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Procedure for determining diode parameters at very low forward voltage

J.C. Ranuárez, F.J. García Sánchez*, A. Ortiz-Conde

Laboratorio de Electrónica del Estado Sólido, Universidad Simón Bolívar, Apartado Postal 89000, Caracas, 1080A, Venezuela

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Abstract

A technique is proposed to extract the reverse saturation current parameter and ideality factor of semiconductor junctions from the low forward voltage region of the device's characteristics. The method involves performing a mathematical operation on the experimental data that allows to calculate the parameters at values of forward current smaller than the reverse saturation current. The procedure was tested and its accuracy verified on synthetic *I–V* characteristics, with and without added simulated experimental error or noise. Good agreement is obtained between the parameters used in modeling and the extracted values. The procedure was also applied to experimentally measured I_B–V_{BE} characteristics of a real power BJT. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The current voltage characteristics of *p–n* junction or Schottky barrier diodes may be modeled in general by a modified single exponential Shockley diode expression [1]:

$$I = I_0\left[\exp\left(\frac{V_j}{nV_t}\right) - 1\right], \tag{1}$$

where the pre-exponential factor I_0 is the reverse current, V_j is the voltage at the junction, $V_t = kT/q$ is the thermal voltage, and n is the so-called quality or junction ideality factor. It is important to point out that the value of the ideality factor is typically in the range $1 < n < 2$. However, because of the several conduction mechanisms that may be dominant at various forward voltage ranges, the experimentally measured characteristics frequently exhibit a more complex behavior than that which can be represented by a single exponential expression with constant reverse saturation current and ideality factors, as in Eq. (1). Representing the various conduction mechanisms can be important to study the phenomenology present in *p–n* homojunctions, heterojunctions, Schottky diodes and Gummel plots of BJTs. It is therefore customary to express the junction current by the superposition of various conduction mechanisms. The junction equation then consists of a summation of two or more exponential expressions, each one of them with values of reverse saturation current and ideality factors that try to model the different conduction mechanisms prevalent, such as thermionic emission, diffusion, generation-recombination, tunneling, leakage, high injection, etc. For example, the following expression represents two conduction mechanisms:

$$I = I_{01}\left[\exp\left(\frac{V_j}{n_1V_t}\right) - 1\right] + I_{02}\left[\exp\left(\frac{V_j}{n_2V_t}\right) - 1\right], \tag{2}$$

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* Corresponding author. Tel.: +582-906-4010; fax: +582-906-4025.

E-mail address: fgarcia@ieee.org (F.J. García Sánchez)

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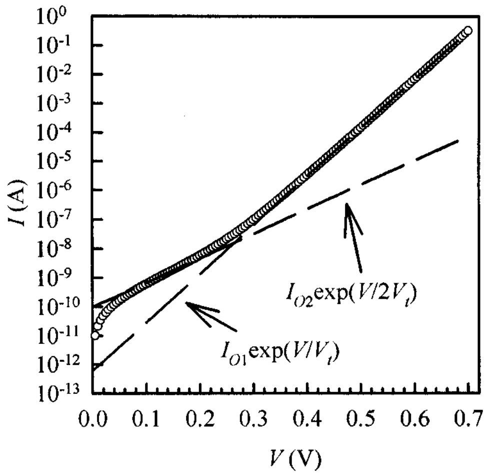

Fig. 1. Synthetic I–V characteristics of a junction simulated by the double exponential expression (2) with $I_{01}=0.6$ pA, $I_{02}=100$ pA, $n_1=1$, $n_2=2$, T = 300 K and 5 mV voltage steps. Also shown with dashed lines are the $n_1=1$ and $n_2=2$ slopes.

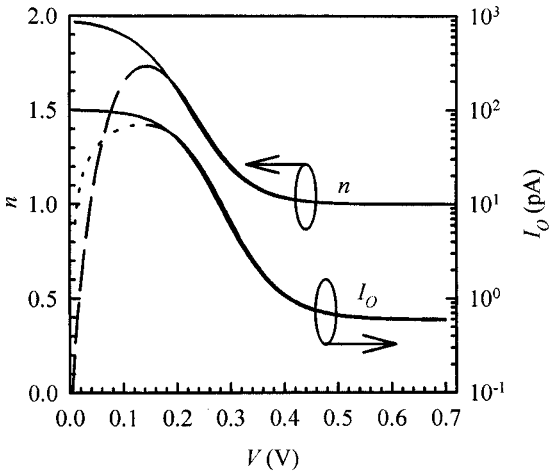

Fig. 2. Extracted ideality factor n and reverse current I_0 as a function of forward voltage, for the synthetic characteristics of Fig. 1. Dotted and dashed lines: conventionally extracted values, showing the low voltage region where the conventional method fails to produce the true values of $n_2=2$ and $I_{02}=100$ pA. Continuous lines: values extracted by the present method.

which may correspond to diffusion and generation-recombination in the space-charge region, modeled by the values of $n_1=1$ and $n_2=2$, *and* $I_{01} < I_{02}$ in the equation, respectively.

There are several methods to extract the pre-exponential factor, I_0, and the junction ideality factor, n, parameters from experimentally measured forward I–V characteristics [2–8]. The most common is the traditional method of plotting the logarithm of the current as a function of the forward voltage [9], so that

$$\ln I \approx \ln I_0 + \frac{V_j}{nV_t}. \tag{3}$$

Using Eq. (3) the value of n is extracted from the slope $(1/nV_t \approx \partial(\ln I)/\partial V_j)$ and the value of the pre-exponential factor I_0 from the ordinates axis intercept. This conventional method is valid only for $I \ll I_0 (V_j \ll nV_t)$ because Eq. (3) assumes that the "-1" term in Eq. (1) can be neglected. This is not true at low voltages where the lnI–V characteristics deviate from linearity due to the nonexponential behavior of the junction near the origin. Other methods are based on the use of first or second derivatives of the current [10], but an equivalent limitation is also present at low forward voltage because of the same above mentioned invalid assumption that the "-1" term in Eq. (1) can be neglected. Methods based on integration have been proposed recently [7,8] in order to reduce the effect of experimental noise in the parameter extraction. These methods [7,8] also neglect the "-1" term. This means that when a junction presents a conduction mechanism dominant only at very low voltage, its parameters n and I_0 pertaining to that mechanism may not be extracted using conventional methods. Fig. 1 presents synthetic I–V characteristics of a hypothetical junction with two conduction mechanisms simulated by a double exponential expression with $n_1=1$, $n_2=2$, $I_{01}=0.6$ pA and $I_{02}=100$ pA. In this case the low voltage conduction mechanism (n = 2) is not clearly discernible, and since the slope $\partial(\ln I)/\partial V_j)$ never becomes equal to $1/(2\ V_t)$ anywhere in that region, parameter I_{02} can not be extracted by extrapolating to the ln$I$ axis. This restriction is illustrated in Fig. 2 using the synthetic characteristics presented in Fig. 1. The dotted and dashed line plots in Fig. 2 correspond to the ideality factor n and reverse current I_0 that result from applying the conventional logarithm of the current method. That is, n has been calculated from the slope and I_0 from the ln$I$ axis intercept of the extrapolation. As can be distinctly observed, the plots unduly fall in the low voltage region, failing to provide the correct values of $n_2=2$ and $I_{02}=100$ pA. To circumvent this difficulty we propose a simple method which does not make the assumption that the "-1" term in Eq. (1) can be neglected and thus allows to extract the conduction model parameters at low forward voltages, as close to zero as needed. The solid lines in Fig. 2 correspond to the values of n and I_0 extracted by the proposed method, which will be described in the next section.

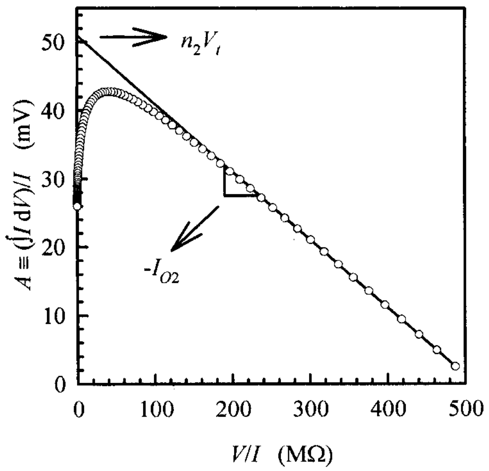

Fig. 3. Plot of Eq. (5) using simulated data of Fig. 1 from 0 to 50 mV. The slope gives an extracted value of $I_{02} = 99.4$ pA, and the ordinates axis intercept gives an extracted value of $n_2 = 1.97$.

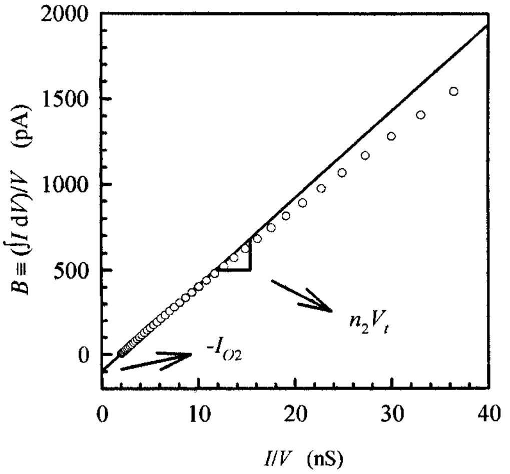

Fig. 4. Plot of Eq. (6) using simulated data of Fig. 1 from 0 to 50 mV. The slope gives an extracted value of $n_2 = 1.97$, and the ordinates axis intercept gives an extracted value of $I_{02} = 99.3$ pA.

2. Methodology

Consider the integration of the forward current from zero up to the maximum voltage value of interest. Integrating Eq. (1)

$$\int_0^V I\,dx = nV_tI - VI_0 \tag{4}$$

where $x = V$ is a dummy variable of integration. We now define the following two auxiliary functions:

$$A \equiv \frac{\int_0^V I\,dx}{I} = nV_t - \frac{V}{I}I_0 \tag{5}$$

and

$$B \equiv \frac{\int_0^V I\,dx}{V} = nV_t - \frac{I}{V} - I_0 \tag{6}$$

According to Eq. (5) a plot of A as a function of V/I should produce a straight line with slope $-I_0$ and ordinates axis intercept of nV_t. Similarly, according to Eq. (6) a plot of B as a function of I/V should produce a straight line with slope nV_t and ordinates axis intercept $-I_0$. The use of either one of these equations represents the basis of the proposed method.

3. Procedure validation and discussion

In order to test the effectiveness of the method, it is applied to the synthetic I–V characteristics of Fig. 1 corresponding to a double exponential expression of the type of Eq. (2) with $I_{01} = 0.6$ pA, $I_{02} = 100$ pA, $n_1 = 1$, $n_2 = 2$ and $T = 300$ K. The corresponding plot of auxiliary function A as calculated by Eq. (5) is presented in Fig. 3. A value of $I_{02} = 99.4$ pA can be extracted from its slope, and the ordinates axis intercept gives an extracted value of $n_2 = 1.97$. Alternatively, a plot of auxiliary function B as calculated by Eq. (6), is shown in Fig. 4. It has a slope that corresponds to a value of $n_2 = 1.97$, and an ordinates axis intercept corresponding to an extracted value of $I_{02} = 99.3$ pA. The ideality factor n was extracted by the present method as a function of voltage and reverse current I_0 was then calculated using Eq. (1). Both extracted parameters are displayed as solid lines in Fig. 2 together with the conventionally extracted values, which are represented by dotted and dashed lines. The figure clearly demonstrates that the present method properly extracts the correct values of both parameters at low voltage, where the conventional method fails to do so. Fig. 2 additionally indicates that the new method is also able to extract the correct values at higher voltages.

To test the procedure's sensitivity to measurement error and noise, the synthetic data of Fig. 1 was distorted repeatedly with added random relative error of up to 4%. Table 1 presents the resulting maximum percentile errors observed in parameters extracted under these conditions using auxiliary functions A and B (Eqs. (5) and (6)). The resulting uncertainty at zero data error, which depends on the number of data points used, is also presented for comparison. As can be seen from the table, the sensitivity of either auxiliary function A or B are practically the same. Also can

Table 1
Maximum percentual error in the extracted parameters

Percent of noise in data	Eq. (5)		Eq. (6)	
	n_2	I_{O2}	n_2	I_{O2}
0	0.6	1.5	0.7	1.5
1	2.5	2.0	2.7	2.0
2	2.5	3.0	2.9	2.0
4	6.4	10.0	6.6	10.0

be seen in Table 1 that the largest error in I_{02} is 10%, and that the largest error in n_2 is 6.6%.

As a final test, the extraction procedure was applied to measured base current versus forward base-emitter voltage characteristics of an experimental power BJT at T = 298 K with $V_{BC}=0$ and 10 mV voltage steps. The I–V characteristics are presented with symbols in Fig. 5. Also displayed by the continuous line in the same figure is the simulated low forward voltage characteristics, modeled using the values of $n_2=2$ and $I_{02}=215$ pA once they were extracted by the present method. The high forward voltage characteristic is also presented in this figure, using the extracted values of $n_1=1.4$ and $I_{01}=16.3$ pA. Fig. 6 presents the values of ideality factor n and reverse base current I_{B0} as a function of base-emitter voltage, extracted by the conventional method (dotted and dashed lines) and extracted by the present method (continuous lines). The figure again indicates that the conventional method fails in the low voltage region. Figs. 7 and 8 present the plots of auxiliary functions A and B as calculated by Eqs. (5) and (6). The slope of A gives an extracted value of $I_{B02}=215$ pA, and its ordinates axis intercept gives an extracted value of $n_2=2.00$. The slope of function B

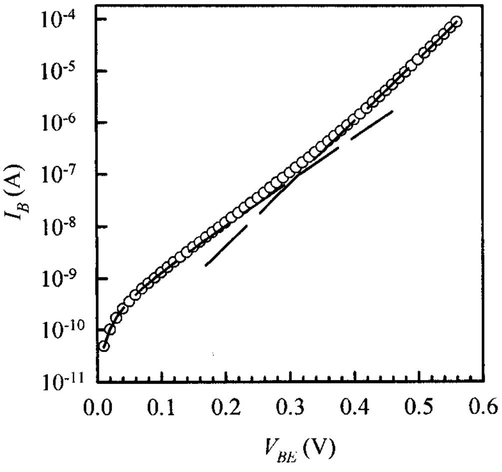

Fig. 5. Experimental characteristics (symbols) of the base current as a function of forward base-emitter voltage of a power BJT measured at T = 298 K with $V_{BC}=0$ and 10 mV voltage steps. Also shown by the continuous line is the simulated low forward voltage characteristics, calculated with Eq. (1) using the values of n = 2 and $I_0=215$ pA extracted by the present method.

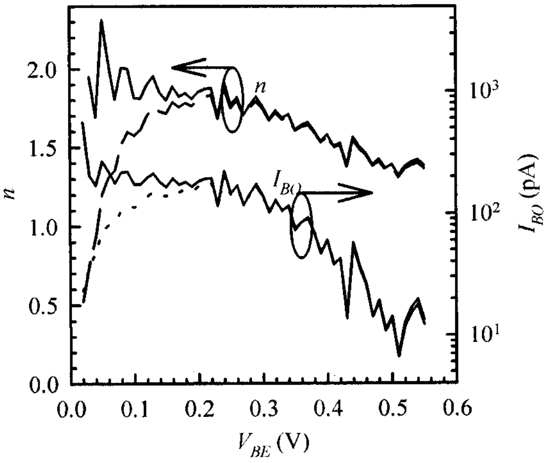

Fig. 6. Extracted ideality factor n and reverse base current I_{B0} as a function of base-emitter voltage, for the experimental characteristics of Fig. 5. Dotted and dashed lines: conventionally extracted values, showing the low voltage region where the conventional method fails as evidenced by the fall of the plots. Continuous lines: values extracted by the present method.

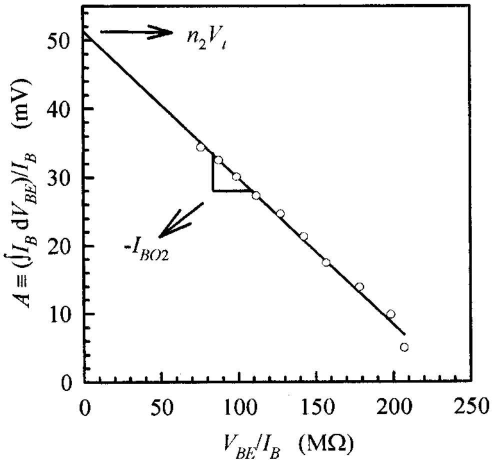

Fig. 7. Plot of Eq. (5) for the experimental data of Fig. 5 ($0 < V_{BE} < 100$ mV). The slope gives an extracted value of $I_{B02}=215$ pA, and the ordinates axis intercept gives an extracted value of $n_2=2.00$.

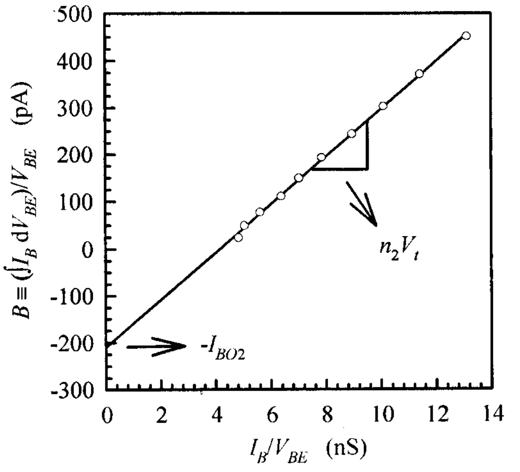

Fig. 8. Plot of Eq. (6) for the experimental data of Fig. 5 ($0 < V_{BE} < 100$ mV). The slope gives an extracted value of $n_2 = 1.98$, and the ordinates axis intercept gives an extracted value of $I_{02} = 210$ pA.

gives an extracted value of $n_2 = 1.98$, and its ordinates axis intercept gives an extracted value of $I_{02} = 210$ pA.

4. Conclusion

The proposed procedure represents a simple way to extract the intrinsic diode model parameters in the range of very low forward voltages, which is important when the conduction mechanism of interest is dominant only in that range. The method does not need the usual assumption that the forward current be much larger than the reverse current, thus it allows to extract the conduction model parameters as close to zero as needed. The procedure was positively validated by comparing the low voltage diode parameters extracted from synthetic I–V characteristics, modeled by a double exponential expression, to the known parameters used in the model. The procedure was also used to extract the low voltage diode parameters of measured I_B–V_{BE} characteristics with $V_{BC} = 0$ of a real power BJT device.

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