Parameter extraction in polysilicon nanowire MOSFETs using new double integration-based procedure


A. Ortiz-Conde* a, A.D. Latorre Rey a, W. Liu b, W.-C. Chen c, H.-C. Lin c, J.J. Liou d, J. Muci a, F.J. García-Sánchez a

a Solid-State Electronics Laboratory, Simón Bolívar University, Caracas 1080, Venezuela
b School of Electrical Engineering and Computer Science, University of Central Florida, Orlando, FL 32816-2450, USA
c Institute of Electronics, National Chiao Tung University, Hsinchu, Taiwan
d Department of ISEE, Zhejiang University, Hangzhou, China

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A B S T R A C T

A new double integration-based method to extract model parameters is applied to experimental polysilicon nanowire MOSFETs. The threshold voltage and Subthreshold Slope factor are extracted from noisy measured current–voltage characteristics. It is shown that the present method offers advantages over previous extraction procedures regarding data noise reduction. In addition, the normalized mutual integral difference operator method is scrutinized and an improvement of the method is presented.

1. Introduction

Some of the more promising devices, being considered as possible alternatives to conventional CMOS, are monocrystalline double- and surrounding-gate MOSFETs [1–5]. At the same time, amorphous silicon (a-Si) thin-film transistors (TFTs) have traditionally dominated display applications, but today there is a growing need for better performance than what a-Si technology can provide. Consequently, polycrystalline silicon (poly-Si) TFTs are also receiving a great deal of attention as alternatives for large-area, low cost displays, as well as for other 3-D and large-area electronics applications. However, the performance of conventional planar poly-Si TFTs is still significantly impaired by the abundance of grain boundary defects in the polysilicon film [6]. These defects disturb carrier transport and particularly give rise to high Subthreshold Slope factor and off-state leakage current.

Many polysilicon MOSFET applications require reducing the amount of defects present in the channel body in order to decrease their harmful impact on the device's performance. Several technologies have been proposed to increase the polysilicon film grain size. They include excimer laser annealing [7] and metal-induced lateral crystallization [8], among others.

An interesting alternative to increasing grain size is to reduce the influence of grain boundaries by significantly shrinking the channel body size. The use of polycrystalline nanowire (NW) channel structures seems to be an appealing course of action towards that objective, since the total number of defects decreases significantly when the NW cross section is decreased. In that line, several NW polysilicon MOSFETs have been reported [9–14]. Polycrystalline long-channel ultra-thin body surrounding-gate NW MOSFETs have been proposed and fabricated [15,16] for flexible macroelectronics, as well as for other unconventional applications such as highly sensitive biosensors [17,18].

Modeling the phenomenology specific to polysilicon MOSFETs has been a topic of research for the last three decades [19,20].
Although the present dominating trends point towards continuous models and away from regional approximation-based models, regional parameters such as threshold voltage and Subthreshold Slope (SS) factor are still considered very important for quality and reliability assessment purposes [21–24].

In the present paper we present a new integration-based method to extract the threshold voltage and SS factor of MOSFETs. This method is applied to measured characteristics of experimental polysilicon nanowire MOSFETs. Other methods are also scrutinized in Section 8.

2. Current model

The transfer characteristics in the weak inversion or subthreshold region of most MOSFETs may be modeled by an exponential function of the gate voltage of the form [25]:

\[ I_{DW} = I_0 \exp \left( \frac{V_G}{\eta_{th}} \right), \]  

(1)

where \( I_0 \) is some global coefficient, \( \eta_{th} = k_BT/q \) is the thermal voltage, \( V_G \) is the externally applied gate-to-source voltage, and \( n \) is the so-called subthreshold ideality factor. The subscript \( w \) in \( I_{DW} \) refers to the drain current in the weak inversion region.

On the other hand, the strong inversion region at low drain voltage exhibits a super linear behavior with \( V_G \) and a linear behavior with \( V_D \), that can be modeled by a power law, or monomial type, equation of the form [26]:

\[ I_{DS} = K(V_G - V_{TH})^m V_D, \]  

(2)

where \( V_D \) is the externally applied drain voltage, \( K \) is a global conductivity coefficient, \( m \) is the monomial’s order, usually around 2, which reflects the distribution of states in the conduction band tail, and \( V_{TH} \) is the \( I_{DS} = 0 \) intercept, which can be viewed as a “strong inversion region-defined” threshold voltage. In this case, the subscript \( s \) denotes that the equation is valid in the strong inversion region.

3. Previous method

An integration-based method was proposed in 2001 for extracting model parameters of non-crystalline MOSFETs biased in the saturation region [26]. Its mathematical nature lessens the effect of data noise, in contrast to traditional derivative-based procedures which inherently worsen the data noise problem. The auxiliary function used in that method had been originally proposed in 1999 by our group to extract the model parameters of PN junctions at very low forward voltages [27]. The auxiliary function has the form:

\[ H_1(V_G, I_D) = \frac{\int_{V_{C1}}^{V_G} I_D(V_C) dV_C}{I_D(V_C) dV_C} - \frac{I_D(V_C) dV_C}{I_D(V_C) dV_C}, \]  

(3)

where \( I_{C1} \) is \( I_D(V_C = V_{C1}) \), and \( V_{C1} \) is the lower limit of integration. The value of \( V_{C1} \) must be selected such that Eq. (1) is valid at this point; i.e., the current is exponentially dependent on gate bias.

Substituting (1) into (3) and performing the indicated integration we get for the weak inversion, or subthreshold, region:

\[ H_{1w}(V_G, I_D) = \frac{n \nu_{th} I_D \left( \exp \left( \frac{V_G}{\eta_{th}} \right) - 1 \right)}{I_D \left( \exp \left( \frac{V_G}{\eta_{th}} \right) - 1 \right)} = n \nu_{th}, \]  

(4)

which is a constant value that we will refer to as \( H_{1w} \) from now on. Substituting (2) into (3) and performing the indicated integration we get for the strong inversion region:

\[ H_{1s}(V_G, I_D) = \frac{V_G - V_{TH}}{m + 1}, \]  

(5)

which is a linear equation on \( V_G \) with a reciprocal slope of \( m + 1 \).

This auxiliary function \( H_1 \) defined in (3), which can be obtained by numerical integration of the \( I_D - V_G \) transfer data measured at a small constant \( V_D \), may be used to readily extract parameters \( I_0, n, \) and \( m \) by means of (4) and (5). The use of \( H_1 \) already is an improvement over derivative-based methods regarding data noise reduction. However, because \( H_1 \) still contains the possibly noisy raw current data in the denominator of (3), we propose the use of another auxiliary function to further improve the noise immunity of the procedure.

4. The new auxiliary function

The idea suggested by (3) may be taken one step further with the purpose of reducing even more the effect of data noise. To that end, let us define another function, \( H_2 \), based on successive double integration, to be used as an alternative to (3):

\[ H_2(V_G, I_D) = \frac{\int_{V_{C1}}^{V_G} \int_{V_{C1}}^{V_G} I_D(V_C) dV_C dV_C}{\int_{V_{C1}}^{V_G} I_D(V_C) dV_C} - \frac{\int_{V_{C1}}^{V_G} I_D(V_C) dV_C}{\int_{V_{C1}}^{V_G} I_D(V_C) dV_C}. \]  

(6)

Replacing (1) into (6) and solving the integral yields for the subthreshold region:

\[ H_{2w}(V_G, I_D) = \frac{n \nu_{th} \left( \exp \left( \frac{V_G}{\eta_{th}} \right) - 1 \right) - V_G}{n \nu_{th} \left( \exp \left( \frac{V_G}{\eta_{th}} \right) - 1 \right) - V_G} = n \nu_{th}, \]  

(7)

which is the exact same result obtained in (4) using \( H_1 \). However, as will be confirmed later, the use of \( H_2 \) provides better noise immunity than \( H_1 \).

Replacing the strong inversion transfer Eq. (2) into (6) and solving the integral yields:

\[ H_{2s}(V_G, I_D) = \frac{V_G - V_{TH}}{m + 2}, \]  

(8)

which is a linear equation on \( V_G \) with a reciprocal slope of \( m + 2 \), in a similar fashion as \( H_{1s} \) in (5), except that in this case the reciprocal slope is \( m + 2 \).

5. Extraction procedure

The procedural sequence used to extract the parameter values proceeds as follows:

1) Numerically calculate the first and second integrals versus \( V_G \) of the measured \( I_D(V_G) \) at low \( V_D \). With these calculate function \( H_2 \) using (6).

2) Select an appropriate linear range of \( V_G \) in the strong inversion region to fit equation \( H_{2s} \) in (8) to the calculated \( H_2 \) data.
   a) Extract the values of \( m \) and \( V_{TH} \) from the linear fit.
   b) Calculate \( K \) with (2) using the two extracted values of \( m \) and \( V_{TH} \).

3) Determine \( H_{weak} \) as the value of \( H_2 \) in a range of the weak inversion region where it remains approximately constant.

4) Calculate the phenomenological \( V_{TH} \) as the value of \( V_G \) corresponding to the intersection of \( H_{weak} \) and \( H_{2s} \).
6. Parameter extraction

This new extraction procedure was applied to experimental data of polycrystalline silicon nanowire n-channel MOSFETs, as shown in Figs. 1 and 2, fabricated at the Institute of Electronics, National Chiao Tung University, Hsinchu, Taiwan, using a process similar to that reported in Ref. [28]. In order to avoid very long or narrow devices, they were designed using a layout of multi-nanowire and multi-finger source and drain, as is shown in Fig 3. The devices were later measured at the University of Central Florida, Orlando, FL, USA.

Three devices with the following makeup were used: undoped poly-Si NW body with a rectangular cross section of 60 nm × 18 nm, channel lengths of 0.4, 1.0, and 2.0 µm, n⁺ polysilicon gate with 10²¹ cm⁻³ doping, gate SiO₂ oxide thickness of 20 nm, and S/D doping density of 5 × 10²⁰ cm⁻³.

The measured transfer and output characteristics of three transistors with different mask channel lengths are presented in Fig. 4 at V_D = 10 mV and V_G = 2.5 V respectively.

The first step in the parameter extraction procedure is to calculate the auxiliary function H₂ from the measured transfer characteristics using (6). The result for Lm = 0.4 µm at V_D = 10 mV, with V_Glow = 0, has been plotted in Fig. 5a. The auxiliary function H₁ is also shown to illustrate the advantage of using the double-integral auxiliary function regarding noise reduction.

Fig. 1. Geometrical schematic of the poly-Si NW MOSFETs before (a) and after (b) second gate (top gate) and dielectric deposition.

Fig. 2. Top view (a) and cross-section views along red dashed line A-B (b), C-D (c) and C'-D' (c) of the poly-Si NW MOSFETs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Notice in Fig. 5a that in weak inversion below threshold, H₁_W and H₂_W have approximately the same value, as expected from (4) and (7), although the curve corresponding to H₂ is less noisy. However, in the strong inversion region above-threshold, despite H₁_S and H₂_S having the same shape, they differ in slope, in agreement with the expected m + 1 and m + 2 reciprocal slope behaviors as indicated in (5) and (8). The curve corresponding to H₂_S is also obviously less noisy.
Next, an appropriate $V_G$ range is selected in the strong inversion region to extract the parameters $m$ and $V_{Ts}$ by fitting equation (8) to the corresponding segment of $H_2$. This function is plotted in Fig. 5b together with the linear extrapolation of its strong inversion region. The values extracted from the straight line are $m = 2.1023$, and $V_{Ts} = 0.9171$ V.

The value of $K$ was then calculated using (2) in the same range, with the extracted values of $m$ and $V_{Ts}$. The result is shown in Fig. 6. We point out that $K$ looks fairly constant at a mean value of $K = 158.78$ nA/V$^{(m+1)}$, for the chosen $V_G$ range.

As a confirmation of the procedure's effectiveness, Fig. 7 presents the measured transfer characteristic together with the model playback, calculated with (2) using the extracted values of $m$, $V_{Ts}$, and $K$, for the device of $L_m = 0.4 \mu m$ at $V_D = 10$ mV.

We recall that $V_{Ts}$ is the $I_{Dn} = 0$ intercept, which we have referred to as the “strong inversion region-defined” threshold voltage. However, we propose that a more phenomenological definition of threshold voltage, $V_T$, for these devices would be the weak inversion-to-strong inversion transition gate voltage. In order to find it, we need to know the value of the subthreshold $H_{weak}$. Fig. 8 shows a close up view of $H_2$ in a range of low $V_G$. We see that function $H_2$ is approximately constant from $V_G = 0.6$ V to 0.8 V, and has a mean value of $H_{weak} = 0.1727$. 

![Fig. 3. Layout of the device using multi-nanowire and multi-finger source and drain.](image)

![Fig. 4. Transfer (a) and output (b) characteristics of the experimental poly-Si nanowire $n$-channel MOSFETs, with $L_m = 0.4, 1.0$ and $2.0 \mu m$ gate lengths.](image)

![Fig. 5. (a) Plot of both $H_1$ and $H_2$ functions vs $V_G$, to illustrate the noise reduction effect obtained by using $H_2$. (b) Plot of $H_2$ vs $V_G$ for device with $L_m = 0.4 \mu m$ and $V_D = 10$ mV, and its linear extrapolation (red dashed line) used to determine the value of $V_{Ts}$ as the intersection with the $V_G$-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image)

![Fig. 6. Plot of $K$ vs. $V_G$, as calculated from (2), using the extracted values of $m$ and $V_{Ts}$ for the device with $L_m = 0.4 \mu m$ at $V_D = 10$ mV. The value of $K$ shown corresponds to the mean value of the curve.](image)
Finally, the phenomenological threshold voltage $V_T$ is obtained as the value of $V_G$ where $H_{weak}$ intersects the linear extrapolation of the strong inversion region of $H$ ($H_{2}^S$). A value of $V_T = 1.6254$ V is the result for the device with $L_m = 0.4$ $\mu$m at $V_D = 10$ mV. Fig. 9 presents this last step of the procedure. It is important to point out that $V_{T_s}$ (the threshold voltage for strong conduction) fits well the $I_D(V_G)$ characteristic for strong conduction but not for weak conduction. On the other hand, the phenomenological $V_T$ is defined using the asymptotic behavior of both regions.

7. Extraction results

In what follows we present all the results obtained for the rest of the devices at three values of $V_D = 10$, 20, and 50 mV. The extracted values are presented in Table 1.

The value of the Subthreshold Slope factor (volts of gate voltage change per decade of drain current change) can be readily calculated from function $H_2$ in the weak inversion or subthreshold region ($H_{weak}$) using the following formula:

$$SS = \ln(10)mVth = \ln(10)H_{weak} = 2.3H_{weak}. \quad (9)$$

For the case of the 0.4 $\mu$m channel length device, $H_2$ approximately has a mean value of $H_{weak} \approx 0.1727$, which corresponds to an $SS = 397$ mV/decade. The extracted values of $SS$ are plotted versus channel length in Fig. 10 for three small drain voltages.

8. Comparison and improvements of previous methods

In order to show the advantages of the present method, we will test some previous methods using the same experimental data. We
start with the second-derivative method [29], which determines $V_T$ as the gate voltage at which the derivative of the transconductance (i.e., $d_{gm}/dV_C = d^2I_D/dV_C^2$) is maximum. Fig. 11 shows that this method fails when it is applied to the present experimental data because of the noise. Therefore, it is not possible to evaluate the point at which the maximum occurs.

We will now test the transition method [30], which uses the sub-threshold-to-strong inversion transition region of MOSFETs to extract the threshold voltage. It is based on an auxiliary operator that involves integration of the drain current as a function of gate voltage. The following function $G_1$ is numerically calculated from the measured data.

$$G_1(V_C, I_D) = V_C - 2 \frac{\int_0^C I_D(V_C) dV_C}{I_D}.$$  \hspace{1cm} (10)

A plot of $G_1$ versus $\ln(I_D)$ should be a straight line below threshold where the current is dominated by diffusion and consequently it is predominantly exponential. As soon as $V_C$ is greater than the inflexion point of the plot $I_D(V_C)$, function $G_1$ drops abruptly. Therefore, the maximum value of $G_1$ corresponds to the threshold voltage of the device. This method fails with the present data because the plot $I_D(V_C)$ does not have an inflexion point; therefore, function $G_1$ does not present a maximum value.

We will now test the normalized mutual integral difference operator method [31,32] to extract the threshold voltage. This method has been tested on a batch of experimental polysilicon NW MOSFETs of several gate lengths whose model parameters were estimated by the proposed method and improved normalized mutual double-integral difference operator method.

On the other hand, the operator $D$,

$$D(V_g, I_D) = \int_0^{V_C} V_C I_D(V_C) dV_C - \int_0^{V_C} I_D(V_C) dV_C$$

which was proposed in 1996 [33], has the property of eliminating the linear term and is a measurement of nonlinearity. This operator presents sensitivity to noise because the term $V_C I_D$ does not contain integration. Following the ideas about successive integration in distortion analysis [34], the following operator also eliminates the linear term:

$$D_3(V_C, I_D) = V_C \int_0^{V_C} I_D(V_C) dV_C - 3 \int_0^{V_C} \int_0^{V_C} I_D(V_C) dV_C dV_C.$$  \hspace{1cm} (12)

Normalizing the previous equation, we obtain the improved normalized mutual double-integral difference operator method

$$P_3(V_C, I_D) = \frac{D_3(V_C, I_D)}{V_C \int_0^{V_C} I_D(V_C) dV_C}$$

$$= 1 - 3 \frac{\int_0^{V_C} I_D(V_C) dV_C}{V_C \int_0^{V_C} I_D(V_C) dV_C}.$$  \hspace{1cm} (14)

A plot of $P_3$ is also presented in Fig. 12 and we see how the effects of experimental noise are reduced. The value of $V_T$ is about 1.5 V, which is in agreement with the results presented in Section 7. We observe that this method is not very precise because the maximum value is very broad.

9. Conclusions

We have presented a new method to extract MOSFET regional model parameters based on the first and second integrals of the transfer characteristics. The method has proved capable of extracting the key parameters of polysilicon nanowire MOSFETs regional models, in the subthreshold region, as well as in the strong inversion region, where the drain current of these devices exhibits a power law behavior with respect to the gate voltage. However, the procedure is equally applicable to other devices with linear-like or super linear above-threshold transfer characteristics. The method has been tested on a batch of experimental polysilicon NW MOSFETs of several gate lengths whose model parameters have been extracted. The proposed new method has demonstrated that it offers advantages over traditional extraction procedures regarding data noise reduction and ease of application. The
normalized mutual integral difference operator method [31,32] is scrutinized and an improvement, based on successive integration, is presented.

References


