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The Efficiency of Best-so-far ABC Algorithm Versus Analytical Methods for Schottky Diode Parameters Extraction

W. Filali[1,*], E. Garoudja[1], S. Oussalah[2,†], N. Sengouga[3], M. Henini[4], D. Taylor[4]

[1] *Plateforme Technologique de Microfabrication, Centre de Développement des Technologies Avancées, cité 20 août 1956, Baba Hassen, Algiers, Algeria*

[2] *Microelectronics and Nanotechnology Division, Centre de Développement des Technologies Avancées, cité 20 août 1956, Baba Hassen, 16303, Algiers, Algeria*

[3] *Laboratory of Metallic and Semiconducting Materials, Université de Biskra, B.P 455, 07000 Biskra RP, Algeria*

[4] *School of Physics and Astronomy, Nottingham Nanotechnology and Nanoscience Center, University of Nottingham, Nottingham, NG7 2RD, UK*

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In this work, we investigate the forward current-voltage characteristics of p-type $Ti/Au/Al_{0.29}Ga_{0.71}As$ Schottky diode, which were measured over a range of temperatures from 260 to 400 K. The experimental current-voltage characteristics are used to extract the Schottky diode main electrical parameters such as ideality factor, saturation current, height barrier, and series resistance. The parameters extraction has been reached using the best-so-far Artificial Bee Colony (ABC) algorithm. ABC is an optimization technique, which is used in finding the best solution from all feasible solutions. The efficiency of this method has been assessed using current-voltage characteristics obtained over wide range of temperatures. The accuracy of the best-so-far ABC algorithm is compared to two well-known analytical methods called Cheung and standard. Extracted diode parameters from different methods show that best results are obtained by the suggested method.

Keywords: ABC algorithm, Parameter extraction, Optimization, Schottky diode, Semiconductor.

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1. INTRODUCTION

Metal-semiconductor (MS) structures are important research thematic in the characterization of new semiconductor materials. The fabrication of these structures plays a crucial role in constructing some useful devices in technology. MS structures are divided into two parts, namely Ohmic and Schottky contacts. The last one has found applications in devices operating at low temperatures, infrared detectors and sensors [1, 2].

Gallium arsenide (GaAs) is one of the commonly used materials in order to fabricate Schottky diodes. This is essentially due to a direct transition band gap and high electron mobility. The classical model of Schottky diode assumes the junction to be abrupt with a fixed barrier height. However, such a description fails to account for the observed temperature dependence of diode parameters, these parameters are extracted from the current-voltage (*I-V*) characteristics basis of thermionic emission-diffusion (TED) [1, 2]. There are currently a vast number of experimental studies reports that extract Schottky barrier diode (SBD) parameters such as the ideality factor (n), the saturation current (I_s), the barrier height (Φ_b), and series resistance (R_s) in a great variety of MS contacts [3-7].

The analysis of the SBD I-V characteristics at room temperature only does not give enough information about their conduction mechanism. The temperature dependence of the *I-V* characteristics allows us to understand different aspects of current conduction [8, 9].

In other hand, the performance of the SBD depends on its main electrical parameters (n, I_s, R_s, Φ_b). For this reason, several strategies have been proposed to accurately extract these parameters. These strategies are divided into two types such as analytical methods [9, 10] and swarm intelligence algorithms [11-17]. The first type employs basic equations, which govern the conduction mechanism in Schottky diodes, to extract the aforementioned parameters. The main weakness in this method is it cannot give significant results in some conditions (high frequencies, low temperature). Cheung et al. [9] have used this type of methods to extract the SBD parameters from forward (*I-V*) characteristics. Werner [10] has proposed a method to extract the diode parameters taking into account the possible existence of a parallel shunt resistance.

The other type of methods, which denote the swarm intelligence algorithms, uses biological inspired mechanisms to extract the SBD parameters. Indeed, they mimic a biological system to solve optimization problem.

The swarm intelligence algorithms have gained a considerable attention of many researchers. For instance the basic Artificial Bee Colony (ABC) algorithm has been suggested in [11]. Wang K. et al. have extracted the parameters by using the differential evolution (DE) and the genetic algorithm in [14]. In addition, the vertical optimization method is used [16]. The best-so-far ABC algorithm is a recent variance of the basic ABC algorithm proposed by A. Banharnsakun et al. [17].

In this paper, we propose Schottky diode parameters extraction approach based on the best-so-far ABC algorithm. The efficiency of this method has been evaluated by using real experimental (*I-V*) data of

* wfilali@cdta.dz
† soussalah@cdta.dz

Ti/Au/$Al_{0.29}Ga_{0.71}As$ Schottky diode fabricated at Nottingham University (school of physics and astronomy) [18]. The *I-V* characteristics are obtained for different temperature ranging from 260 K to 400 K. The proposed method has been afterward compared against two other used analytical methods, the Cheung method and standard method.

The rest of our work is organized as follow: the problem statement will be discussed in section 2. Section 3 summarizes the employed experimental setup. Next, the best-so-far ABC algorithm is described in details in section 4. Results and discussion will be presented in section 5. Finally, we conclude our work by a global conclusion.

2. THE PROBLEM STATEMENT

2.1 Schottky Barrier Diode Model

The forward bias current of a Schottky barrier diode (SBD), which is due to the thermionic emission current, is expressed as follows [1, 2, 22]:

$$I = I_s\left[\boldsymbol{exp}\left(\frac{q\left(V-IR_s\right)}{nKT}\right)-1\right], \tag{1}$$

where I_s denotes the saturation current, and it can be given using equation below [22]:

$$I_s = AA*T^2\,\boldsymbol{exp}\left(\frac{-q\Phi_b}{KT}\right). \tag{2}$$

In Eq. (1) and Eq. (2), I and V denote the diode current and the bias voltage respectively, q is the electron charge, K and A^* are Boltzmann and Richardson constants, respectively, A is the Schottky contact area, T is the temperature, R_s is the series resistance, n is the diode ideality factor, Φ_b is the Schottky barrier height.

2.2 The Parameters Extraction Strategy

The accuracy of the model described in Eq. (1) is highly dependent on the accurate knowledge of its parameters, more particularly, I_s, n, R_s and Φ_b. For this reason, this paper suggests an efficient strategy to extract the SBD main parameters with high accuracy. The parameters extraction stage can be seen as an optimization problem, in which the cost function to be minimized is the root mean square error (RMSE) between measured and estimated currents, as follows:

$$RMSE = \sqrt{\frac{I}{N}\sum_{i=1}^{N}\left(g_i\left(I_{meas}, V_{meas}, \xi\right)\right)^2}\;. \tag{3}$$

where

$$\boldsymbol{g(}I_{meas}, V_{meas}, \xi\boldsymbol{)} = I_{meas} - \underbrace{\left[I_s\left(\boldsymbol{exp}\left(\frac{q\left(V_{meas}-I_{meas}R_s\right)}{nkT}\right)-1\right)\right]}_{I_{est}} \tag{4}$$

In Eq. (3), ξ is a vector including the SBD parameters, given as $\xi = [I_s, n, R_s]$. I_{meas} and V_{meas} are the experimental pair of data obtained from the recorded *I-V* characteristics, N is the size of the experimental *I-V* characteristics.

In our work, the cost function minimization will be reached by using the best-so-far ABC algorithm. This algorithm will vary the whole parameters (I_s, n and R_s), each one within a predefined range, in order to get a minimum value of the RMSE. Once I_s, n and R_s are extracted, the value of Schottky barrier height Φ_b will be computed as follows [1]:

$$\Phi_b = \frac{kT}{q}\boldsymbol{ln}\left(\frac{AA*T^2}{I_s}\right) \tag{5}$$

The Schottky diode parameters extraction stage is summarized in Fig. 1. As can be seen from this figure, the aim of the best-so-far ABC algorithm is to minimize the cost function (Eq. (3)) and to return the appropriate parameters to the theoretical model (Eq. (1)) where the estimated current is evaluated.

3. THE EXPERIMENTAL SETUP

In this work, a p-type $Al_{0.29}Ga_{0.71}As$ Schottky diode fabricated at Nottingham University [23, 24] has been used to check the accuracy of the best-so-far ABC algorithm. The electrical characterization of this diode has been carried out in the characterization bench at CDTA (Center for development of advanced technologies) in Algiers, Algeria. This room includes all the necessary tools needed to test and characterize elementary components and integrated circuits, at low/high frequencies and temperatures.

The *I-V* characteristics of this diode were measured and collected using three sorts of Agilent, such as Agilent 4156C precision parameter analyzer, Agilent 4284A LCR-meter, and Agilent 16442B test fixture.

The characterization bench uses a computer to control the measurement system, record the data, and show the characteristics on the screen panel. This computer uses LabVIEW software to control and monitor the characterization. The experimental forward *I-V* measurements are collected at different temperatures and with a sampling rate of 3 ms.

4. RESULTS AND DISCUSSION

The experimental *I-V* characteristics of the Schottky diode have been used to extract the parameters. Forward and reverse experimental *I-V* characteristics of the used sample for different temperatures are depicted in Fig. 1, where it shows the variation of the current as function of bias voltage ranging from – 2 V to 1 V for different temperature values. We can see that, by increasing the temperature, the current value increased too, according to the mobility of the carriers [1, 19].

Using the experimental data, the best-so-far ABC algorithm has been employed to extract the SBD parameters. Finally, the obtained parameters have been checked with those obtained by the standard method [1, 2, 19] and Cheung method [9].

The setting parameters of the best-so-far ABC algorithm are summarized in Table 1. Moreover, the upper and the lower boundaries of the SBD parameters,

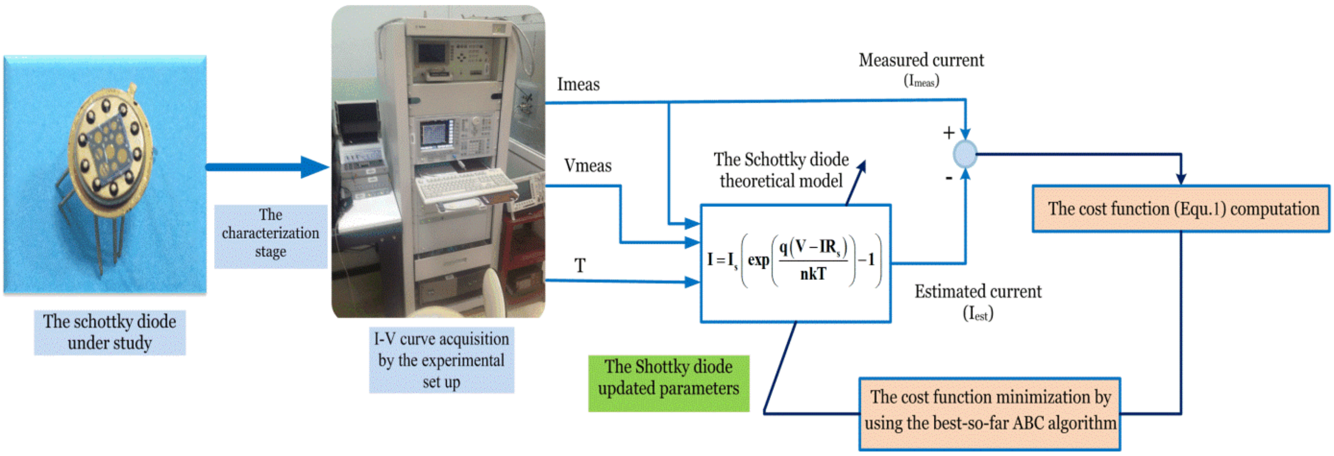

Fig. 1 – The Schottky diode parameters extraction strategy

Table 1 – The best-so-far ABC algorithm setting parameters

The setting parameter	**Number of food sources**	**Number of employed bees**	**Number of onlooker bees**	**The solution dimension**	**Maximum cycle number**	**Limit**
Its corresponding value	160	80	80	3	1000	$160 \cdot 3 = 480$

Table 2 – The upper and lower boundaries chosen for the Schottky diode electrical parameters

The parameters	***I_s*, A**	***n***	***R_s*, Ohm**
The Variation boundaries	$[10^{-9}, 10^{-6}]$	[0, 20]	[0, 50000]

Table 3 – Results of Schottky diode parameter determination obtained by best-so-far ABC algorithm compared to other methods at various temperatures

T, K	Parameters	Best-so-far ABC algorithm	Standard method	Cheung method
T = 260	I_s, A	$6.761 \cdot 10^{-9}$	$1.98 \cdot 10^{-9}$	$4.04 \cdot 10^{-10}$
	n	2.311	2.08	1.78
	R_s, Ohm	40930	50000	45800
	Φ_b, V	0.557	0.621	0.62
	RMSE	**$1.302 \cdot 10^{-7}$**	**$3.502 \cdot 10^{-6}$**	**$2.855 \cdot 10^{-6}$**
T = 300	I_s, A	$4.062 \cdot 10^{-8}$	$7.41 \cdot 10^{-9}$	$4.60 \cdot 10^{-9}$
	n	2.211	1.68	1.7
	R_s, Ohm	34200	50000	37500
	Φ_b, V	0.604	0.69	0.661
	RMSE	**$1.331 \cdot 10^{-7}$**	**$4.278 \cdot 10^{-6}$**	**$3.2146 \cdot 10^{-6}$**
T = 400	I_s, A	$2.551 \cdot 10^{-7}$	$9.10 \cdot 10^{-7}$	$2.37 \cdot 10^{-9}$
	n	1.023	3.56	0.552
	R_s, Ohm	18750	25000	26000
	Φ_b, V	0.7627	0.773	0.924
	RMSE	**$2.708 \cdot 10^{-7}$**	**$6.426 \cdot 10^{-6}$**	**$6.897 \cdot 10^{-6}$**

which have been used by the best-so-far ABC algorithm, are depicted in Table 2.

To be able to set these values, several simulation tests of the algorithm have been accomplished. Indeed, the values of these parameters have a considerable effect on the algorithm performance.

The efficiency of the three methods has been tested by using experimental *I-V* characteristics obtained under different temperatures. The extracted parameters by the three methods are summarized in Table 3 for temperatures of 260, 300, and 400 K respectively. In Table 3, the Schottky barrier height values have been computed by Eq. (5). Moreover, the extracted parameters accuracy is proved by reconstructing an estimated *I-V* characteristic. This can be done by introducing the extracted parameters into Eq. (1) at the same voltage as the measured one. Finally, the accuracy test has been achieved by computing the RMSE value between the real experimental curve and the estimated curve. RMSE values for each method are summarized in Table 3. From Table 3 we observe that the results obtained by the best-so-far ABC algorithm are more accurate than those of the other methods (standard and Cheung). Indeed, RMSE values of this method are the smallest ones for all temperatures. Also, we can observe that at 400 K the Cheung method gives abnormal values of the ideality factor. This is due to the inefficiency of Cheung method in this range of temperature.

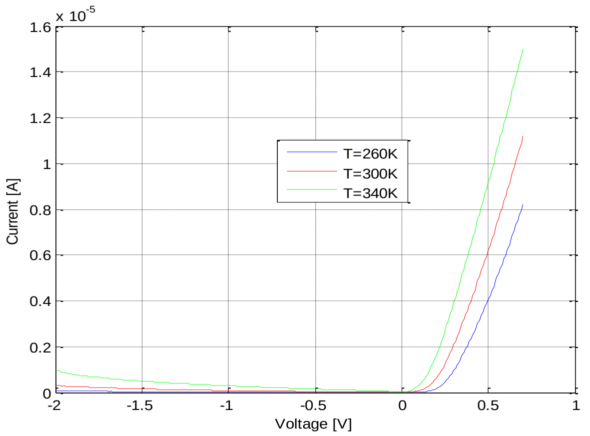

Fig. 2 – Experimental current-voltage characteristics of Ti/Au/$Al_{0.29}Ga_{0.71}As$ Schottky diode measured at different temperatures. The y-axis is in absolute value

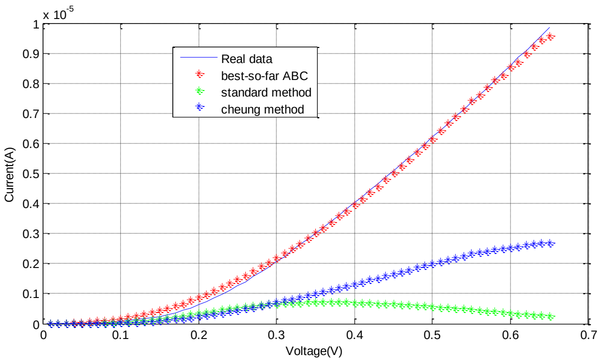

Fig. 3 – Comparison of the experimental (solid line) and estimated (dotted lines) resultants of *I-V* characteristics for the three methods at $T = 300$ K

Fig. 3 shows the experimental *I-V* characteristics against the estimated methods for temperature of 300 K.

Fig. 4 shows the dependence of the extracted ideality factor against temperature using the extraction methods. The plot of the ideality factor using the standard method shows an abnormal behavior from 340 K compared with the other methods. However, the other plots show normal evolution of ideality factor along the temperature range. In other hand, the best-so far ABC method presents a good behavior where the values of the ideality factor are in good agreement with the literature [20] along the entire temperature range.

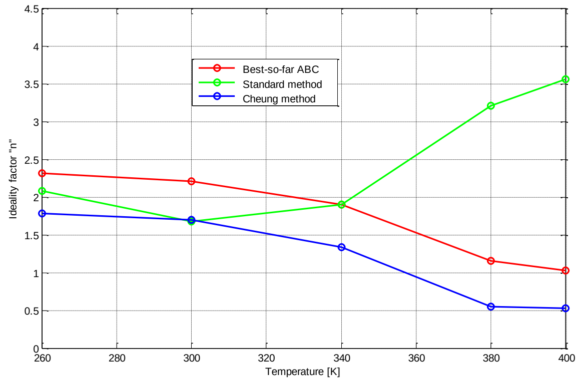

Fig. 4 – The extracted ideality factor as function of temperature using the three methods

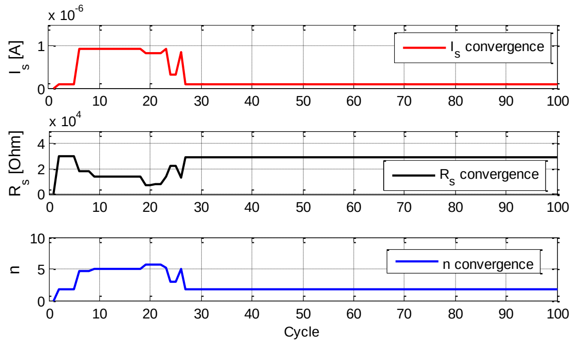

Fig. 5 – The parameters variation during the optimization stage using the best-so-far ABC algorithm

Fig. 5 shows the convergence evolution of the extracted parameters during the optimization step.

5. CONCLUSIONS

The main Schottky barrier diode electrical parameters such as ideality factor, saturation current, height barrier, and series resistance can be extracted using different technics, analytical and swarm intelligence methods. However, the precision of the parameters will determine the accuracy of the Schottky diode current model. In our study, we propose the use of the best-so-far ABC algorithm to extract the main Schottky diode parameters. By comparing the extracted parameters we observe that the RMSE of the used algorithm is less than those obtained with the analytical methods. We conclude that the best-so-far ABC algorithm can provide an efficient parameters extraction method.

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Ефективність поки що найкращого алгоритму ABC порівняно з аналітичними методами для вилучення параметрів діода Шоткі

W. Filali[1], E. Garoudja[1], S. Oussalah[2], N. Sengouga[3], M. Henini[4], D. Taylor[4]

[1] *Plateforme Technologique de Microfabrication, Centre de Développement des Technologies Avancées, cité 20 août 1956, Baba Hassen, Algiers, Algeria*

[2] *Microelectronics and Nanotechnology Division, Centre de Développement des Technologies Avancées, cité 20 août 1956, Baba Hassen, 16303, Algiers, Algeria*

[3] *Laboratory of Metallic and Semiconducting Materials, Université de Biskra, B.P 455, 07000 Biskra RP, Algeria*

[4] *School of Physics and Astronomy, Nottingham Nanotechnology and Nanoscience Center, University of Nottingham, Nottingham, NG7 2RD, UK*

У роботі досліджені прямі вольт-амперні характеристики діода Шотткі *p*-типу Ti/Au/$Al_{0.29}Ga_{0.71}As$, які вимірювались в діапазоні температур від 260 до 400 K. Експериментальні вольт-амперні характеристики використовуються для вилучення основних електричних параметрів діода Шотткі, таких як коефіцієнт ідеальності, струм насичення, висота бар'єру та послідовний опір. Вилучення параметрів було реалізовано за допомогою поки що найкращого алгоритму штучної "бджолиної колонії" (ABC). ABC – це технологія оптимізації, яка використовується для пошуку найкращого розв'язку з усіх можливих розв'язків. Ефективність цього методу була оцінена за допомогою вольт-амперних характеристик, отриманих в широкому діапазоні температур. Точність поки що найкращого алгоритму ABC порівнюється з двома відомими аналітичними методами, такими як метод Чонга і стандартний метод. Вилучені з різних методів параметри діода показують, що найкращі результати отримані запропонованим методом.

Ключові слова: Алгоритм ABC, Вилучення параметрів, Оптимізація, Діод Шотткі, Напівпровідник.