ON ESTIMATING DIFFERENTIAL CONDUCTANCE FROM NOISY *I-V* MEASUREMENTS IN DELINEATING DEVICE PARAMETERS

Indrajit G. ROY
Spaceage Geoconsulting, 5 Bick Place, Banks, ACT 2906, Australia,
Tel.: +61 2 6294 2510, E-mail: spaceage.geocon@gmail.com

ABSTRACT

Differential conductance is a key to characterizing a solid-state device. Estimation of differential conductance from current-voltage characteristic curve amounts to estimate the first order derivative from a discrete set of current-voltage measurements of the device under test. Conventional difference method in estimating derivative is inadequate when data contain noise. A robust method of estimating the first order derivative from a discrete set of evenly distributed current versus voltage measurements is designed where the method does not pose any constraints or limits on the data interval. The proposed method is formalized in the premise of the fundamental theorem of calculus and the inverse problem. The robustness of estimation is ensured using a regularization technique where the regularization operator is considered as a first order differential operator. A modified form of the L-curve technique is used to determine an optimal regularization parameter. The method is tested on synthetic and measured current-voltage characteristics of Schottky diode and MOSFET.

Keywords: *differential conductance, regularization, I-V curve, solid-state device*

1. INTRODUCTION

Characterization of solid state devices for performance analysis or modeling purposes is an essential exercise, which is, however, realized by estimating the design parameters of a device. For example, with a Schottky diode, the current-voltage (*I-V*) characteristic curve is commonly used to estimate the diode parameters, such as the barrier height (Φ_b), saturation current (I_s), ideality factor (η), parasitic series resistance (R_s) etc. [1-3]. In that the variation of differential conductance ($\delta G = dI/dV$) with respect to the bias voltage is used in estimating Schottky diode parameters [4-6]. Similarly, with a metal oxide semiconductor (MOS) device the important device parameters, such as channel conductance ($g_d = dI_D/dV_D$), transconductance ($g_m = dI_D/dV_g$), channel mobility (μ_0) and threshold voltage (V_{th}) are obtained from the measurement of drain current (I_D) versus gate-source voltage (V_g) and the drain current (I_D) versus drain-source voltage (V_D) [7] . Ghibaudo [8] use drain current (I_D) versus gate-source voltage (V_{th}) measurements to estimate the transconductance characteristic $g_m(V_g)$ which is then used in determining the channel mobility (μ_0) and threshold voltage (V_{th}).

Clearly, estimation of derivative from the current-voltage measurements in a DC mode is the key for estimating parameters of a device. The current-voltage measurement of a device is relatively a simple exercise. With a programmable source meter such measurement for a device is normally carried out in small steps (or in interval) over a preset bias voltage range in an automatic fashion, and the data are readily available in a stored media. On the other hand, the exercise of estimating the differential conductance for a device, such as a Schottky diode, from the measured data often becomes non-trivial as noise in the measurements renders an unpleasant situation to an extent where the estimated conductance versus voltage characteristic curve becomes unusable for device parameter estimation.

The presence of noise in the current-voltage measure-

ment for any electronic device is almost inevitable. The sources of noise are of various types, such as Johnson-Nyquist noise, shot noise, flicker noise etc. Among those, the presence of Johnson-Nyquist and shot noise in the current-voltage measurements is, in fact, inevitable. Broadly, we may put those noises under the category of Gaussian distributed random noise. The strength of the noise, measured in terms of signal-to-noise ratio (SNR), often becomes the decisive factor in the exercise of parameter estimation of a device. In this paper we propose a novel technique in estimating derivatives of evenly spaced measurements in a sufficiently robust manner. We demonstrate applicability of the technique using simulated current-voltage data for a Schottky diode and MOSFET contaminated with noise, and with the real measured current-voltage data of Au/*n* GaAs Schottky diode.

2. THEORY

The proposed technique, based on linear inverse theory, uses the method of regularization in estimating derivative. For the sake of convenience suppose that the measurements are carried out in a forward bias mode within an interval $[0, V_{max}]$ with a step of ΔV. Nevertheless, the proposed method is equally applicable for measurements in the reverse bias voltage mode as well. The evenly spaced discrete *I* versus *V* data, if not contaminated with noise, is assumed to form a smooth and continuously differentiable *I-V* curve. The differential conductance δG is a function of the bias voltage and is defined as $\frac{d}{dV}[I(V)]$. Using the first principle of calculus we write

$$I(V) = I(0) + \int_0^{V_{end}} \delta G \ dV, \qquad (1)$$

where $I(0)$ corresponds to V_b^0, a zero-bias built-in voltage or a value related to band bending. Discretizing equation (1) leads to the following matrix equation

$$\mathbf{A}\,\delta\,\mathbf{G} = \mathbf{I}, \qquad (2)$$

where the matrix $\mathbf{A}$ is written as

$$\mathbf{A} = \begin{bmatrix} \Delta V & 0 & 0 & \cdots & 0 & 0 \\ \Delta V & \Delta V & 0 & \cdots & 0 & 0 \\ \Delta V & \Delta V & \Delta V & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \Delta V & 0 \\ \Delta V & \Delta V & \Delta V & \cdots & \Delta V & \Delta V \end{bmatrix}_{N \times N} . \tag{3}$$

where N, the order of matrix $\mathbf{A}$, stands for number of samples in the dataset, $\delta \mathbf{G}$ is the vector of differential conductance and $\mathbf{I}$ is the vector comprised of measured current values corresponding to the bias voltage V at the grid nodes. Truly speaking, the vector $\mathbf{I}$ is replaced with $\mathbf{I}^\varepsilon$ in practical situation, where ε is the noise level in the measured data. To solve equation (2) we use following optimization rule

$$\text{minimize } \|\hat{\mathbf{D}}\, \delta \tilde{\mathbf{G}}\|_2^2 \text{ such that } \|\mathbf{A}\, \delta \tilde{\mathbf{G}} - \mathbf{I}^\varepsilon\|_2^2 \leq c_1 \varepsilon^2,$$

where c_1 is an arbitrary constant, and

$$\hat{\mathbf{D}}\, \delta \tilde{\mathbf{G}} =$$

$$\begin{bmatrix} -\Delta V^{-1} & \Delta V^{-1} & 0 & 0 & \cdots & 0 \\ 0 & -\Delta V^{-1} & \Delta V^{-1} & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \cdots & \vdots \\ \vdots & \vdots & 0 & -\Delta V^{-1} & \Delta V^{-1} & 0 \\ 0 & 0 & \cdots & 0 & -\Delta V^{-1} & \Delta V^{-1} \end{bmatrix} \begin{bmatrix} \delta \tilde{G}_1 \\ \delta \tilde{G}_2 \\ \vdots \\ \delta \tilde{G}_{N-1} \\ \delta \tilde{G}_N \end{bmatrix} . \tag{4}$$

where dimension of the matrix $\hat{\mathbf{D}}$ is $(N-1) \times N$ and dimension of the vector $\delta \tilde{\mathbf{G}}$ is $N \times 1$. On what follows

$$\left(\mathbf{A}^T \mathbf{A} + \lambda \hat{\mathbf{D}}^T \hat{\mathbf{D}}\right) \delta \tilde{\mathbf{G}} = \mathbf{A}^T \mathbf{I}^\varepsilon, \tag{5}$$

where λ is an arbitrary scalar, known as a regularization parameter whose optimal value, being crucial, is determined. Ideally an optimal value of regularization parameter should be chosen based on the noise level in data. Literature abounds in techniques of choosing optimal value of regularization parameters; however an optimal regularization parameter which makes a trade-off or in other words, balances the smoothness constraint and the data fitting is possibly the suitable one. Recently, selection of regularization parameter based on balancing principle is getting an increased attention [9-11]. However, as demonstrated in [11], the method requires at least an ad-hoc estimation of the noise level in the data. Unfortunately, often it is not possible to have an estimation of noise level in the measured data *a priori*. An intuitively appealing approach of determining an optimal value of regularization parameter is the *L*-curve technique [12-13], although the method possesses certain limitations [14]. The regularization parameter corresponding to the corner of the curve is chosen as an optimal value which is sometimes computationally challenging as, often, corner of the curve is not conspicuous to identify. We consider here a technique as suggested in [15] to determine an optimal value of the regularization parameter λ_{op}. The discrepancy and the smoothness constraint terms corresponding to the derivative are given respectively in the following

$$\Theta = \|\mathbf{A}\,\delta\hat{\mathbf{G}} - \mathbf{I}^\varepsilon\|_2 \tag{6}$$

and

$$\Pi = \|\delta\tilde{\mathbf{G}}\|_2. \tag{7}$$

We define a new function $\Psi(\lambda)$ as

$$\Psi(\lambda) = \Theta \cdot \Pi. \tag{8}$$

For a set of values of λ the plot of $\Psi(\lambda)$ versus λ curve in a double logarithmic scale demonstrates the presence of a prominent local minimum within the chosen range of λ values. The value of λ corresponding to the local minimum is considered as an optimal value of the regularization parameter. Once, an optimal value of regularization parameter λ_{op} is estimated the robust estimate $\delta \tilde{\mathbf{G}}$ with respect to the bias voltage V follows. Since an optimal value of regularization parameter λ_{op} satisfies the optimization rule for solving the linear set of equations with the noise contaminated data vector in the right hand side then it can be said $\mathbf{A}\delta\tilde{\mathbf{G}}$ would provide $\tilde{\mathbf{I}}$, a best estimate of the true value of $\mathbf{I}$. Hence,

$$\|\tilde{\mathbf{I}} - \mathbf{I}^\varepsilon\|_2^2 \approx \varepsilon^2. \tag{9}$$

Equation (9) is used as a stopping condition and also as an appraisal of the estimated output. We use the proposed methodology in device characterization exercise.

3. NUMERICAL EXPERIMENTS

We conducted numerical experiment to validate the proposed methodology as a practical means of characterizing a device through the measurement of current-voltage characteristic. We conducted numerical test which was comprised of two stages. In the first stage, we simulated the *I-V* data for a device, which was contaminated with random noise and applied the proposed methodology to estimate the differential conductance. To compare the performance of the proposed method with the conventional one we also tested the noise contaminated data using a central difference scheme to estimate derivative. In the second stage we used the proposed methodology to real measured data for characterization of two types of devices viz. Schottky diode and MOSFET.

3.1. Diode equation

With the application of bias voltage V there exists the diode current I_d across the junction due to thermionic and/or quantum tunneling mechanisms flows. The bias voltage V and the diode current I_d are modeled with a well known diode equation based on thermionic emission theory [1] as

$$I_d = I_s \left[\exp\left(\frac{q(V - I_d R_s)}{\eta \kappa_B T}\right) - 1 \right], \tag{10}$$

where I_d is the measured diode current due to the applied bias voltage V and η is the ideality factor, a dimensionless parameter. The small saturation current I_s that arises due to motion of minority carriers is given as

$$I_s = A_{\text{eff}} A^{**} T^2 \exp\left(-q\Phi_b / \kappa_B T\right), \tag{11}$$

where A_{eff} is an effective area of the diode expressed in cm^2, A^{**} is reduced Richardson constant expressed in

$A\,cm^{-2}\,K^{-2}$. For n-type semiconductor the value of A^{**} is $112\,A\,cm^{-2}\,K^{-2}$ and for p-type semiconductor the value of A^{**} is $32\,A\,cm^{-2}\,K^{-2}$ or sometimes $79\,A\,cm^{-2}\,K^{-2}$, Φ_b is the Schottky barrier height (SBH) expressed generally in eV, $q = 1.602 \times 10^{-19}\,C$ is the electronic charge in Coulomb, $\kappa_B = 1.3806 \times 10^{-23}\,J/K$ is a Boltzmann constant, T is absolute temperature in Kelvin. For an ideal diode the SBH (Φ) is independent of bias voltage and the ideality factor (η) becomes unity. On what follows

$$I_d = I_s \exp\left(\beta V_d\right) \qquad (12)$$

and

$$I_s = A_{\text{eff}} A^{**} T^2 \exp\left(-\beta \Phi_b\right), \qquad (13)$$

where $\beta = q/\kappa_B T$ and $V_d = V - I_d R_s$. For the sake of notational simplicity we replace we replace I_d and V_d by I and V respectively. For an ideal Schottky diode the plot of dI/dV versus V in a semi-logarithmic scale is a straight line with a slope $d(\ln I)/dV = \beta$, The intercept I_s made by the straight line in the I axis would help in estimating the value of SBH and other parameters as well.

3.2. Numerical tests with diode

We generate the synthetic current-voltage (I-V) data simulating an ideal Schottky diode with an n-type semiconductor, the values of parameters taken from [7] is given in Table 1. The I-V characteristic curve is generated for the forward bias voltages distributed between $0 - 0.2\,V$ with a step of 2 mV. The synthetic data are then contaminated with additive Gaussian random noise before being implemented in the numerical test. The test was conducted with noise level of 2 and 5% respectively.

Table 1 Parameters of a Schottky diode taken from [3] used to calculate synthetic I-V characteristic response

Parameters	Values	Units
Barrier height (Φ_b)	0.6	eV
Area of diode (A)	0.00384	cm^2
Reduced Richardson constant (A^{**})	112	$A\,cm^{-2}\,K^{-2}$
Abs. temperature at $25°\,C$ (T)	298.16	$°K$
Boltzman constant (κ_B)	1.3806×10^{-19}	$cm^2 kgs^{-2} K^{-1}$
Series reistant (R_s)	50	Ω

The test results are presented in the panels (a)-(f) in Fig. 2. Panels (a) and (d) present current-voltage characteristics contaminated with Gaussian random noise with level 1 and 2% respectively.
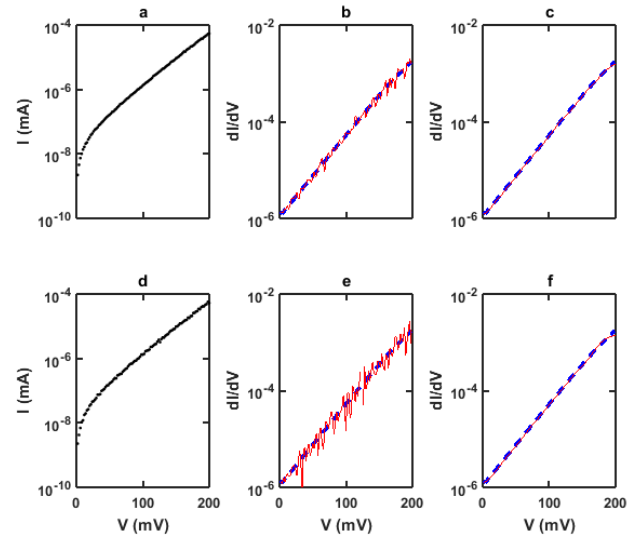

Fig. 1　Panel (a) & (d) plots of diode current I vs. forward bias voltage V. using parameters given in Table 1, and (b)-(f) plots of dI/dV versus V. The upper and lower panels correspond to synthetic data contaminated by 1, and 2 % Gaussian random noise respectively. Panels (b) & (e) are dI/dV versus V using difference scheme with noise (solid line) and also with no noise (broken lines) corresponding to noise level 1 and 2% respectively. Panels (c) & (f) are same as panels (b) & (e) except that derivatives are computed using the proposed scheme (solid line). The curves with broken lines correspond to derivative with no noise in data.

Panels (b) and (e) present estimated differential conductance ($\delta G = dI/dV$) using the central difference scheme corresponding to the Gaussian noise 1 and 2% respectively. Panels (c) and (f) present estimated differential conductance using the proposed scheme corresponding to the Gaussian noise 1 and 2% respectively. Note that broken lines (color blue) represent the analytical computed differential conductance while the solid line (color red) represents the estimated one.
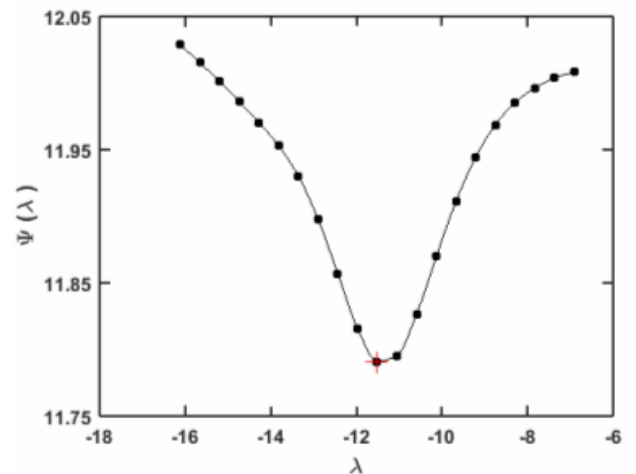

Fig. 2　Plot of $\ln[\Psi(\lambda)]$ versus $\ln(\lambda)$. The bullets are the discrete values and the solid line correspond to an interpolated curve. The location of optimum value of λ is marked with a red colored cross mark.

Clearly, the conventional difference scheme fails to demon-

strate sufficient robustness whereas the proposed scheme provides desired robustness in estimating the first order derivative of noisy *I-V* measurements. In Fig. 2 we present the plot of $\Psi(\lambda)$ versus λ in a double logarithmic scale which is used to estimate an optimal value of λ

We next consider a non-ideal Schottky diode which possesses inhomogeneous Schottky barrier Height (SBH). Variable crystallographic orientation of polycrystalline structure of metallic layer is one of the causes of inhomogeneity in SBH [16]. For a non-ideal diode the plot of dI/dV versus V in a semi-logarithmic scale does not demonstrate the shape of the curve as a straight line especially with a bias dependent barrier height [17]. The power exponent method has been suggested in [6] to determine Schottky diode parameters in a more generalized situation. The power exponent α is defined as [6]

$$\alpha = \frac{d(\ln I)}{d(\ln V)}. \tag{14}$$

The power exponent α is a function of the forward bias voltage V. The plot of α versus V allows determining diode parameters. However, Olikh in [4] demonstrates with the synthetic data contaminated with 1% of random noise that the parameter estimation using α versus V plot affects severely due to lack robustness in generating the $\alpha - V$ curve. In the following example we demonstrate how the proposed method provides robust estimate of $\alpha - V$ curve from noisy *I-V* characteristic. We consider experimental data of *I-V* curve of an Au/*n*GaAs Schottky diode as used in [17]. Due to unavailability of the experimental data directly, we redrew the Fig. 2 of [17] and digitized part of the figure with a grid interval of 2 mV. The process of redrawing and digitization causes noise in the simulated experimental data. Since, our objective is to generate a smooth $\alpha - V$ curve from a noisy *I-V* curve, this situation is ideal. The digitized I-V curve is shown in Fig. 3.
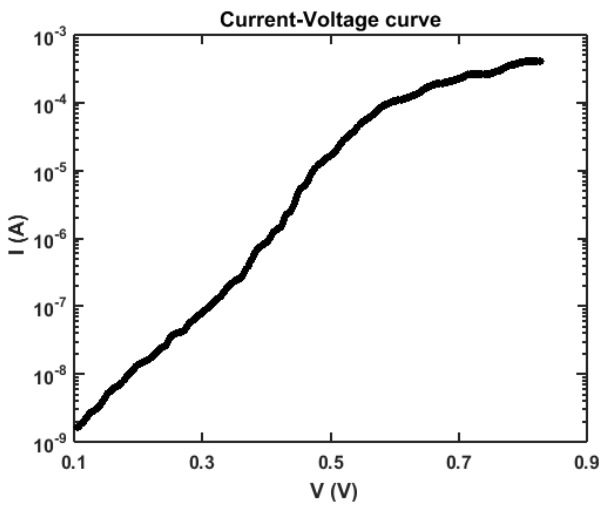

Fig. 3   Plot of *I-V* curve of experimental data of Au/*n*GaAs Schottky diode taken from [17]. The original curve of [17] was redrawn and digitized with an interval of 2 mV.

Note that the *I-V* curve in Fig. 3 is far from being smooth. Clearly there exists noise in the data; but estimating noise level is difficult. Nonetheless, the proposed

method does not require any a priori estimation of noise. We used the proposed scheme on the noisy *I-V* data. The estimated first order derivative dI/dV versus the bias voltage V is plotted in Fig. 4.
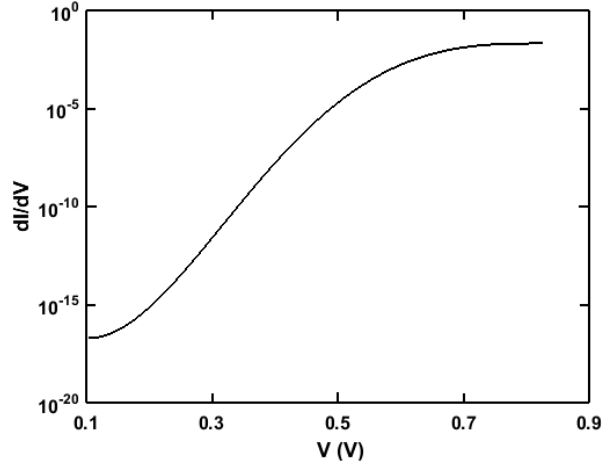

Fig. 4   Plot of dI/dV versus V.

Note that the estimated dI/dV versus V curve using the proposed scheme is sufficiently smooth. In the following we present power exponent α versus forward bias voltage V curve.
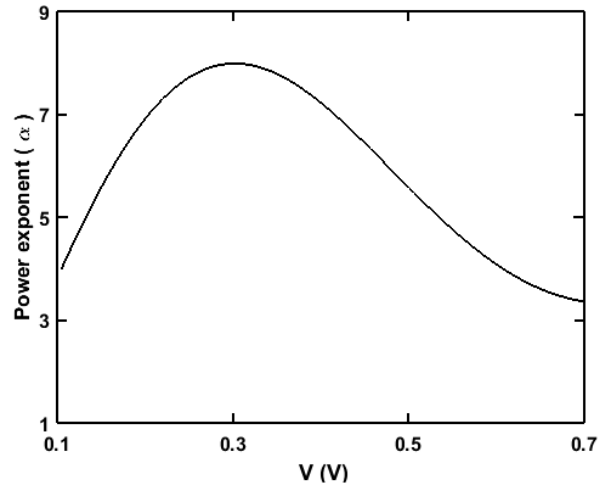

Fig. 5   Plot of α versus V curve.

Note that the estimated power exponent α versus V curve is sufficiently smooth which is used in estimating Schottky diode. The estimated parameter is in close agreement with the reported values. Determination of optimal value of regularization parameter λ_{op} is a key in the proposed scheme. The plot of $\ln[\Psi(\lambda)]$ versus $\ln(\lambda)$ in Fig. 6 demonstrates the ease in determining an optimal value of the regularization parameter, as the presence of the local minimum is quite conspicuous.
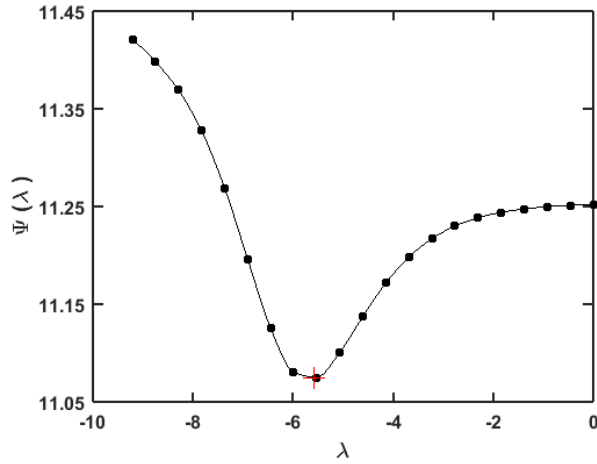
Fig. 6   Plot of $\ln\left[\Psi(\lambda)\right]$ versus $\ln(\lambda)$. The bullets are the discrete values and the solid line is interpolated one.

Table 2 Parameters of a MOSFET used to calculate synthetic *I-V* characteristic response

Parameters	Values	Units
Effective channel width (W)	20	μm
Effective channel length L	7	μm
Gate oxide capacitance (C_{ox})	157	nFcm^{-2}
Drain voltage ($V_{d,s}$)	200	mV
Low field mobility (μ_0)	280	cm^2/Vs
Mobility attenuation factor (θ_1)	0.02	V^{-1}
Mobility attenuation factor (θ_2)	0.05	V^{-2}
Coulomb scattering parameter (ν)	0.04	

3.3. Numerical tests with MOSFET

We next conducted numerical test considering parameter extraction principle for a MOSFET device. Ghibaudo [8] demonstrates that the characteristic of drain-source current $I_{d,s}$ versus gate overdrive voltage ($V_{g,s} - V_{th}$) of a MOSFET can be used to estimating extract threshold voltage V_{th}, low-field mobility μ_0 and the mobility attenuation coefficient θ. The revised formula for drain-source current according to [18] is given as

$$I_{d,s} = \mu_{\text{eff}} C_{ox} \frac{W}{L} (V_{g,s} - V_{th})(V_{d,s} - I_{d,s} R_p), \tag{15}$$

where W and L are the effective channel width and length respectively, C_{ox} is the gate oxide capacitance, $V_{d,s}$ is the drain-source voltage, R_p is the parasitic resistance at source and drain contacts and μ_{eff} is the effective mobility given as [19]

$$\mu_{\text{eff}} = \mu_0 \frac{A_\nu (V_{g,s} - V_{th})^\nu}{1 + \theta_1 (V_{g,s} - V_{th}) + \theta_2 (V_{g,s} - V_{th})^2} \tag{16}$$

where μ_0 is the low field mobility, θ_1 is the attenuation mobility factor due to phonon scattering, θ_2 is mobility attenuation factor due to surface roughness scattering, parameter ν is related to Coulomb scattering due to surface roughness. A_ν, the scale factor, equals to unity. The parasitic resistance R_p is, however, neglected in the current case. The transconductance g_m is written as

$$g_m = \frac{d I_{d,s}}{d V_{g,s}} \tag{17}$$

The plots of $I_{d,s}/\sqrt{g_m}$ and $1/\sqrt{g_m}$ versus $V_{g,s} - V_{th}$ allow to extract parameters. Using design parameters of an p-MOSFET on Si(110) wafer (Table 2) and also equation 14 we generated synthetic drain current versus gate overdrive voltage characteristic. The synthetic data contaminated with 1% Gaussian random noise are used in the numerical test.

The noise contaminated $I_{d,s}$ versus gate overdrive voltage (bullets), the estimated transconductance g_m versus gate overdrive voltage ($V_{g,s} - V_{th}$) using the proposed method (broken lines) and the conventional difference formula (solid line) are presented in Fig. 7. The test results clearly demonstrate the superior performance of the proposed method over the conventional one.
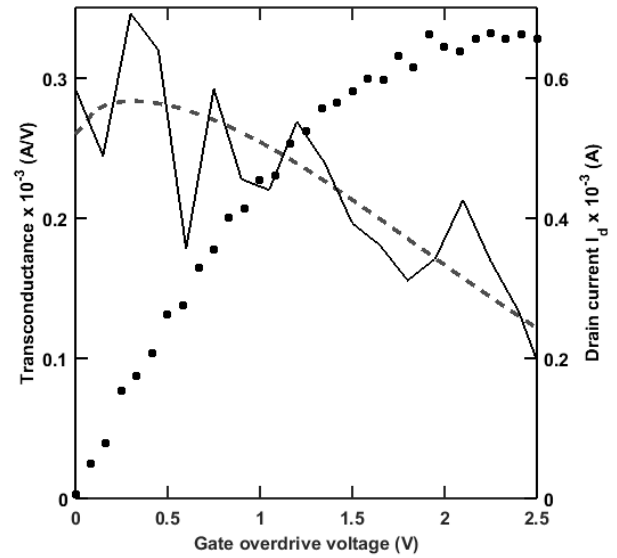

Fig. 7   Plots of synthetically generated drain current with 1% additive white Gaussian noise (bullets) the estimated transconductance using proposed scheme (gray broken lines), and using conventional difference scheme (solid line) versus gate overdrive voltage for a *p*-MOSFET on Si(110) wafer.

4. CONCLUSIONS

The robust estimate of the first order derivative of *current-voltage* characteristic curve is highly essential in transforming the foretold curve into *conductance-voltage* characteristic curve, which, in turn, allows estimating the design parameters of a solid-state device. Presence of noise in the current-voltage measurements makes the task of es-

timating derivative remains challenging while using a conventional difference scheme. The proposed regularization based method allows robust estimation of derivative without using *a priori* knowledge of the noise level in the measured data. Numerical experiment with synthetic and the real measured data demonstrates the applicability of the proposed method in estimating differential conductance and transconductance of Schottky diode and MOSFET respectively.

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BIOGRAPHY

Indrajit G. Roy was born in 20.5.1958. He did Masters (M.Sc.Tech) degree in Applied Geophysics from Indian School of Mines, Dhanbad, India. He did PhD in Applied Geophysics from Indian School of Mines in 1987. He specializes in signal processing, computational methods in geophysics and physics and also in design of instruments. He was Senior Scientist at Geoscience Australia. Currently, he is a Principal Scientist at Spaceage Geoconsulting, a research oriented consulting firm in Australia.