Stable Threshold Voltage Extraction Using Tikhonov's Regularization Theory

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***Abstract*—We propose a new threshold voltage extraction with stability based on Tikhonov's regularization theory. It suppresses the instability of the transconductance change method and gives mathematically exact solution. Following the mathematical derivation, we convert the procedure into the MATLAB programming for users' convenience. Finally, the proposed method extracts the threshold voltage close to the physically meaningful one which means the gate-to-source voltage where $\phi_s = 2\phi_f + V_{\mathrm{SB}}$. To confirm the proposed one, we compare it with others such as the linear extraction and the normalized mutual integral difference method. It was found that the proposed one extracted the physically meaningful threshold voltage very closely. Moreover, it is also observed that there is a high correlation between the proposed and the normalized mutual integral difference method.**

***Index Terms*—Extraction, regularization, threshold voltage, transconductance change method.**

I. Introduction

THRESHOLD voltage (V_{TH}) is one of the most important parameters for MOSFET analysis. For example, physically meaningful threshold voltage extraction will help the SPICE compact modeling to emulate real device characteristics precisely, which will save the time and effort required for system design. Here, the physically meaningful threshold voltage is defined as the gate-to-source voltage (V_{GS}) at which the surface potential (ϕ_s) is nearly $2\phi_f + V_{\mathrm{SB}}$ [1]. ϕ_f and V_{SB} represent the difference between intrinsic Fermi potential and Fermi potential and the substrate bias, respectively.

Therefore, there have been many threshold voltage extraction methods proposed to extract a physically meaningful one from measured electrical characteristics: the constant current method, the linear extraction method, the ratio method, and the transconductance change method [2], [3]. However, each of them has some disadvantages. The constant current method suffers from the arbitrariness in constant current choice. The linear extraction method is strongly dependent not only on the series resistance but also on the mobility degradation. The ratio method has a demerit of failure in line interception.

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It has been widely known that only the transconductance change method can yield a result which approaches the physically meaningful threshold voltage and that eliminates the effects of the interface state, the mobility degradation, and the parasitic resistance [4]–[6]. Thus, it becomes more important as the device is scaled down to nanoscale region. Recently, it has also been reported that the transconductance change method reflects the volume inversion behavior of double-gate MOSFETs well [7], [8]. It defines the threshold voltage as the gate-to-source voltage at which the rate of transconductance change g_{m2} $(=d^2I_D/dV_{\mathrm{GS}}^2)$ is a maximum, and enhances the exactness of the SPICE model by a adopting physically meaningful one. The superiority of the transconductance change method to others can be figured out if one considers its underlying physical meaning. The inversion charge increases exponentially with surface potential. Below threshold voltage, the surface potential is almost linear with gate-to-source voltage. Accordingly, the change in the inversion charge with respect to gate-to-source voltage is almost exponential below threshold. This change in the inversion charge is proportional to the transconductance. On the other hand, beyond the threshold voltage, the surface potential begins to stay almost constant as the gate-to-source voltage increases, which induces a slow down in the rate of increase of inversion charge with respect to the gate-to-source voltage. It means a decrease in the rate of transconductance increase, i.e., the transconductance versus gate-to-source voltage curve goes through an inflection point near the threshold voltage. The transconductance change method detects this inflection point which is relatively insensitive to device degradation because it is not extrapolated from a region in which the drain current is large where the device is sensitive to degradation [4].

Although this method has a great merit mentioned above, there is a big obstacle to practical use: the second-order differentiation. Since the second derivative of drain current with regard to the gate-to-source voltage is required in the transconductance change method, it tends to be very noisy [2], [9]. Therefore, it is difficult to extract the exact threshold voltage as depicted in Fig. 1(b).

In mathematical meaning, the problem can be interpreted as follows. The threshold voltage extraction is viewed as an inverse process to get the input quantities from the output quantities of a sequence of measuring operations. We should make a proper model to represent the measuring process and, additionally, find the inverse representation of the measuring process to extract the input quantities from the output data. These inverse problems occur in many other fields and are being investigated

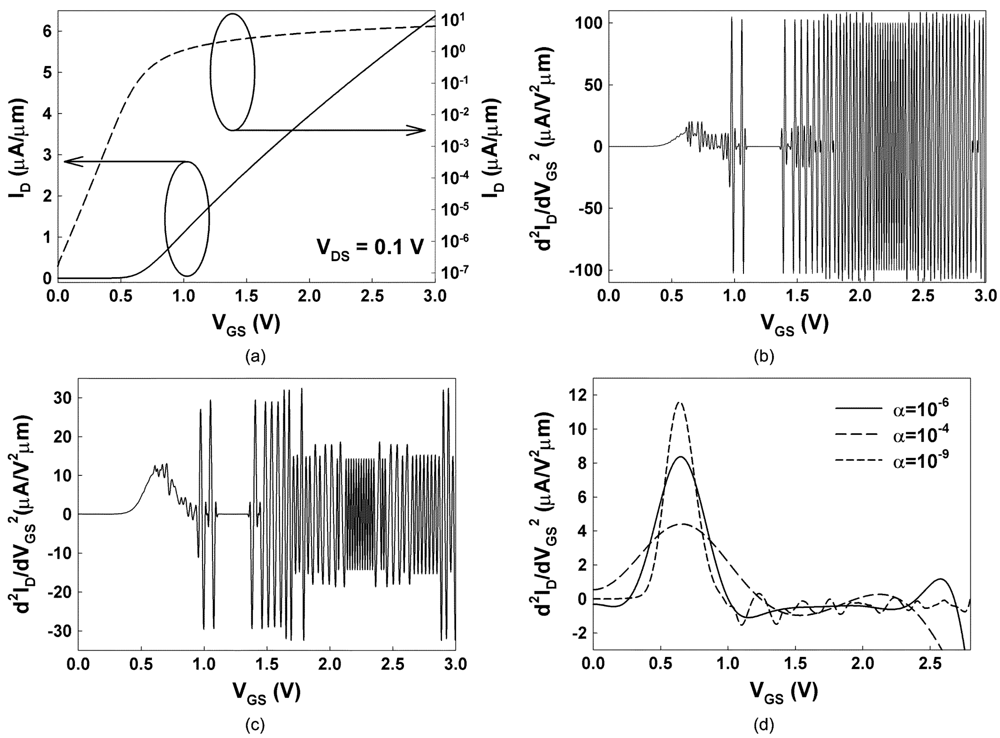

Fig. 1. Comparison of the $d^2I_D/dV_{\rm GS}^2$ profiles of a 1.5-μm-long nMOSFET with 25-nm gate oxide measured at 0.1-V drain bias. (a) The transfer curve of the 1.5-μm–long nMOSFET which gives the numerical data for $d^2I_D/dV_{\rm GS}^2$ extraction. (b) $d^2I_D/dV_{\rm GS}^2$ profiles extracted by the least square method. (c) $d^2I_D/dV_{\rm GS}^2$ profiles extracted by the five-point least-square-fit method. (d) $d^2I_D/dV_{\rm GS}^2$ profiles extracted by the proposed regularization method. Because the regularized value depends on the regularization parameter α, it is necessary to optimize the regularization parameter.

intensively [10]. Differentiation is the inverse operation of integration. The former is very sensitive to some perturbation of the data distribution to be differentiated, which is so-called ill-conditioned, while the latter is robust to that. So some perturbations of the measured data lead to a heavy change of the differentiated data. Generally, weak noise contamination of the original data curve would result in a highly unstable and oscillatory shape of the differentiated data curve. In the transconductance change method, the unstable property of the second-order differentiation makes it difficult to extract an exact threshold voltage since the measured raw data are usually contaminated by noise.

In this paper, we propose a stable threshold voltage extraction by implementing stable numerical second-order differentiation using the Tikhonov's regularization technique [11]. Here, "stable" means that small changes in the initial data should give only correspondingly small changes in the final results.

II. Numerical Second-Order Differentiation Using the Tikhonov's Regularization Technique

In mathematical sense, given a measured data set y with size n, this problem is to find a good approximation $\hat{x}$ to a vector $x \in R^n$ satisfying an approximate linear equation $Ax \approx y$, where $A^{-1} \in R^{n\times n}$ is the matrix representation of second-order differentiation. Usually, y is the result of measurement contaminated by small errors such as noise. In such situations, the vector $\hat{x} = A^{-1}y$, if it exists at all, is usually a meaningless, bad approximation to x. So the regularization technique is necessary to obtain meaningful solution estimates for such ill-conditioned problems, where some parameters are ill-determined by the conventional least square method [12].

As stated previously, we concentrate on evaluating

$$g(V) = A_h^{-1} f_\lambda \tag{1}$$

which represents the second-order differentiation problem in threshold voltage extraction. A_h^{-1} is the second-order differentiation operator and $g(V)$ is the regularized differentiated data we want to extract, V represents an independent variable in measurement, and f_λ is the raw data we have extracted in measurement. In our case, $g(V), V, f_\lambda$ are the g_{m2} extracted by the regularization method, the gate-to-source voltage, and the drain current. Subscript λ represents the discrepancy value which will be discussed below. Instead of (1), we set the problem in the sense of the least square method with the Tikhonov's regularization scheme as

$$M[g] = \int_c^d |A_h g(V) - f_\lambda|^2 \, dV + \alpha \int_c^d \left[\{g(V)\}^2 + \{g'(V)\}^2\right] dV \tag{2}$$

where $M[g]$ is the Tikhonov's regularization functional and α is the regularization parameter. The lower and upper bound of the integral are represented by c and d, respectively. In the right side of (2), there are two integral terms. The former is conventional root mean square (rms) term and the latter is the integral of the first order differentiation. Our task is finding the $g(V)$ to minimize $M[g]$. This operation forces both the first and the second integral to be minimized. The first term tries to minimize the rms error from the original data distribution but the second term tries to reduce the fluctuation of the $g(V)$ data distribution and guarantees the smoothness of the data distribution. The regularization parameter α balances two integral terms of (2). So the structure of $g(V)$ to minimize $M[g]$ is expected to have a smooth and slowly oscillating form. As α approaches zero, we can get similar results to those in the least square method i.e., small error but much noise. On the other hand, as α gets larger, we can extract more regularized data i.e., large error but little noise.

We use the variational principle to find optimal $g(V)$ which makes $M[g]$ minimal [10]. We project (1) on the discrete domain. Then it can be expressed as follows:

$$M[g] = \sum_{i=1}^{n} |A_h g(V_i) - f_\lambda(V_i)|^2 h + \alpha \sum_{i=1}^{n} \Big[|Bg(V_i)|^2 + |Cg(V_i)|^2\Big] h \quad (3)$$

where V_i denotes the ith measurement node and A_h is the matrix representation of the inverse of the second-order differentiation operator given by (4), shown at the bottom of the page, where h is the sampling interval and ε is an arbitrarily small positive real number to prevent the matrix A_h being singular. The identity matrix B and the matrix C representing the first order differentiation are, respectively, represented by

$$B = \begin{pmatrix} 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & 1 & 0 \\ 0 & 0 & \cdots & 0 & 1 \end{pmatrix} \quad (5)$$

and

$$C = \frac{1}{h} \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & -1 & 1 & 0 \\ 0 & 0 & 0 & \cdots & 0 & -1 & 1 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 \end{pmatrix} \quad (6)$$

In the variation theory, the minimum condition for $M[g]$ is given by

$$\begin{aligned} \delta M[g] &= \sum_{i=1}^{n} \Big[|A_h g(V_i) + A_h \delta g(V_i) - f_\lambda|^2 - |A_h g(V_i) - f_\lambda|^2\Big] h \\ &\quad + \alpha \sum_{i=1}^{n} \Big[|Bg(V_i) + B\delta g(V_i)|^2 - |Bg(V_i)|^2 \\ &\quad + |Cg(V_i) + C\delta g(V_i)|^2 - |Cg(V_i)|^2\Big] h = 0. \end{aligned} \quad (7)$$

By using the knowledge of the linear algebra, we can derive the relations shown below

$$\begin{aligned} &|A_h g(V_i) + A_h \delta g(V_i) - f_\lambda|^2 - |A_h g(V_i) - f_\lambda|^2 \\ &\quad = \{A_h g(V_i) - f_\lambda\}^\dagger A_h \delta g(V_i) + \Big[\{A_h g(V_i) \\ &\qquad - f_\lambda\}^\dagger A_h \delta g(V_i)\Big]^\dagger. \end{aligned} \quad (8)$$

$$\begin{aligned} &|Bg(V_i) + B\delta g(V_i)|^2 - |Bg(V_i)|^2 \\ &\quad = \{Bg(V_i)\}^\dagger B\delta g(V_i) + \Big[\{Bg(V_i)\}^\dagger B\delta g(V_i)\Big]^\dagger. \end{aligned} \quad (9)$$

$$\begin{aligned} &|Cg(V_i) + C\delta g(V_i)|^2 - |Cg(V_i)|^2 \\ &\quad = \{Cg(V_i)\}^\dagger C\delta g(V_i) + \Big[\{Cg(V_i)\}^\dagger C\delta g(V_i)\Big]^\dagger. \end{aligned} \quad (10)$$

We use $A^\dagger$ for an adjoint matrix of A.

If we substitute (8), (9), and (10) to (7), it becomes

$$\begin{aligned} \delta M[g] = \int_c^d &[[\{A_h g(V) - f_\lambda\}^\dagger A_h + \alpha\{Bg(V)\}^\dagger B \\ &+ \alpha\{Cg(V)\}^\dagger C]\delta g(V) + \Big[[\{A_h g(V) - f_\lambda\}^\dagger A_h \\ &+ \alpha\{Bg(V)\}^\dagger B + \alpha\{Cg(V)\}^\dagger C]\delta g(V)]^\dagger\Big]\, dV = 0. \end{aligned} \quad (11)$$

Let $N = \{A_h g(V) - f_\lambda\}^\dagger A_h + \alpha\{Bg(V)\}^\dagger B + \alpha\{Cg(V)\}^\dagger C$, then (7) is derived as

$$\delta M[g] = \int_c^d [\{N\delta g(V)\} + \{N\delta g(V)\}^\dagger]\, dV = 0. \quad (12)$$

$$A_h = \left[\frac{1}{h^2} \begin{pmatrix} -1+\varepsilon & 1 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -2 & 1 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -2 & \cdots & 0 & 0 & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0 & 0 & \cdots & -2 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & -1+\varepsilon \end{pmatrix}\right]^{-1} \quad (4)$$

To meet the requirement of (12) for arbitrary $\delta g(V)$, N should be zero. Then $g(V)$ can be expressed in the simple form

$$g(V) = \{A_h^\dagger A_h + \alpha(B^\dagger B + C^\dagger C)\}^{-1} A_h^\dagger f_\lambda. \tag{13}$$

The dimension of each matrix depends on the number of the measurement data.

We measured the electrical characteristics of a 1.5-μm nMOSFET and performed the second-order differentiation with the MATLAB by modulating the regularization parameter α. Fig. 1(a) shows the transfer curve of the 1.5-μm nMOSFET in linear region. By using the data from Fig. 1(a), we performed the second-order differentiation referring to (13). When adopting the least square method, i.e., α is zero, we can get no information due to much noise from numerical differentiation as shown in Fig. 1(b). Even if we use a more advanced least square method i.e., a five-point least-square-fit method, significant noise still remains as shown in Fig. 1(c), [13]. On the contrary, adopting the regularization method, i.e., α is not zero, we can suppress the noise from differentiation as depicted in Fig. 1(d). Thus, it is possible to extract some useful information for MOSFET characterization. However, the regularized value depends on the regularization parameter α, which is selected arbitrarily by the user. If we set α to be small, the results approach those of the least square method: much noise. On the other hand, if we set α to be large, there will be significant error in the regularized values. Therefore, it is indispensable to have a criterion to determine the value of the optimized regularization parameter.

To determine the regularization parameter, we adopt the general discrepancy principle [9] and introduce a function "dis" defined as

$$\mathrm{dis} = \int_c^d |A_h g - f_\lambda|^2 \, dV - \lambda^2. \tag{14}$$

The criterion for optimizing the regularization parameter is defined as

$$\mathrm{dis}(\alpha^*) = 0. \tag{15}$$

where g, λ, and α^* are the regularized value which depends on the regularization parameter, the discrepancy value and optimized regularization parameter, respectively. The regularization parameter satisfying (15) will be the optimized value. The discrepancy value optimizes the regularization parameter and determines the confidence of the regularized data distribution. If one measures the same quantity infinite times, there will be an averaged error λ between true and measured values. Therefore, (14) is considered as follows. Extracted raw data f_λ encircle a true value within a radius of λ. Inversely, it means that a true value exists within λ from f_λ. Contrary to the previous section, the discrepancy value can be decided referring to the confidence level that we want. In most cases, λ can be determined considering the confidence of a measurement equipment. However, even if the exact confidence of the equipment is not available, there are no difficulties in extracting the threshold voltage. As summarized in Table I, as long as the peak of g_{m2} is conserved, the extracted threshold voltage is insensitive to the variation of λ. In other words, the peak position is fixed and only the overall profiles are moved with λ varied.

TABLE I
EXTRACTED THRESHOLD VOLTAGES WITH VARIATION OF λ. THE THRESHOLD VOLTAGES ARE INSENSITIVE TO THE CHANGES IN THE VALUE OF λ

λ (A^2V)	Extracted threshold voltage (V)
5×10^{-8}	0.61
1×10^{-8}	0.61
5×10^{-7}	0.61
1×10^{-6}	0.61
5×10^{-6}	0.61

III. APPLICATION TO STABLE THRESHOLD VOLTAGE EXTRACTION

To implement the aforementioned idea, we apply it to threshold voltage extraction based on the transconductance change method. We fabricated and simulated MOSFETs with various channel lengths to extract threshold voltage. The MEDICI is utilized as a device simulator. And their transfer characteristics were carefully fitted to each other. All of the data used in this paper is from simulation that was corrected by experimental data. We set the discrepancy value λ to be 5×10^{-7} A^2V, taking into consideration the confidence we want. The sampling interval h is set to be 0.01 V.

Fig. 2 shows the regularized g_{m2} profiles of MOSFETs with various channel lengths. It shows mathematically exact results of the second-order differentiation with smoothness. To confirm the proposed method, we compared $V_{\mathrm{TH}}(\mathrm{TC}), V_{\mathrm{TH}}(\mathrm{LE})$, and $V_{\mathrm{TH}}(\mathrm{NMID})$ with $V_{\mathrm{TH}}(P)$ in a variety of devices. $V_{\mathrm{TH}}(\mathrm{TC}), V_{\mathrm{TH}}(\mathrm{LE})$, and $V_{\mathrm{TH}}(\mathrm{NMID})$ represent the threshold voltage extracted by the transconductance change method, the linear extraction method and the normalized mutual integral difference method [6]. $V_{\mathrm{TH}}(P)$ represents the physically meaningful threshold voltage at which the surface potential ϕ_s is $2\phi_f + V_{\mathrm{SB}}$. $V_{\mathrm{TH}}(\mathrm{LE})$ and $V_{\mathrm{TH}}(\mathrm{NMID})$ are selected because they are a *de facto* industry standard and a state-of-the-art method, respectively. In long-channel MOSFETs whose channel length ranges from 1 to 2 μm, $V_{\mathrm{TH}}(\mathrm{TC})$ and $V_{\mathrm{TH}}(\mathrm{NMID})$ predict $V_{\mathrm{TH}}(P)$ more exactly than $V_{\mathrm{TH}}(\mathrm{LE})$ as shown in Fig. 3(a). It is observed that $V_{\mathrm{TH}}(\mathrm{TC})$ is larger than $V_{\mathrm{TH}}(\mathrm{NMID})$ about twice the thermal voltage, which is the same result in [6]. The same is the case in short-channel MOSFETs whose channel length ranges from 60 to 100 nm, as depicted in Fig. 3(b). However, it is found that $V_{\mathrm{TH}}(\mathrm{TC})$ is almost the same as $V_{\mathrm{TH}}(\mathrm{NMID})$ in the short-channel region. This can be understood as follows. The transconductance

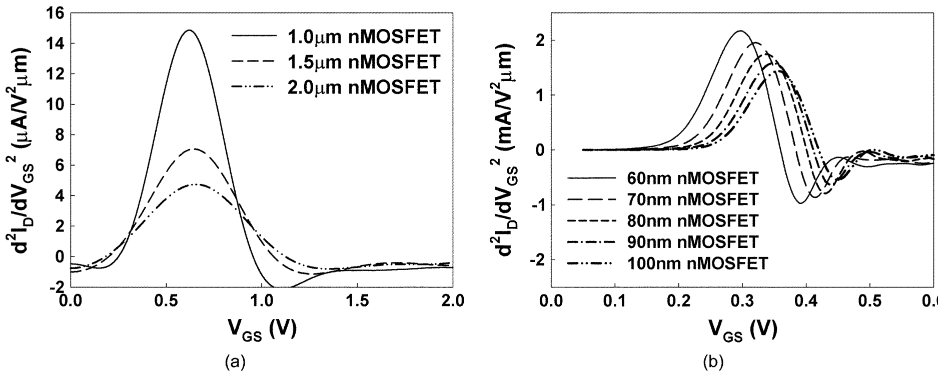

Fig. 2. Regularized $d^2 I_D / dV_{\mathrm{GS}}^2$ profiles of MOSFETs with various channel lengths. By using the general discrepancy principle, it is possible to determine the regularization parameter objectively. We set the discrepancy value λ to be 5×10^{-7} $\mathrm{A^2V}$. (a) Long-channel MOSFET cases. (b) Short-channel MOSFET cases.

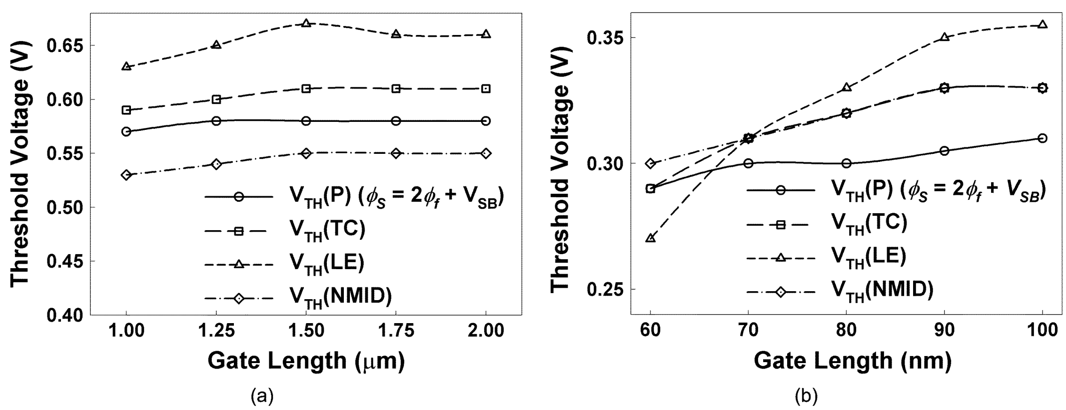

Fig. 3. Comparison of each threshold voltage of MOSFETs with various channel lengths. (a) Long-channel MOSFET cases. $V_{\mathrm{TH}}(\mathrm{TC})$ and $V_{\mathrm{TH}}(\mathrm{NMID})$ shows better correlation with $V_{\mathrm{TH}}(P)$ than with $V_{\mathrm{TH}}(\mathrm{LE})$. (b) Short-channel MOSFET cases. $V_{\mathrm{TH}}(\mathrm{TC})$ and $V_{\mathrm{TH}}(\mathrm{NMID})$ shows better correlation to $V_{\mathrm{TH}}(P)$ than $V_{\mathrm{TH}}(\mathrm{LE})$.

change and normalized mutual integral difference method have a similar meaning. The former extracts the threshold voltage by monitoring the change in inversion charges while the latter does by detecting the transition of the transfer curve from exponential to linear. To sum up, both of them interpret the same phenomenon in either physically oriented or mathematically oriented viewpoint.

To make it clear, we introduced a statistical methodology. Correlation coefficients are calculated from the pairs of the threshold voltages. The correlation coefficient R_{xy} for quantity x and y is defined as

$$R_{xy} = \frac{\mathrm{cov}(x, y)}{\sigma_x \sigma_y} \tag{16}$$

where $\mathrm{cov}(x, y)$, σ_x, and σ_y are the covariance and the standard deviations for quantity x and y, respectively. In Table II, correlation coefficients between $V_{\mathrm{TH}}(P)$ and $V_{\mathrm{TH}}(\mathrm{TC})$ are larger than those between $V_{\mathrm{TH}}(P)$ and $V_{\mathrm{TH}}(\mathrm{LE})$ regardless of the gate length, which shows better correlation between $V_{\mathrm{TH}}(P)$ and $V_{\mathrm{TH}}(\mathrm{TC})$. This result is easy to understand when we recall the physical meaning of the transconductance change method as mentioned before. It is also observed that $V_{\mathrm{TH}}(\mathrm{NMID})$ has a close correlation with $V_{\mathrm{TH}}(\mathrm{TC})$.

TABLE II
CORRELATION COEFFICIENTS CALCULATED FROM THE PAIRS OF THE THRESHOLD VOLTAGES. $V_{\mathrm{TH}}(P)$ AND $V_{\mathrm{TH}}(\mathrm{TC})$ SHOW VERY CLOSE CORRELATION WITHOUT REGARD TO CHANNEL LENGTHS

	Long channel MOSFETs (1~2 μm)	Short channel MOSFETs (60~100 nm)
Correlation coefficient between $V_{TH}(P)$ and $V_{TH}(TC)$	0.958	0.995
Correlation coefficient between $V_{TH}(P)$ and $V_{TH}(LE)$	0.884	0.931
Correlation coefficient between $V_{TH}(P)$ and $V_{TH}(NMID)$	0.958	0.981
Correlation coefficient between $V_{TH}(TC)$ and $V_{TH}(NMID)$	1	0.985

IV. CONCLUSION

We proposed a stable threshold voltage extraction using the Tikhonov's regularization theory. It was based on the transconductance change method. To remove arbitrariness in the regularization parameter selection, we adopted the general discrepancy principle. Based on the mathematical derivation, we converted the procedure into the MATLAB programming, which made the proposed method much easier to be used. It guaranteed smooth differentiated values within the discrepancy value λ. Applying it to threshold voltage extraction, we found that $V_{\rm TH}({\rm TC})$ could be extracted with stability and simple procedure. $V_{\rm TH}({\rm TC})$ showed a close correlation to $V_{\rm TH}(P)$ and $V_{\rm TH}({\rm NMID})$. Therefore, it can provide us with a powerful analysis tool for device modeling and characterization.

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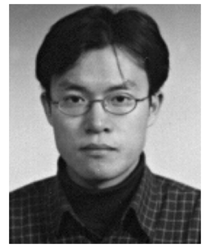

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