engineering, Centro Universitário da FEI, Av. Humberto de Alencar Castelo Branco, 3972, CEP 09850-901 – São Bernardo do Campo, São Paulo, Brazil.
e-mail: ortizzc@ieee.org

ABSTRACT

A MOSFET model parameters extraction procedure that overcomes the difficulties of separating the effects of source-drain series resistance and mobility degradation factor is presented. Instead of the conventional direct fitting, the present procedure involves the use of indirect bidimensional fitting of the source-to-drain resistance of a single device, as obtained from the below-saturation output characteristics measured at several above-threshold gate voltages. The procedure is verified with a simulated long channel FinFET device with externally added resistances and is later applied to experimental planar bulk DRAM MOSFET devices with channel lengths ranging from 0.23µm to 2.0µm. The procedure is shown to be advantageous in terms of computational efficiency and it is appropriate even with high values of externally added series resistances. For the case of devices with various channel lengths, the accuracy of the procedure is improved if the value of \( R_{SD} \) is extracted from the shortest channel length. This value of \( R_{SD} \) could be used for extracting the other parameters for devices with longer channel.

Index Terms: MOSFET, mobility degradation, source-and-drain resistance, parameter extraction, indirect bidimensional fitting.

1. INTRODUCTION

Mobility degradation and source-and-drain series resistance are two model parameters of particular significance for MOSFET characterization. Unfortunately, they manifest themselves in a similar manner on the device’s transfer characteristics. This fact complicates their extraction independently from one another. Some extraction methods have been proposed in the past to get around this stumbling block [1-7].

We present here a way to separate the effects of mobility degradation and source-and-drain series resistance. It is based on the bidimensional (\( V_{GS}V_{DS} \)) fitting of the source-to-drain resistance measured in above-threshold and below-saturation conditions. The procedure is first verified with simulated data from a long channel FinFET device with the presence of externally added resistances. It is then applied to experimental data from test DRAM MOSFETs of various channel lengths. The procedure’s computational efficiency is satisfactory in terms of initial values range tolerance and number of iterations needed.

The extraction of the MOSFET model’s parameters is commonly performed using direct optimization [1-2], by fitting the measured current-voltage characteristics to the above-threshold implicit drain current (\( I_D \)) equation in the triode region, using a simple universal mobility model [8]:

\[
I_D = \frac{K}{1 + \theta(V_{gs} - V_T)} \left( V_{gs} - V_T - \frac{V_{ds}}{2} \right) V_{ds} \quad ,
\]

where

\[
V_{gs} = V_{GS} - \frac{I_D R_T}{2} \quad ,
\]

\[
V_{ds} = V_{DS} - \frac{I_D R_T}{2} \quad ,
\]
Extraction of Mobility Degradation and Source-and-Drain Resistance in MOSFETs
Muci, Rey, García-Sánchez, Muñoz, Ortiz-Conde, Ha, Libu, Pavanello, & Doria

\[ K = \frac{W}{L_{\text{eff}}} C_{\text{ox}} \mu_0 \]  
(4)

\[ R_T = R_{\text{SD}} + 2R_{\text{ext}} \]  
(5)

\( V_{\text{GS}} \) and \( V_{\text{DS}} \) represent the externally applied gate and drain voltages, respectively, \( R_T \) is the total series resistance, \( R_{\text{SD}} \) is parasitic source-and-drain series resistance and \( R_{\text{ext}} \) is an externally added resistance to both the source and drain terminals, \( \mu_0 \) is the low-field mobility, \( \theta \) is the mobility degradation factor due to the gate field \( [8] \), \( \alpha \) is a bulk-charge factor to globally account for threshold voltage dependence on channel potential due to depletion thickness nonuniformity along the channel \( [9] \), \( L_{\text{eff}} = L_m - \Delta L \) is the effective channel length, \( L_m \) is the mask channel length, and the rest of the parameters have their usual meaning. Although this model does not include carrier velocity saturation or other short channel effects, these effects may be included in the model without any loss of generality.

Using direct optimization on the implicit current equation 1 usually makes the extraction of \( R_{\text{SD}} \) and \( \theta \) a difficult task, considering the already mentioned equivalent effect that the total source-and-drain series resistance and the mobility degradation have on the shape of the \( I_D(V_{\text{GS}}) \) characteristics. Instead, here we broaden our recently proposed procedure, based on performing bidimensional fitting to the measured source-to-drain resistance \( [7,10] \), and extract the parameters as functions of channel length for the experimental devices. The use of the indirect fitting procedure provides a clear advantage in computational efficiency, since it reduces by a factor of about 3 the number of iterations needed to converge to the correct values.

2. EXTRACTION PROCEDURE

The measured source-to-drain resistance defined by:

\[ R_m = \frac{V_{\text{DS}}}{I_D} \]  
(6)

may be obtained from equation 1. After some algebra the following equation results:

\[ a_{V_D} V_{\text{DS}} + a_{V_G} (V_{\text{GS}} - V_T) - 2R_m = 0 \]  
(7)

where the two coefficients are given by:

\[ a_{V_D} = R_m R_T K (2\alpha - 1) - R_m^2 K\alpha + R_T^2 K (1 - \alpha) + R_T \theta \]  
(8)

and

\[ a_{V_G} = 2R_m^2 K - 2R_m \theta - 2R_m R_T K \]  
(9)

The first step in the procedure is to extract the threshold voltage, \( V_T \), value from the \( I_D(V_{\text{GS}}) \) characteristics at low \( V_{\text{DS}} \) through any of the available \( V_T \) extraction methods \( [11] \). We use here the transition method developed a few years ago \( [12] \). Next, the parameters \( R_T, \theta, \alpha, \) and \( K \), are extracted by bidimensional \( (V_{\text{GS}}, V_{\text{DS}}) \) fitting of equation 7 to the source-to-drain resistance, \( R_m \), obtained from the measured \( I_D(V_{\text{GS}}, V_{\text{DS}}) \) data. A Levenberg-Marquardt type algorithm \( [13] \) with a step size of \( 10^{-2} \) and a tolerance of \( 10^{-10} \) is used for fitting equation 7 to the measured source-to-drain resistance.

Because the relative weight of \( R_{\text{SD}} \) within the measured \( R_m \) increases as channel length decreases, the value of \( R_{\text{SD}} \) is extracted from the shortest channel length device, when available, to get the best possible accuracy. Thereafter \( R_{\text{SD}} \) is assumed to be the same for the rest of the devices with longer channel lengths from the same batch. The remaining parameters \( \theta, \alpha, \) and \( K \) are then extracted for each channel length using this value. In order to corroborate the validity of the proposed method, we will study in section 4 the evolution of the extracted parameters as a function of the mask channel length.

3. VERIFICATION WITH SIMULATED DATA

We applied the procedure to an n-channel silicon triple-gate FinFET, with a channel doping of \( N_A = 10^{15} \text{cm}^{-3} \), gate work function \( \Phi = 4.7 \text{eV} \), \( L_m = 10 \mu m \), fin width \( W_{\text{Fin}} = 20 \text{nm} \), fin height \( H_{\text{Fin}} = 60 \text{nm} \) and \( t_{\text{ox}} = 2 \text{nm} \). The mobility models used in the simulations \( [14] \) were Klaassen’s (Phillips) for low electric field, Lombardi’s for surface roughness and Canali’s for velocity saturation effects. There are 8 tridimensional simulations with the Sentaurus Device Simulator from Synopsys corresponding to the same device with 8 different values of externally added resistances, \( R_{\text{ext}} = 100 \Omega, 200 \Omega, 500 \Omega, 1 \text{K}\Omega, 2 \text{K}\Omega, 5 \text{K}\Omega, 10 \text{K}\Omega \) and 20 K\Omega. The externally added resistances are connected in series at both the source and drain terminals of the device. A threshold voltage of \( V_T = 0.49 \text{V} \) was extracted from the transfer characteristics of the device with \( R_{\text{ext}} = 100 \Omega \), at a low drain voltage of 10 mV, using the transition method \( [12] \).

Figure 1 presents the simulated output and transfer characteristics of the FinFET used in this study. We see in this figure that the plots seem to be merging together for a decreasing \( R_{\text{ext}} \) because \( R_{\text{ext}} \) is starting to be negligible with respect to \( R_{\text{SD}} \).

For the case of this long channel FinFET device, we first extracted the value of the bulk-charge effect parameter \( \alpha = 1.02 \) using the method presented in \( [9] \), which is very close to the approximation of \( \alpha = 1 \) commonly used for long channel double gate devices. This approximation of \( \alpha = 1 \) corresponds to a...
Extraction of Mobility Degradation and Source-and-Drain Resistance in MOSFETs

Muci, Rey, García-Sánchez, Muñoz, Ortíz-Conde, Ho, Liou, Pavanello, & Doria

105 Journal Integrated Circuits and Systems 2010; v.5 / n.2:103-109

first level of MOSFET modeling and leads to slightly larger relative errors than those obtained using the extracted value of 1.02, as will be shown later.

Once the value of $V_T = 0.49 \text{V}$ is obtained, we proceed to extract the parameters $R_T$, $\theta$ and $K$, by indirect fitting of equation 7 to the simulated data using $\alpha = 1$.

Figure 2 presents the output characteristics and its corresponding source-to-drain resistance, $R_{\text{inv}}$, for the case of an externally added resistance of $R_{\text{ext}} = 100 \text{ \Omega}$. The resulting model playbacks calculated by using the extracted parameters are also shown.

Figure 3 shows the extracted parameters vs the externally added resistance, using the classic value of the bulk-charge effect parameter, $\alpha = 1$. Parameters $\theta$ and $K^{-1}$ exhibit fairly constant behavior as expected for a long channel device. On the other hand, the extracted $R_T$ shows a linear dependence on $R_{\text{ext}}$ with a slope of 1.99 which is close to the expected value of 2 according to equation 5. The value of the intrinsic $R_{\text{SD}}$ corresponds to the $R_T$ axis intercept ($R_{\text{ext}} = 0$), as equation 5 indicates. In the present case, a value of $R_{\text{SD}} = 8.35 \text{ K}\Omega$ is obtained, as shown in Fig. 3(a).

It should be pointed out that if no externally added resistances are present, this last step would be unnecessary since $R_T = R_{\text{SD}}$ and $R_{\text{SD}}$ would be directly extracted.

In order to consider the effect of using either the classic approximation of $\alpha = 1$, or the extracted value of $\alpha = 1.02$, we calculated the relative errors for both cases. The comparison is done using $V_{\text{GS}} = 1 \text{V}$ and an external resistance $R_{\text{ext}} = 20 \text{K}\Omega$.

Figure 4 shows that the relative errors are only lightly higher when using $\alpha = 1$, hence this value is a good approximation for this long channel double gate device.

4. APPLICATION TO EXPERIMENTAL DEVICES

The extraction procedure was applied to experimental test planar bulk DRAM MOSFETs with a SiO$_2$ gate oxide of 4nm, a width of 10µm and mask channel lengths of $L_m = 0.23 \mu\text{m}$, 0.60µm, 1.00µm and 2.00µm. The drain currents for the devices were measured below-saturation as a function of drain voltage at three above-threshold values of gate voltage.

Figure 5 presents the output characteristics of the shortest channel device (0.23µm), together with

---

Figure 1. Transfer (a) and output (b) characteristics of the simulated FinFET for 8 values of external resistance. Plots seem to be merging together for a decreasing $R_{\text{ext}}$ because $R_{\text{ext}}$ is starting to be negligible with respect to $R_{\text{SD}}$

Figure 2. Output characteristics (a), and corresponding source-to-drain resistance (b), of the FinFET with $R_{\text{ext}} = 100 \text{ \Omega}$. Also shown are the model playbacks (red solid lines) obtained by using the extracted parameters indicated in the inset.
its corresponding source-to-drain resistance, $R_{\text{sd}}$, used in the extraction procedure. The resulting model playbacks calculated by using the extracted parameters are also shown in the same figure with solid lines. The maximum errors in drain current and total resistance are 0.24 $\mu$A and 5 $\Omega$ respectively.

Figure 6 shows the resulting model playbacks of the above-threshold transfer characteristics and the corresponding source-to-drain resistance, $R_{\text{sd}}$, as functions of $V_{\text{GS}}$ for the same 0.23 $\mu$m device at three low drain voltages (10, 20, and 50 mV), together with the original measured experimental data. The extracted threshold voltage for this device is 0.65 V. The playbacks are shown only in the strong inversion region where the model is valid. Parameter $\theta$ only describes the mobility degradation for high gate voltages. It should be kept in mind that there is a region of moderate inversion for gate biases around the threshold voltage, for which neither the weak nor the strong inversion approximations are valid [15,16].

It is important to point out that the relative effect of $R_{\text{sd}}$ diminishes as the channel length increases and that $R_{\text{sd}}$ is nearly independent of the channel length. Therefore, we will assume that $R_{\text{sd}}$ is constant for any channel length and that its value is equal to that extracted from the shortest channel length (0.23 $\mu$m) device where its effect is most significant.
Figures 7 and 8 present similar results for the longest channel device (2 \mu m). The extracted threshold voltage for this device is 0.62 V. The resulting maximum errors in drain current and total resistance, presented in Fig. 7, are 12 \mu A and 20 \Omega respectively.

The parameters of two additional devices with intermediate channel lengths of 0.60 and 1 \mu m were also extracted.

Regarding the computational efficiency of the indirect fitting procedure, for these experimental devices, the required number of iterations is less than 30 when using initial guess values for the parameters of about four times their actual values. Given that the same trend was observed for the previously shown simulated data, it seems reasonable to expect the same computational efficiency in general.

Figure 9 shows the evolution of the \theta, \alpha and \K parameters as the mask channel length increases from \Lm = 0.23 \mu m to 2.00 \mu m. A \Delta L = \Lm - \Leff = 34 nm may be estimated from the plot of \K^{-1} versus \Lm [17], which is consistent with the technology of these experimental devices.

Indirect bidimensional fitting procedures such as the one presented here could be applied to more complex models than the one represented by equation 1, allowing carrier velocity saturation and other short channel effects to be included[18].

Figure 6. Experimental above-threshold transfer characteristics (a), and corresponding measured source-to-drain resistance (b), of a test 0.23 \mu m channel device, measured at three low drain voltages (open circles). Also shown are the model playbacks (solid lines) obtained by using the extracted parameters.

Figure 7. Experimental below-saturation output characteristics (a), and corresponding measured source-to-drain resistance (b), of a test 2 \mu m channel device, measured at three above-threshold gate voltages (open circles). Also shown are the model playbacks (solid lines) obtained by using the extracted parameters.

Figure 8. Experimental above-threshold transfer characteristics (a), and corresponding measured source-to-drain resistance (b), of a test 2 \mu m channel device, measured at three low drain voltages (open circles). Also shown are the model playbacks (solid lines) obtained by using the extracted parameters.
5. CONCLUSIONS

We have presented a procedure to separate and extract the mobility degradation factor and the source-and-drain series resistance parameters of MOSFET models, while also extracting the “α and K”. The frequent difficulty encountered in separating the effects of source-and-drain series resistance and mobility degradation factor is overcome by using bidimensional fitting of the current-voltage characteristics model equations to the measured $I_{DS}/V_{GS}, V_{DS}$ data.

The most significant feature of this procedure is the use of indirect fitting of the source-to-drain resistance expression to the measured data of a single device. We have used the Sentaurus Device Simulator from Synopsys to simulate a triple gate FinFET with externally added resistances ranging from 100Ω to 20KΩ. Our results show that the value of $R_{SD}$ can be extracted even in the presence of high external resistances. The procedure was then applied to a batch of DRAM MOSFETs, with channel lengths ranging from 0.23µm to 2.00µm and their model parameters were extracted as functions of the channel length. To get the best possible accuracy in a given batch of devices with various channel lengths, the series resistance should be extracted from the shortest channel device, if available, since its relative effect within the measured resistance is highest.

REFERENCES

