Parasitic series resistance-independent method for device-model parameter extraction

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Abstract: A new method is presented that permits the extraction of a semiconductor device's intrinsic model parameters from its experimental extrinsic forward *I–V* characteristics, independently of the parasitic resistance that might be present in series within the real device. The extraction is performed from an auxiliary function which contains the integral of the experimentally measured data. Integrating the data also serves as a smoothing procedure. The diode quality factor, reverse current and series resistance parameters of a single exponential diode model are extracted from a real *p-n* junction diode in order to illustrate the method.

1 Introduction

Parasitic series resistance is frequently significant in semiconductor devices, such as Schottky diodes, *p-n* diodes, bipolar transistors, MOSFETs, etc. It represents a complication for the extraction of device-model parameters from experimental *I–V* characteristics. Many methods have been proposed to perform the parameter extraction even in the presence of series resistance [1]. Some of these methods rely upon differentiating the measured *I-V* characteristics, which tends to worsen the experimental measurement errors that might be present in the data. We recently proposed another method [2] based on the use of the integral of the data, instead of the derivative. Integration acts as a lowpass filter and, thus, tends to lessen the effect of measurement errors on the extraction procedure. However, that method was not independent of the parasitic series resistance of the device. In the present work we have extended our previous extraction procedure to make it independent of the parasitic series resistance, as long as this resistance can be considered to be constant within the range of analysis.

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2 Theoretical basis

Consider two generalised two-terminal devices, *d* and *r*, which are connected in series. A terminal voltage V is applied to the series combination causing a current I to flow through the devices which produces voltage drops V_d and V_r across them. Let this current be defined by the functions $f(V_d)$, $h(V_r)$ and $g(V)$ of the voltages across the terminals of the two devices and the series combination, respectively. Thus,

$$I = f(V_d) = h(V_r) = g(V) \tag{1}$$

The voltages can be expressed by their corresponding inverse functions of current as

$$g^{-1}(I) = f^{-1}(I) + h^{-1}(I) \tag{2}$$

Using geometric considerations, equivalent to integrating by parts, the following equalities can be written:

$$\int_0^{V_{do}} I\, dV_d + \int_0^{I_o} V_d\, dI = I_o V_{do} \tag{3}$$

$$\int_0^{V_{ro}} I\, dV_r + \int_0^{I_o} V_r\, dI = I_o V_{ro} \tag{4}$$

$$\int_0^{V_o} I\, dV + \int_0^{I_o} V\, dI = I_o V_o \tag{5}$$

where V_{do}, V_{ro} and V_o are upper voltage integration limits corresponding to an upper current integration limit I_o at a certain point in the *I–V* characteristics of the devices and terminal. Integrating the sum of the two voltages of the devices with respect to current from 0 to I_o gives

$$\int_0^{I_o} V\, dI = \int_0^{I_o} V_d\, dI + \int_0^{I_o} V_r\, dI \tag{6}$$

The substitution of eqns. 3, 4 and 5 into eqn. 6 produces a similar expression for the integrals of the current with respect to the three voltages

$$\int_0^{V_o} I\, dV = \int_0^{V_{do}} I\, dV_d + \int_0^{V_{ro}} I\, dV_r \tag{7}$$

Finally, subtracting eqn. 7 from eqn. 6, we can define a 'difference function' D as

$$D = \int_0^{I_o} V\,dI - \int_0^{V_o} I\,dV \tag{8}$$

$$= \left(\int_0^{I_o} V_d\,dI - \int_0^{V_{do}} I\,dV_d\right) + \left(\int_0^{I_o} V_r\,dI - \int_0^{V_{ro}} I\,dV_r\right)$$

This function is valid, not only for this case of two devices in series, but also in general for any number of generalised devices connected in series, if the two-term addition in the right-hand side of eqn. 8 is substituted by a summation over all the devices involved. It could be easily demonstrated that it holds true also for parallel or mixed connections of generalised devices. This function has a form analogous to Tellegen's theorem of conservation of power [3], which would be written as eqn. 8 with the minus signs replaced by plus signs.

3 Case of a constant series resistance

We analyse now the case when one of the two devices is linear. Let device d be a generalised nonlinear device, and let the current be a linear function of the voltage across device r, as defined by

$$I = h(V_r) = \frac{V_r}{R} \tag{9}$$

where R is constant. Substituting eqn. 9 into eqn. 8 yields an expression that no longer contains the series resistance

$$D = \int_0^{I_o} V\,dI - \int_0^{V_o} I\,dV = \int_0^{I_o} V_d\,dI - \int_0^{V_{do}} I\,dV_d \tag{10}$$

where the nonlinear behaviour of the device has been isolated.

Eqn. 10 can be expressed in a way that only one numerical integration of the measured I–V data is required by substituting eqns. 3 and 5 into it.

$$D = I_o V_o - 2\int_0^{V_o} I\,dV = I_o V_o - 2\int_0^{V_{do}} I\,dV_d \tag{11}$$

This expression relates the I–V data measured at the terminals, on the left-hand side, to only the model of the nonlinear part of the device, on the right-hand side. As an illustrative example of how to use this method for parameter extraction we will next apply it to the simple case of modelling a real diode by a single exponential ideal diode with series parasitic resistance.

4 Diode with constant series resistance

Real p-n junctions are frequently modelled by a single exponential function of the type described by Shockley's equation

$$I = f(V_d) = I_s\left[\exp\left(\frac{V_d}{nV_t}\right) - 1\right] \tag{12}$$

where I_s is the reverse current, V_d is the intrinsic voltage across the junction, n is the so-called diode quality factor and V_t is the thermal voltage kT/q. If there seems to be a significant parasitic series resistance present, the real diode is often modelled by a modified Shockley equation that includes a constant series resistance,

$$I = g(V) = I_s\left[\exp\left(\frac{V - IR}{nV_t}\right) - 1\right] \tag{13}$$

The extraction of the model's parameters I_s and n is customarily performed either by direct numerical fitting, by some other method involving pre-manipulation of the data, or by graphical analysis of ln(I) against V plots. However, the presence of R can significantly reduce the linear portion of these plots to such an extent that the determination of I_s and n becomes unreliable. Eliminating the effect of R is therefore very important for the extraction procedure. A method, developed by Norde [4], for the particular case of n = 1, uses an auxiliary function to extract I_s and R. Then, a straight line fit of the ln(I) against (V - IR) plot is used to calculate the exact value of n. Extensions of Norde's method have been developed to allow direct extraction of the diode quality factor [5]. Other methods that follow Norde's idea have also been proposed [6]. However, any method based on the forward I–V characteristics still depends on first finding the value of the parasitic series resistance. This difficulty imposed by the presence of a parasitic series resistance is circumvented by the use of the present concept of the difference function.

If we restrict the procedure, as is usually done, to a region of the I–V characteristics where $I_o >> I_s$ but low enough for high injection effects to be negligible, the substitution of eqn. 12 into the right-hand side of eqn. 11, yields

$$D \approx I_o n V_t\left[\ln\left(\frac{I_o}{I_s}\right) - 2\right] \tag{14}$$

Dividing this equation by the current I_o we can define an auxiliary function $G(I_o, V_o)$ of the experimental terminal current and voltage as

$$G(I_o, V_o) = \frac{I_o V_o - 2\int_0^{V_o} I\,dV}{I_o} \approx nV_t\left[\ln\left(\frac{I_o}{I_s}\right) - 2\right] \tag{15}$$

When this auxiliary function $G(I_o, V_o)$, obtained by numerical calculation from the experimental data, is plotted against ln(I_o), it should produce a straight line, whose slope and intercept allow the direct calculation of n and I_s, respectively. The variations of both I_s and n along the I–V characteristics may now be visualised, even where R is not negligible. This is not possible to do from ln(I) against V plots when R is large. Therefore, in contrast to the more conventional methods, the n and I_s values extracted by the present method are not obscured or otherwise affected by the value of the parasitic series resistance R.

To illustrate the procedure we applied it to a real diode with high series resistance, the source-body junction of a Siliconix MOSFET measured at room temperature [2]. Next, the measured current was integrated numerically with respect to the applied voltage and the function $G(I_o, V_o)$ was calculated in accordance with the left-hand side of eqn. 15. Fig. 1 presents the plot of the auxiliary function $G(I_o, V_o)$ against ln(I). Although this function is not totally linear, it presents a large quasilinear portion. It exhibits a minimum at low current and levels off at high current, in the regions where the approximation has become invalid and high injection effects can no longer be neglected. The slope and intercept of the straight-line fit of the quasilinear portion of $G(I_o, V_o)$, also shown in Fig. 1, produces values of $I_s = 5.1 \times 10^{-14} A$ and $n = 1.12$.

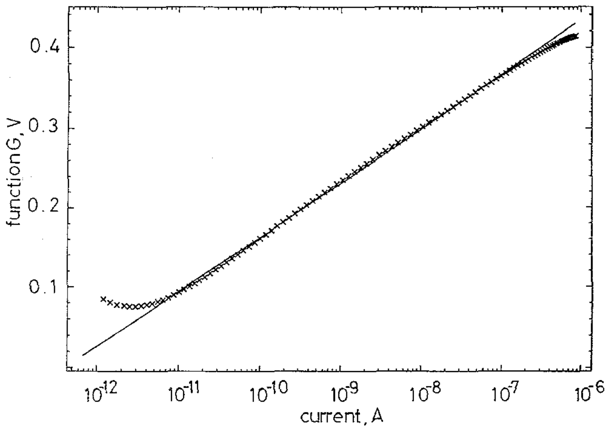

Fig. 1 *Auxiliary function $G(I_o, V_o)$ as a function of current (symbols) and linear fit of its quasilinear portion (continuous line)*

Parameters n and I_s can also be calculated point by point from the derivative of $G(I_o, V_o)$ with respect to the logarithm of the current. Fig. 2 presents the resulting values of n and I_s plotted as functions of increasing voltage. They allow visualisation of the relative dominance at different voltages of the various conduction mechanisms present in the device. Finally, the value of the parasitic series resistance can be easily calculated, for instance, by taking the difference between the junction voltage, as calculated from the model of eqn. 12, and the measured terminal voltage, and dividing it by the measured current. For the purpose of this illustrative example we extracted near 0.6V a value of series resistance of 12kΩ.

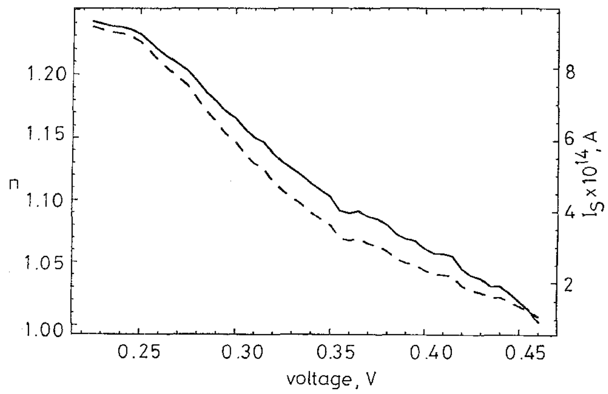

Fig. 2 *Diode quality factor (continuous line) and reverse current (broken line) as a function of applied voltage*

Fig. 3 presents the comparison between the experimentally measured data and the modelled I–V characteristics, as calculated from eqn. 13, with the abovementioned extracted values of I_s, n and R substituted into it. A comparison of the two curves, shows that the parameters used represent only a good compromise choice which is necessary for fitting a single exponential model to the measured I–V characteristics. The choice obviously depends on the operation range of interest. It should be pointed out that for the fit to be any better, this device needs to be modelled by a double exponential equation [7], as suggested by the inflexion present around the middle region of the experimental I–V characteristics or by the variation of n and I_s, clearly displayed in Fig. 2.

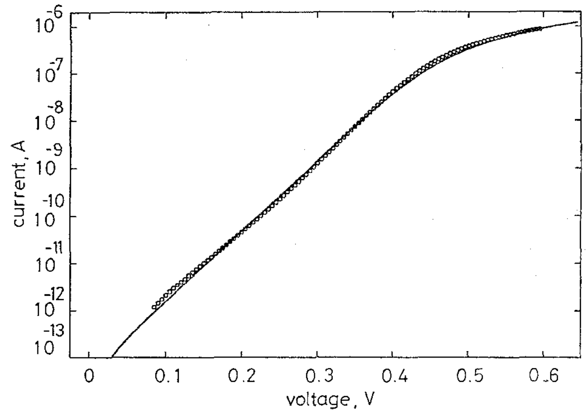

Fig. 3 *Experimentally measured data (symbols) and I–V characteristics modelled by eqn. 13, using extracted parameters $I_s = 5.1 \times 10^{-14} A$, $n = 1.12$ and $R = 120k\Omega$ (continuous line)*

5 Conclusions

We have shown that the proposed concept of the difference function D provides a means of isolating the nonlinear behaviour of a two-terminal semiconductor device, thus allowing the extraction of its intrinsic model parameters independently of any parasitic resistance present, as long as this resistance can be considered to be constant within the range of interest. Analogous procedures could be attempted to facilitate the extraction of the intrinsic parameters of other semiconductor devices, such as the barrier height in Schottky diodes or the source-drain characteristics of MOSFETs.

6 References

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