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Optimal estimation of Schottky diode parameters using a novel optimization algorithm: Equilibrium optimizer

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a new approach based on a novel optimization algorithm (Equilibrium optimizer) to determine the critical characteristic parameters of the Au/GaN/GaAs Schottky barrier diodes, such as ideality factor, series resistance and barrier height. In order to simplify the nonlinear equation of the thermionic emission model; we used the Lambert W function.

The evaluation of the Equilibrium optimizer algorithm performance was done, by comparing their results to that of analytical methods of Kaminski and Cheung and Cheung technique.

The proposed approach (EO) has shown remarkable estimation performance in terms of the accuracy and reliability. The main Schottky diode electrical parameters, which were extracted using the EO, are the barrier height $\varphi_{bn} = 0.62$ eV, the serial resistance $R_S = 16.21\ \Omega$ and the mean ideality factor $n = 1.88$.

1. Introduction

The current-voltage (I–V) characteristics provide the fundamental parameters information about microelectronic devices. In industrial use, microelectronic chip manufacturers check their products by controlling the quality assurance of semiconductor chips using this form of characterization.

The analysis of the Schottky conduction can be useful in extracting the parameters concerning ideality factor n, barrier height φ_{bn} and series resistance R_S of the Schottky diodes. These parameters are very required for researchers working on the development of microelectronic devices.

A lot of methods to determine the Schottky diode parameters have been introduced over the last few years. A conventional process involves the presence of a linear zone on the *ln(I)* vs. *V* plot [1]. Then two parameters can be derived from the plot intercept and slope, respectively, the barrier height and the ideality factor. Unfortunately, with R_S involvement, this first study fails.

Besides, Norde has developed an adjunct model focused on thermionic emissions to determine the barrier height and series resistance values [2–4]. Cheung and Cheung extracted the Schottky diode parameters from the $H(V)$ vs. I and $dV/d(\ln I)$ vs. I plots [5, 6].

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Werner showed that for $V_d = (V - IR_S) \gg nkT/q$, the plot of $\left(\frac{dI}{dV}\cdot\frac{1}{I}\right)$vs. $\left(\frac{dI}{dV}\right)$ gives a straight line leading to the ideality factor and the series resistance [7]. Cibils and Buitrago established an auxiliary function F_a *(V)* its extension of Norde's function to estimated n and R_S values [8].

However, most of these approaches are step-by-step procedures which rely on the identification of every parameter from restricted I–V characteristic regions where the influence of other parameters is considered negligible [9].

To overcome the shortcoming, and the limitation of those methods which depends heavily on assumptions to simplify the problem, AI techniques were introduced in the semiconductor devices analysis and parameters extraction.

Evolutionary algorithms (EAs) based on artificial intelligence are potent methods for modelling semiconductor devices. EAs such as the particle swarm optimization (PSO), the differential evolution (DE), genetic algorithm (GA), genetic programming (GP), colony optimization (ACO) and the evolution strategy (ES) are stochastic methods of optimization. That seems very useful in optimizing real-valued multimodal target functions.

Wang used particle swarm optimization (PSO) method to solve the parameter estimation problem of the Schottky-barrier diode model [10].

Hybrid genetic algorithm (GA) was developed to extract parameters of analytical or part-analytical models of BSIMPD MOSFET parameters by Fang [11].

Unlike numerical analysis, Evolutionary algorithms are capable of handling nonlinear systems without needing knowledge about derivatives and is weakly dependent on execution parameter values added before the algorithm runs [12]. EAs are viewed as more competitive than other forms of computing [13].

In this work, parameters estimation for the Au/2 nm-GaN/GaAs Schottky diode (ideality factor n, the barrier height φ_{bn} and the series resistance R_S) are formulated as a multi-dimensional optimization problem, and the Lambert function with a novel optimization algorithm (Equilibrium optimizer) is implemented to solve this problem.

2. Experimental procedures

The Au/2 nm-GaN/GaAs Schottky contacts were fabricated using Si-doped n-GaAs wafer, with thickness of 400 μm, (100) orientation and doping concentration of $N_d = 4.9 \times 10^{15} cm^{-3}$. For the fabrication process, n-GaAs wafer was ultrasonically cleaned in Sulfuric acid (H_2SO_4), deionized water (H_2O), cold methanol (CH_3OH), hot methanol (CH_3OH) and dried by nitrogen gas (N_2), sequentially. To clean the deep impurities and defects, the n-GaAs wafer was bombarded using the ionic bombardment Ar^+source, with 1 keV ion energy and 5 μAcm^{-2} sample current in (UHV) zone. Then, the wafer was heated at 500 °C for duration of 1 h, and nitrided using glow discharge source (GDS). The 2 nm of the undoped GaN layer was growing under flow nitrogen, with power of 5 W of, for 30 min at 500 °C of temperature, in UHV chamber. After nitridation process, the structures were annealed at 620 °C for 60 min, to restructure and reorganize the growing GaN layer. Finally, the Schottky contacts were formed by evaporating of Au dots of about *0.*6 mm diameter and *0.*1 μm of thickness, on the top side, using the Knudsen evaporator. The Sn ohmic contacts were evaporated on back side of the n-GaAs wafer, at temperature of 350 °C for 5 min. The schematic view of the elaborated Au/2 nm-GaN/GaAs Schottky diodes is shown in Fig. 1. The electrical measurements current-voltage (I–V) characteristics of the Schottky devices were measured in the dark and at room temperature, using an HP Semiconductor Parameters Analyzer 4155B.

3. Schottky-barrier diode model

According to thermionic emission, the current density of a forward-biased diode is given by:

$$I_{TE} = I_S\left(\exp\left(\frac{q(V - I_{TE}R_S)}{nkT}\right)\right) \tag{1}$$

where *Is* is the saturation current, and given by:

$$I_s = AA^*T^2\exp\left(\frac{-q\varphi_{b_n}}{kT}\right) \tag{2}$$

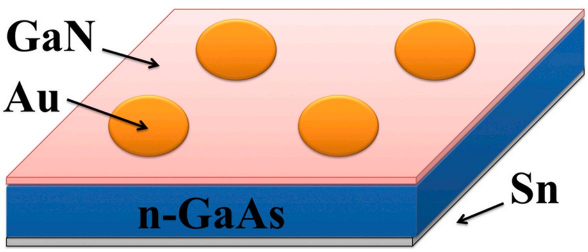

Fig. 1. Schematic diagram of the elaborated Au/2 nm-GaN/GaAs Schottkysdiode.

q is the electron charge, φ_{bn} is the barrier height, R_S is the series resistance, n the ideality factor, k is the Boltzmann constant, A^* is the effective Richardson constant (for GaAs is 8.16 Acm^{-2}k^{-2} [14]), A is the effective diode area and T is the temperature in Kelvin.

The current-voltage characteristic curve of Au/2 nm-GaN/n-GaAs Schottky diode is shown in Fig. 2.

Eq. (1) is a strongly non-linear equation that is not easily solved by automatically extracting. To solve this problem, the Schottky diode model suggested by Eq. (1) can be remodel using the Lambert function:

Firstly, the terms showing the thermionic current are grouped together:

$$I_S \exp\left(\frac{qV}{nkT}\right) = I_{TE} \exp\left(\frac{qR_S I_{TE}}{nkT}\right) \tag{3}$$

Then, to show the W-Lambert function, we use the change of variable:

$$w = \frac{qR_S I_{TE}}{nkT} \tag{4}$$

Eq. (2) then becomes:

$$w \exp(w) = \left(\frac{qR_S}{nkT}\right) I_S \exp\left(\frac{qV}{nkT}\right) \tag{5}$$

The property of the W-Lambert function allows us to express w in the following form:

$$w = W_0\left[\left(\frac{qR_S}{nkT}\right) I_S \exp\left(\frac{qV}{nkT}\right)\right] \tag{6}$$

For Eq. (1) only the main branch of the W-Lambert function is necessary since it fulfils the condition W0(x) = 0 for x = 0.

By substituting w in Eq. (5), we can then express the current of a branch by Eq. (6):

$$I_{TE} = \frac{nkT}{qR_S} W_0\left[\left(\frac{qR_S}{nkT}\right) I_S \exp\left(\frac{qV}{nkT}\right)\right] \tag{7}$$

In Matlab, the Lambert function is implemented under the name Lambert by MathWorks. Fig. 3 shows a plot of really valued Lambert function.

The electrical parameters of Schottky diode are determined using the following process: Provided a collection of measured current-voltage data. We would then be able to use the Equilibrium optimizer to adjust the electrical parameters until the measured data are in accordance with Eq. (6).

4. Equilibrium optimizer

Equilibrium optimizer (EO) is a new meta-heuristic optimization algorithm based on the laws of physics, developed to solve optimization problems with different complexities. More detail about EO's inspiration can be found in Refs. [16]. The EO algorithm model is demonstrated in the Steps mentioned below:

1) (EO) begins with initialization:

Equilibrium Optimizer (EO) uses a large number of particles through this step, and each particle signifies the vector of

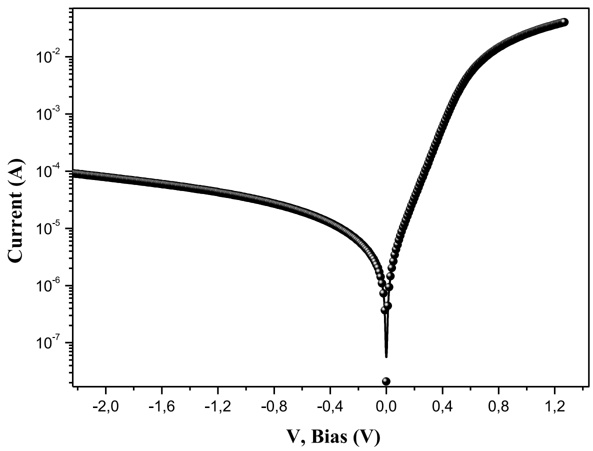

Fig. 2. Current-Voltage characteristic of Au/2 nm-GaN/GaAs diode.

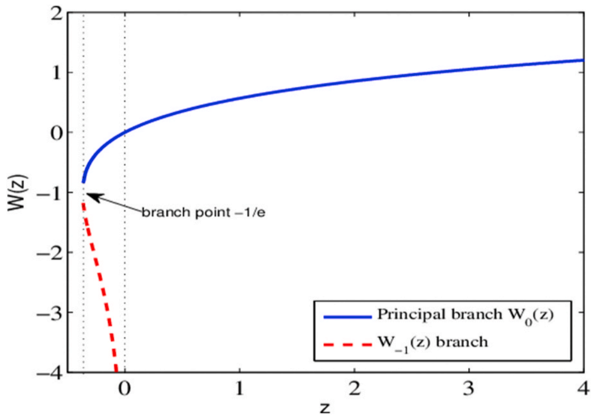

Fig. 3. Plots of real valued Lambert function branches W_0 (z) and W_{-1} (z) [15].

concentration containing the optimization problem solution. In the search space, the initial concentration vector is generated at random [17].

2) Equilibrium pool and candidates:

There is an aim for any meta-heuristic algorithm that each one seeks to accomplish depending on their existence. For examples, the WOA searches for prey in Ref. [18]. In Ref. [19] the artificial bee colony (ABC) looks for a supply of honey, while for Equilibrium optimizer EO, it aims for the system's equilibrium state. EO can arrive at the near-optimal solution when it gets to the equilibrium state. In the optimization phase, EO does not know the level of concentrations that attaining the optimum conditions. Thus, it selects the perfect four particles contained in the equilibrium candidate group and yet another with the best average of four particles. The first four particles allow EO to have a higher diversification capability, and the standard helps to increase in the extraction. These five candidates are contained in a vector, i.e. the equilibrium pool, Further detail on the equilibrium candidates, can be found in Ref. [16, 17].

3) updating the concentration:

This concept allows EO to provide a realistic harmony among concentration and enhancement because the turnover rate will contrast, after some time in a good control size, which is assumed to be a random vector between 0 and 1 [17].

5. Results and discussion

To estimate the current-voltage of the Schottky diode, we chosen the following objective function J to minimize the Root Mean Square Error (RMSE) as follows:

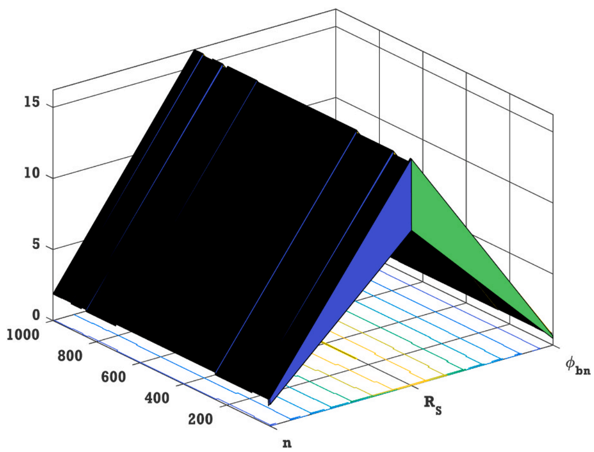

Fig. 4. The evolution of Schottky diode parameters during the tuning optimization.

$$J = \min_{x} \sqrt{\frac{\sum_{i=1}^{n} e^2}{n}} \tag{8}$$

where $e = I - \widehat{I}$ is the error between the estimated and the real measurement, n is the experimental data length, x is the optimization vector contains the parameters of Schottky diode.

After maximal iteration equal to 1000, and for each parameter the search range is defined as follows: $\varphi_{bn} \in [0; 1]$, $n \in [1,2]$, $R_S \in [0; 100]$. EO provides an optimal parameters estimation with minimum possible of J, where Fig. 4 and Fig. 5 shown the optimization evolution in each iteration of EO. The best parameters estimation are mentioned in Table 1.

To check the feasibility of the suggested EO algorithm in the identification of the electrical parameter, the extracting parameters (barrier heigh φ_{bn} , series resistance R_S and ideality factor n) of the Schottky diodes are compared to the original values calculated by two methods; the first one is Kaminski method [20] while the second one is the Cheung and Cheung method [5].

- Kaminski I method

This method based on the Y_j versus X_j plot, where:

$$Y_j = \frac{1}{I_j - I_1} \int_{V_1}^{V_j} I dv and X_j = \frac{I_j + I_1}{2} \tag{9}$$

where 1 <i < Np and 2<j < Np the Y_j versus X_j plot should be linear

$$Y = \frac{nkT}{q} + R_S X \tag{10}$$

And linear fitting allows for calculation of R_S and n.

The Y_j vs X_j plot is shown in Fig. 6.

- Cheung and Cheung method

The R_S and n values can be calculated from the functions below:

$$\frac{\partial V}{\partial(\ln I)} = \frac{nKT}{q} + IR_S \tag{11}$$

Linear fitting allows for determination of R_S and n.

Cheung and Cheung formulated a function to get barrier height as:

$$H(I) = V - \left(\frac{nKT}{q}\right) \ln\left(\frac{I}{AA^* T^2}\right) = n\varphi_{bn} + IR_S \tag{12}$$

The *H(I) vs. I* even gives a straight line, with an intercept of the y-axis equivalent to $n\varphi_{bn}$.

The *H(I)* vs. *I* and *dV/d(lnI)* vs. *I* plots are shown in Fig. 7.

The estimated parameters by EO algorithm and the original values are collected in Table 1;

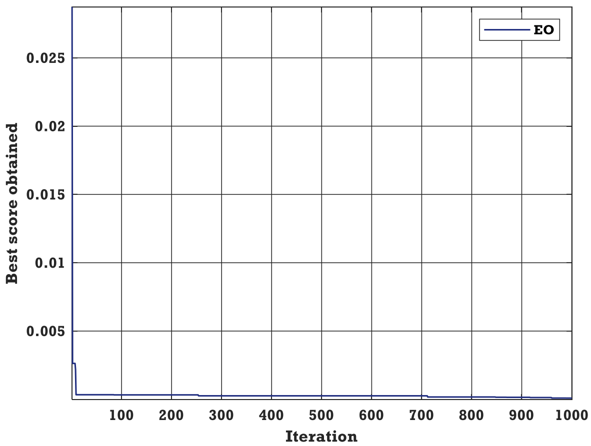

Fig. 5. The objective function in terms of EO iteration.

Table 1
Results of parameter identification.

Method of calculation	n	R_S (Ω)	φ_{bn} (eV)
EO	1.88	16.21	0.62
Kaminski I	1.97	15.87	-
Cheung and Cheung	1.92	16.22	0.62

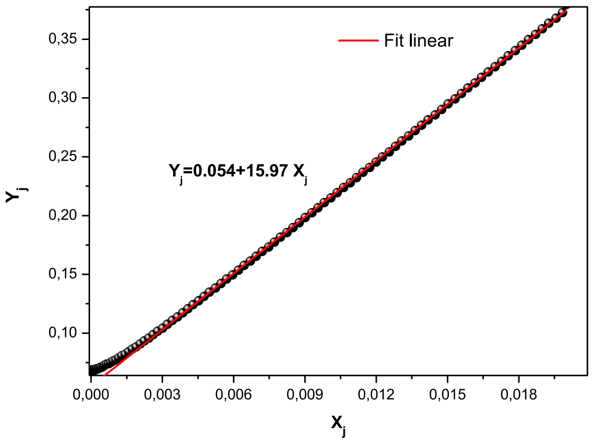

Fig. 6. Illustration of Y_j vs. X_j.

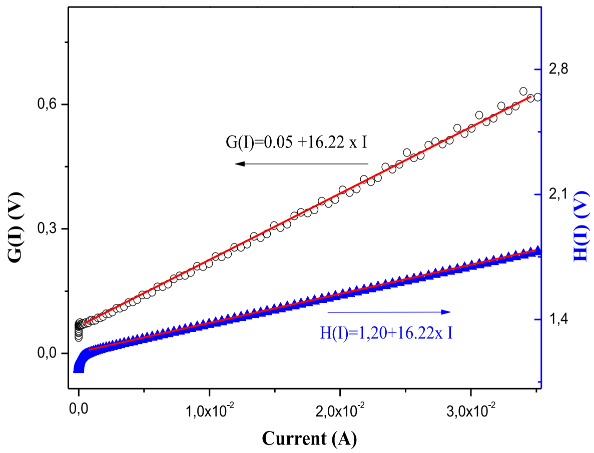

Fig. 7. G(I) and H(I) functions.

As shown in Table 1, the ideality factor obtained by different methods are greater than unity. This is due to the effect of tunnel currents, such as thermionic field emission TFE and field emission FE mechanisms [21]. Also, indicates the inhomogeneity of the Schottky barrier height across the metal contact, most probably due to the presence of generation-recombination centers or trap centers (defect centers) at the structure interface [12,13].

It is also noticed that the parameters estimated by the optimization technique (EO) correspond perfectly to the values obtained by Cheung and Kaminski methods, which revealed that the algorithm reached the global optimum with very high accuracy.

Fig. 8 shows the synthetic current-voltage curve created according to the obtained parameters by Cheung and Cheung method and the currant-voltage characteristic curve generated by EO algorithm. The I–V characteristics curve obtained by EO is in excellent agreement with synthetic results.

6. Conclusions

In this paper, a new optimization algorithm called equilibrium optimizer (EO) has been introduced to determine the electrical parameters of Au/2 nm-GaN/GaAs Schottky diode.

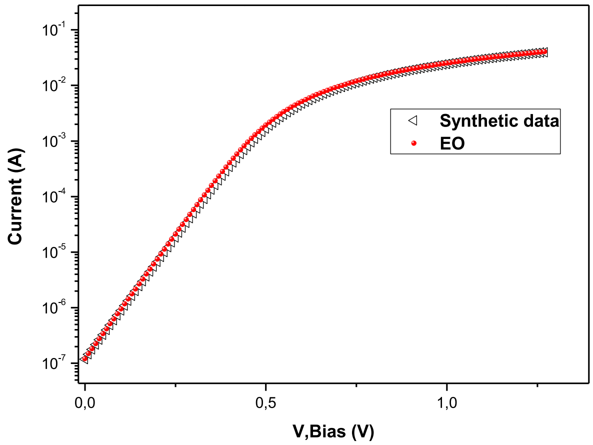

Fig. 8. Current-Voltage characteristic fitted by EO method and the synthetic data.

The effectiveness, accuracy and the validity of the algorithm are confirmed by its application to the synthetic I–V characteristics with known parameter values. We found that the estimated values of electrical parameters such as n, φ_{bn} and R_S, using (EO) algorithm are matching precisely with those extracted using analytical methods (Kaminski and Cheung and Cheung methods).

Additionally, the suggested technique (EO) is fast and straightforward, which allows the whole bias array to be used and does not need initial assumptions as closely to the solutions as possible, only a wide range for each parameter is required.

Credit author statement

Abdelaziz Rabehi: Writing - original draft, Conceptualization, Methodology, Data curation. **Bachir Nail:** Optimization algorithm, Software. **Hicham Helal:** Writing - review & editing. **Abdelmalek Douara:** literature search, state of art. **Abderrezzaq Ziane:** Writing - review & editing. **Mohamed Amrani:** Supervision, Project administration, Methodology, Conceptualization. **Boudali Akkal:** Supervision, Project administration, Methodology, Conceptualization. **Zineb Benamara:** Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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