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Extraction of Schottky diode parameters including parallel conductance using a vertical optimization method

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Abstract

An improved method based on a computer-aided curve fitting technique that uses vertical optimization for the simultaneous determination of various Schottky diode parameters (I_s, n, R_s and G_p) from the I–V characteristics has been re-examined. In particular, it is shown that the inclusion of the effect of a shunt conductance in the analysis of transport properties allows the determination of more realistic values for the parameters of various quality diodes. The present method appears to be accurate even in the presence of noise and/or random errors during measurements.

1. Introduction

The evaluation of Schottky diode (SD) parameters provides a useful guidance of modeling and simulation of the characteristics of these devices. I–V measurements, in particular, are routinely used to extract various SD parameters. In doing so, it is often assumed that pure thermionic emission is the dominant transport process in SDs. The experimental I–V data can be described in this case by the equation:

$$I_d = I_s\left[\exp\left(\frac{\beta}{n}V_d\right) - 1\right] \tag{1}$$

where I_d is the diode current at bias V_d, $\beta = (q/kT)$ is the usual inverse thermal voltage, n is the ideality factor and I_s is the saturation current which is given by:

$$I_s = AA^{**}T^2\exp(-\beta\varphi) \tag{2}$$

Here A is the diode area, A^{**} is the modified Richardson constant and φ is the Schottky barrier height (SBH).

The standard method [1–3] widely used to extract the SD parameters requires the presence of a linear region in the $\ln(I_d)$ versus V_d plot. The desired parameters are then obtained from the slope and intercept of the linear region using the Eqs. (1) and (2) above.

This relatively simple analysis fails when a parasitic series resistance (R_s) is present. The presence of R_s affects the I–V characteristics mostly at high voltages and to account for this, Eq. (1) is re-arranged to become:

$$I_d = I_s\left[\exp\left(\frac{\beta}{n}(V - R_sI)\right) - 1\right] \tag{3}$$

In this case the problem of parameter extraction becomes slightly more complicated in comparison with the standard method.

Several alternative methods have been proposed over the last few years to circumvent the problem introduced by R_s when extracting the desired parameters [4–9]. Almost all of the published methods use the construction of some auxiliary functions that allow the separation of the effect of R_s. In other proposed analytical methods, the R_s problem is solved using the small-signal conductance, differentiation or integration of the current with respect to voltage and addition of an external resistance in series with the diode in the measured I–V data

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[10–15]. Numerical techniques have been also used to calculate the parameters of the diode. These are based on the application of algorithms to optimize functions defining the difference between the experimental characteristics and the theoretical model [16–19,21,22]. The main advantages, limitations and drawbacks of the proposed methods have been analyzed in many papers (see for example Refs. [3,11,18,20–22]).

Among the recent published methods [21,22], the so called lateral and vertical optimization are now very popular due to their simplicity in concept, accuracy and efficiency for extracting SD parameters. The popularity and power of such methods owe also to the availability of powerful computers and sophisticated programming techniques (software).

In all the methods above the influence of a possible shunt conductance (G_p) on the I–V characteristics is, however, overlooked and not taken into account. In fact, the complete representation of a real I–V characteristics in the presence of G_p is given by:

$$I = I_d + I_p = I_s\left[\exp\left(\frac{\beta}{n}(V - R_sI)\right) - 1\right] + G_p(V - R_sI) \tag{4}$$

where I_p describes the shunt current through the shunt resistance $R_p = 1/G_p$.

The shunt resistance affects the I–V characteristics at low forward voltages and more importantly the reverse characteristics of diodes with high SBH. Only few methods, to the best of our knowledge, have been proposed to extract simultaneously the four diode parameters (I_s, n, R_s and G_p). One of the most widely accepted procedures is the one proposed by Werner [11] in which the conductance G_p is evaluated for high reverse voltages assuming linearity of the reverse I–V characteristics. Evangelou et al. [18] proposed an alternative method based on a fitting procedure which was shown to yield more accurate results even in the presence of experimental noise. They have used the Merlin multidimensional minimization program to analyze the I–V characteristics of SDs to yield the desired parameters.

In this paper, the well-known vertical optimization method is applied to analyze the I–V characteristics while accounting for the effects of both the series resistance and the parallel conductance. The method is initially applied to noise-free computer-calculated I–V curves. 1% electronic noise is subsequently generated by the computer and added to the values of the current. The SD parameters are then extracted from the noisy I–V curves. The influence of the noise on the I–V curves and the extracted parameters is discussed below as well as the test used to check reliability, robustness and accuracy of the method in evaluating the parameters in the presence of different values of R_s and G_p.

2. Method development

The problem to be solved is the evaluation of a set of four parameters $\theta = (I_s, n, R_s, G_p)$ in order to fit a given experimental I_e (V) characteristics using an analytical model described by Eq. (4).

The method is based on the definition of an object function S for the difference between both experimental and theoretical characteristics. The fitting is performed on both forward and reverse I–V characteristics. An optimization process of this function will then give values of the required parameters.

If the criterion chosen to define the object function is the least squares estimator we get for the condition of the sum of the squares:

$$S = \sum_{i=1}^{m}\left(\frac{I_{ei} - I_i}{I_i}\right)^2 \tag{5}$$

Here (I_{ei}, I_i) are the measured and the fitted values of the current at the ith point among m data points respectively.

Newton's method can be used to obtain an approximation to the exact solution. Although Newton's method converges only locally and may diverge under an improper choice of reasonably good starting values for the parameters, it remains attractive with the number of variables being limited (four in this case) and their partial derivatives easily obtainable.

To illustrate the approach, we have first applied the method to a computer calculated curve reproducing the same diode characteristic used by Evangelou et al. [18], i.e, $I_s = 1.97 \times 10^{-6}$ A, $n = 1.2$, $R_s = 10$ Ω and $G_p = 1 \times 10^{-6}$ S. To test the effects of different initial values on the method, the known exact solutions were multiplied by the factors 1.5, 0.5 and 0.9 respectively and after carrying out the calculations, the extracted SD parameters were almost identical to the theoretical ones. Also noticed is the obvious and expected fact that the CPU calculation time decreases quickly when the initial values used are closer to the exact solution. In order to check the accuracy of the method, a 1% computer generated noise was added on top of the initial current. The values of the diode parameters extracted from the "noisy" data are given in Table 1. For comparison, the values of the parameters extracted using previous methods (reported from Table 1 of Ref. [18]) are also given.

It is clear that all the parameters extracted with the proposed method are in excellent agreement with their theoretical values. Among all methods presented, only the Merlin method gives the same accuracy for all parameters except for G_p where a small deviation between the computed and the theoretical values is manifest.

The above results indicate that the method proposed here could be confidently used to make a good estima-

Table 1
Theoretical and extracted parameters values of a diode using various methods

Diode parameters	Theoretical values	Sato et al. [5]	Cheung et al. [10]	Werner [11]	MERLIN [18]	In this work
I_s (A)	1.97×10^{-6}	1.97×10^{-6}	1.90×10^{-6}	1.90×10^{-6}	1.97×10^{-6}	1.98×10^{-6}
n	1.20	1.17	1.19	1.19	1.2	1.2
R_s (Ω)	10	10.15	10.02	10.02	9.99	10.06
G_p (S)	10^{-6}	Not considered	Not considered	Theoretical value was used	1.8×10^{-6}	1.00×10^{-6}

The results presented here correspond to the largest value of errors among 250 simulations (Worst case). $A = 3.14 \times 10^{-2}$ cm^2, $A^{**} = 120$ A/K cm^2, $T_1 = 300$ K and $T_2 = 343$ K. T_2 is used only for the Sato et al. method [5].

tion of G_p even when electrical noise or random errors are present during measurements.

A further test of accuracy of the present method was carried out with different values of R_s and G_p since large values of R_s and/or G_p can obscure the extraction of the SD parameters. Fig. 1 shows the I–V characteristics simulated using $I_s = 1.97 \times 10^{-6}$ A, $n = 1.2$, $R_s = 10\ \Omega$ and several different values of G_p.

To account for possible electronic noise or random errors during measurements, the current can be written as [22]:

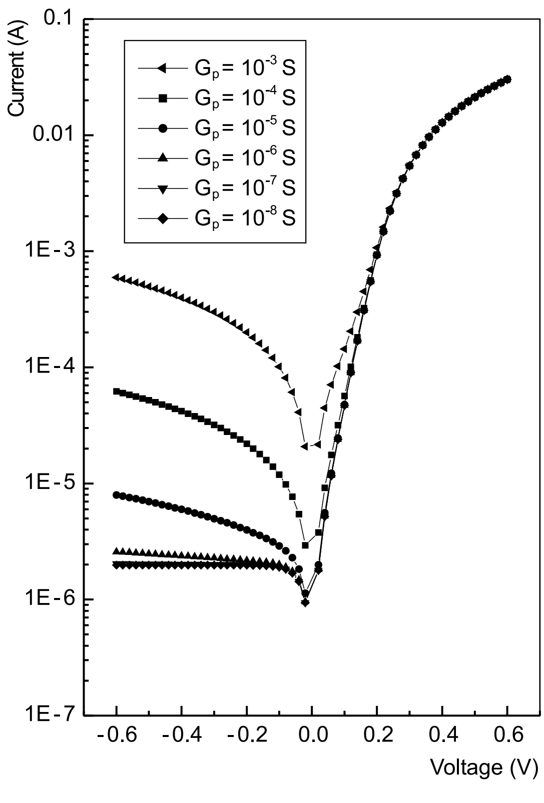

Fig. 1. Simulated I–V characteristics using the parameters $I_s = 1.9756 \times 10^{-6}$ A, $n = 1.2$, $R_s = 10\ \Omega$ and different values of G_p.

$$I_{\text{with noise}} = I_{\text{without noise}} \times (1 + \text{percent} \times \text{random}) \tag{6}$$

$I_{\text{without noise}}$ is the simulated current, $I_{\text{with noise}}$ is the current including noise used in the procedure of extraction, percent is the relative percentage of error to be added and random is a randomly generated number between -1 and $+1$.

Fig. 2 shows the results obtained for the relative errors of I_s, n, R_s and G_p for several different values of R_s. The procedure of adding noise to the simulated data and then the extraction of the parameters was done 250 times for each case after which the largest value of relative errors was selected. It is observed that the extracted I_s, n and R_s have very small relative errors when the noise level is below 20%, which is well within the tolerance of a typical experimental setup. The accuracy of the extracted parameters becomes questionable when the resistance value is approaching 100 kΩ. However, the relative error on G_p is more important in particular when the noise is increased beyond 10% and/or the resistance value is beyond 100 kΩ.

Fig. 3 shows the results obtained for the relative errors of I_s, n, R_s and G_p for several different values of G_p. It is further observed that the extracted I_s, n and R_s have small relative errors (<20%, <5% on the ideality factor n). The accuracy of the extracted parameters becomes large when the conductance value increases and approaches 10^{-4} S. However, the relative error on G_p decreases quickly once the conductance value increases beyond 10^{-6} S. This is probably due to the fact that the influence of G_p on the I–V characteristics is more significant at high values of G_p as can be observed in Fig. 1.

3. Conclusion

The presence of the series resistance and the shunt conductance causes considerable complication when analyzing I–V plots of some Schottky diodes or p–n junctions. A widely used direct vertical optimization method has been re-examined and applied to analyze (theoretically) I–V characteristics by taking into consideration the series resistance as well as the parallel

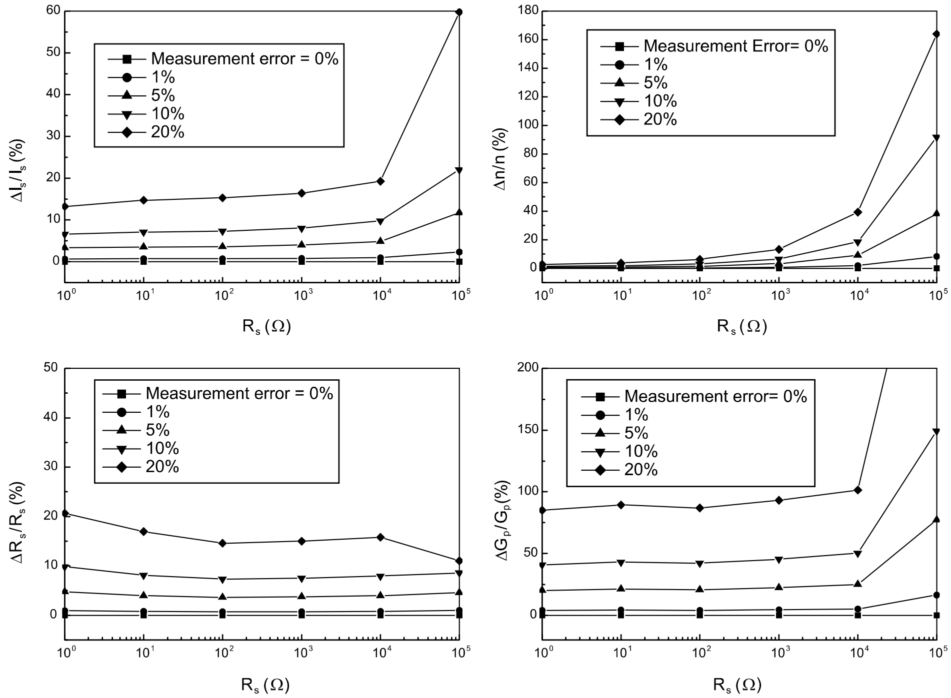

Fig. 2. The relative errors of I_s, n, R_s and G_p extracted for different values of R_s and various levels of noise measurements. For each case, the procedure of adding noise to the simulated data is done 250 times, then the largest value of relative errors is selected.

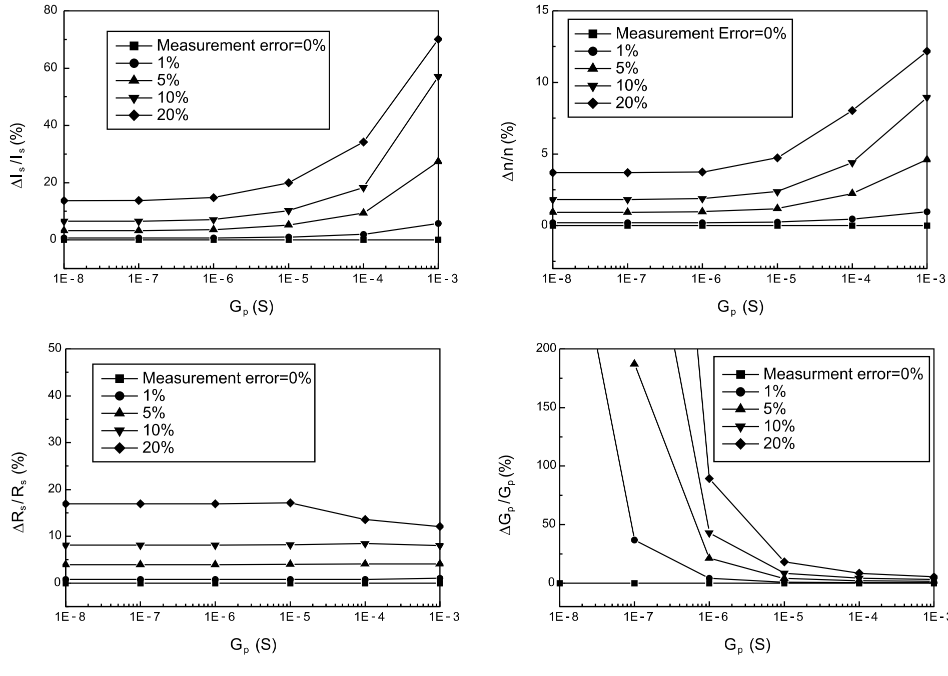

Fig. 3. The relative errors of I_s, n, R_s and G_p extracted for different values of G_p and various levels of noise measurements. For each case, the procedure of adding noise to the simulated data is done 250 times, then the largest value of relative errors is selected.

conductance. The approach enables to use the whole bias range including reverse direction which is generally omitted and results in some loss of information. The method is quite accurate even when electrical noise or random errors are part of the measured I–V, where some methods usually fail. The proposed method is fast, does not require any kind of graphs and allows automation of the measurement process.

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