# A Novel Parameter Identification Approach for $C-V-T$ Characteristics of Multi-Quantum Wells Schottky Diode Using Ant Lion Optimizer

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**Abstract**—We report the capacitance-voltage ($C-V$) characteristics of multi quantum wells Schottky diode. This diode is based on Aluminum gallium arsenide, which is highly promising wide band gap semiconductor for applications in high power electronic and optoelectronic devices. The elaboration process and the characterization phase have been carried out at Nottingham University. The $C-V$ characteristics have been measured at different temperature ranging from 20 to 400 K. The barrier height and effective density were than extracted from $1/(C/A)^2$ plot using heuristic algorithm which called ALO (Ant Lion Optimizer). The accuracy of the extraction method is verified through the gotten results.

## INTRODUCTION

Metal–semiconductor (MS) structures are important research tools in the characterization of new semiconductor materials [1, 2]. At the same time, the fabrication of these structures plays a crucial role in constructing some useful devices in technology. Moreover, Gallium arsenide (GaAs) and its alloyed (AlGaAs for instance) have gain a remarkable attention as semiconductor for optoelectronic applications and high-speed electronic devices.

This is due to its high electron mobility and its wide band gap [3–5]. Schottky diodes are found at several applications and under different operating conditions [6]. The elaboration of this type of microelectronic devices requires different steps, which is called fabrication process, starting from the growth of the substrate, than the deposition of various semiconductors and buffer layers. After that, the metallization phase is achieved by creating Schottky or ohmic contacts [7, 8]. Finally, the electrical characterization of the fabricated device is afterward established. After having characterized the diode, the obtained characteristics (current-voltage "$I-V$" and capacitance-voltage "$C-V$") are exploited to extract the Schottky diode parameters. In this context, a lot of previously works [9–13] have used the $I-V$ characteristics to deal with this concern, in contrary with the use of $C-V$ characteristics [14, 15]. Many advantages promote the use of the $C-V$ measurements, such as the temperature and frequency dependence and the ability to extract the diode parameters (the Barrier height, built in voltage and the effective doping density) [2].

In the literature, the problem of extracting the diode parameters has been solved by using both analytical and heuristics methods [11, 12, 16–20]. The main weakness of the analytical methods is that it's applied only at small voltage range, in contrast with the heuristics methods, which are useful in wide voltage interval.

Many heuristics algorithms were proposed to deal with this issue, such as differential evolution (DE), artificial bee colony algorithm (ABC) and genetic algorithm (GA). These algorithms employ a biological behavior to solve an optimization problem. Ant Lion
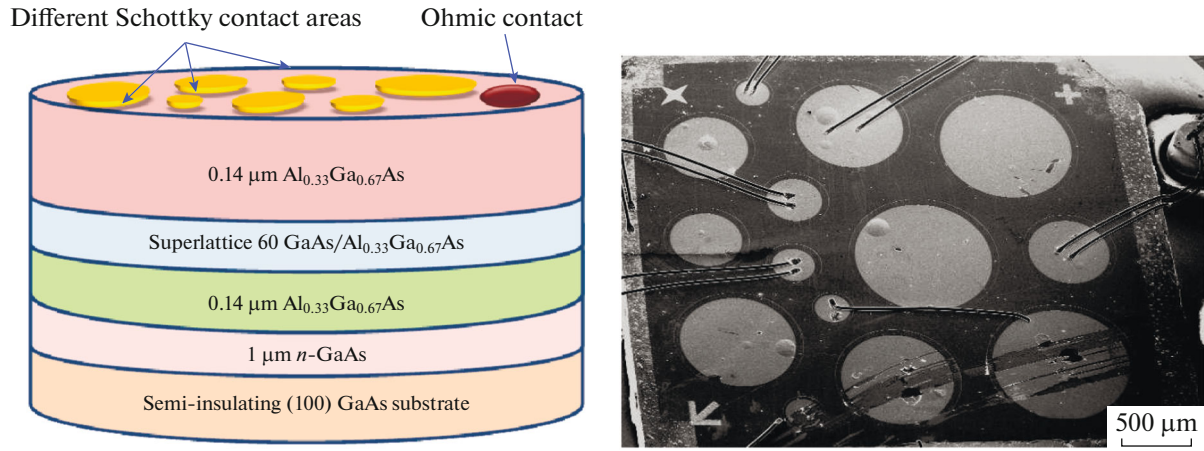
**Fig. 1.** (a) Schematic representation of the NU1054 Multi-Quantum Wells (MQWs), (b) picture by SEM of NU1054 of (MQWs).

Optimizer (ALO) algorithm, which mimics the hunt mechanism of the Antlions in the nature, have been freshly developed by Mirjalili [21]. This algorithm proves its ability to provide better results in terms of global convergence, exploration and exploitation [22].

In this paper, the authors suggest the application of ALO algorithm to extract the barrier height, built in voltage and effective density from the $C-V$ characteristics for different temperature ranging from 20 to 400 K.

The second section gives the experimental details of fabrication process and characterization phase. The third section describes the proposed approach of parameters extraction. Results and discussion are given in the fourth section. Finally, conclusion and future perspectives are presented in the fifth section.

## 1. EXPERIMENTAL DETAILS

In this work, sample referenced by NU1054 was fabricated at Nottingham University [7, 8]. It is $n$-type Silicon doped GaAs/AlGaAs multi quantum wells Schottky diode. The fabrication process starts by the growth of a semi insulating GaAs substrate with conventional orientation (100) using molecular beam epitaxy (MBE) technic. After that, GaAs and $Al_{0.33}Ga_{0.67}As$ epilayers were deposited and doped of $2 \times 10^{16}$ and $1.33 \times 10^{16}$ cm$^{-3}$, respectively, at growth temperature of 630°C.

The structure layers of the Schottky diode, starting from the substrate, are; (i) 1 μm GaAs ($n$-type with concentration $2 \times 10^{16}$ cm$^{-3}$) buffer layer, (ii) 0.14 μm $Al_{0.33}Ga_{0.67}As$ ($n = 1.33 \times 10^{16}$ cm$^{-3}$) barrier, (iii) a 60 periods of GaAs (50 A°) and $Al_{0.33}Ga_{0.67}As$ MQW's, (iv) 0.14 μm $n$-type $Al_{0.33}Ga_{0.67}As$ as effective region.

Regarding the contacts, the ohmic one is made by the evaporation of Ge/Au/Ni/Au (54 nm/60 nm/20 nm/136 nm thick layers) and annealing at 360°C for 30 s. While, the Schottky contacts is made by evaporating

Ti/Au (40 nm/175 nm) on the top of the $n$-type $Al_{0.33}Ga_{0.67}As$ layer at 410°C.

Finally, $C-V$ characteristics were measured at the temperature range 20–400 K and 1 MHz frequency, within the characterization bench (School of Physics and Astronomy, Nottingham University). Figure 1 shows both the schematic representation of the Schottky diode and its SEM (Scanning Electronic Microscope) image.

## 2. THE PROPOSED APPROACH OF EXTRACTION

The $C-V$ characteristics of Schottky diode can be modeled by the following equation [2]:

$$\frac{C}{A} = \sqrt{\frac{\pm q \varepsilon N_{eff}}{2\left(\pm V_{bi} \pm V - kT/q\right)}}. \quad (1)$$

Where the sign (+) applies for $p$-type and the (−) sign applies for $n$-type, A is the contact area, $q$ is the electron charge, $\varepsilon$ is the material permittivity, $N_{eff}$ is the effective density of the carriers and $V_{bi}$ is the built in voltage. Our work are based on $n$-type Schottky diode, therefore, the $N_{eff}$ will denote donor density $N_D$ (because $N_D \gg N_A$).

In Eq. (1), $C$ and $V$ are the diode capacitance and operating voltage, respectively. And it is mainly depending on $N_{eff}$ and $V_{bi}$. Moreover, the Schottky barrier height $\phi_b$ can be determined as function of $V_{bi}$ and $N_D$ as given bellow [2]:

$$\phi_b(C-V) = V_{bi} + \frac{kT}{q}\ln\left(\frac{N_c}{N_D}\right). \quad (2)$$

Where $N_c = 1.11 \times 10^{16}$ cm$^{-3}$ is the effective density of states in the conduction band for $Al_{0.33}Ga_{0.67}As$ [23]. The accuracy of this model depends strongly on the precision of its parameters ($V_{bi}$, $\phi_b$ and $N_D$).
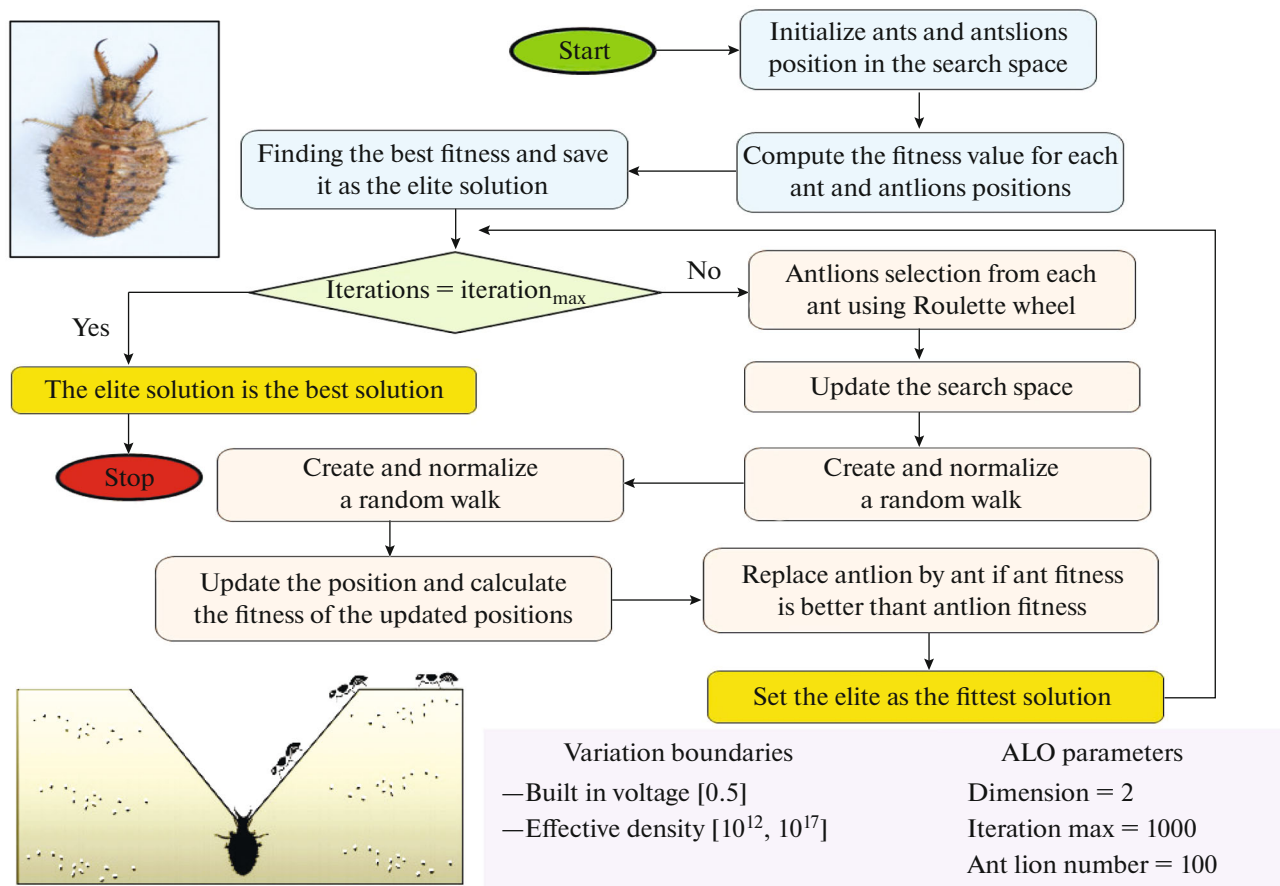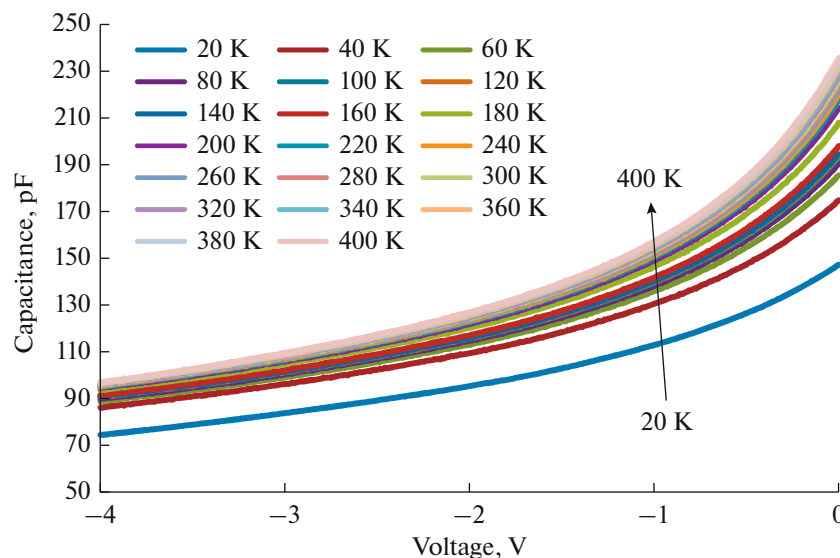
**Fig. 2.** Flowchart of ant lion optimizer.



**Fig. 3.** The real measured $C-V$ characteristics of the NU1054 Multi-Quantum Wells (MQWs) Schottky diode for different temperatures.

In this paper, the authors consider the extraction parameter stage as an optimization issue, in which, a recent heuristic algorithm ALO [21] is applied to minimize the cost function. Where, the cost function is the Root Mean Square Error (RMSE) between real measured $C-V$ characteristics and the estimated ones [24].
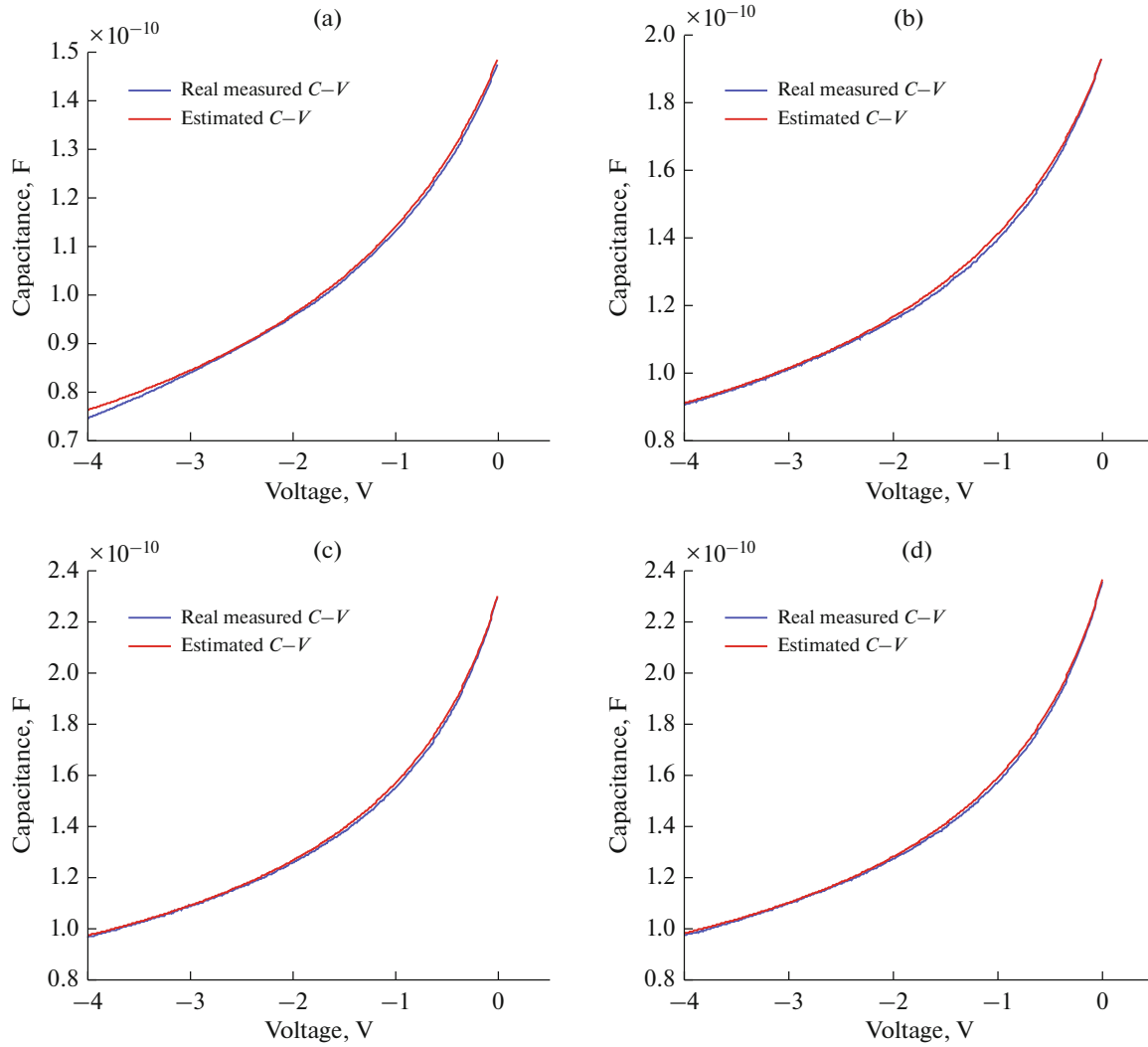
**Fig. 4.** Real measured and estimated $C–V$ characteristics at (a) $T = 20$ K, (b) $T = 100$ K, (c) $T = 340$ K and (d) $T = 400$ K.

Ant lion optimizer algorithm models mathematically the interaction between ants and antlions in nature. This algorithm is defined by five essential phases [21], such as (i) random walk of the ants, (ii) traps building, (iii) trapping in antlion's pits, (iv) preys (ants) catching and finally (v) pits re-building. The different steps of ALO algorithm are summarized in Fig. 2. For more details about ALO algorithm, see [25].

**Table 1.** The values of barrier height, effective doping density and built in voltage as function of temperature

| Temperature (Kelvin) | Built-in volatge, V | Effective doping, cm$^{-3}$ | Barrier height, eV | Root mean square error |
|---|---|---|---|---|
| $T = 20$ K | 1.432 | $3.145 \times 10^{15}$ | 1.432 | $3.582 \times 10^{-13}$ |
| $T = 80$ K | 1.172 | $4.22 \times 10^{15}$ | 1.179 | $3.773 \times 10^{-13}$ |
| $T = 100$ K | 1.156 | $4.269 \times 10^{15}$ | 1.147 | $4.195 \times 10^{-13}$ |
| $T = 140$ K | 1.145 | $4.289 \times 10^{15}$ | 1.137 | $4.26 \times 10^{-13}$ |
| $T = 180$ K | 1.047 | $4.452 \times 10^{15}$ | 1.033 | $4.253 \times 10^{-13}$ |
| $T = 220$ K | 0.971 | $4.51 \times 10^{15}$ | 0.989 | $4.521 \times 10^{-13}$ |
| $T = 260$ K | 0.943 | $4.53 \times 10^{15}$ | 0.960 | $1.054 \times 10^{-13}$ |
| $T = 300$ K | 0.915 | $4.54 \times 10^{15}$ | 0.940 | $4.672 \times 10^{-13}$ |
| $T = 340$ K | 0.892 | $4.558 \times 10^{15}$ | 0.865 | $4.406 \times 10^{-13}$ |
| $T = 400$ K | 0.859 | $4.604 \times 10^{15}$ | 0.828 | $4.360 \times 10^{-13}$ |
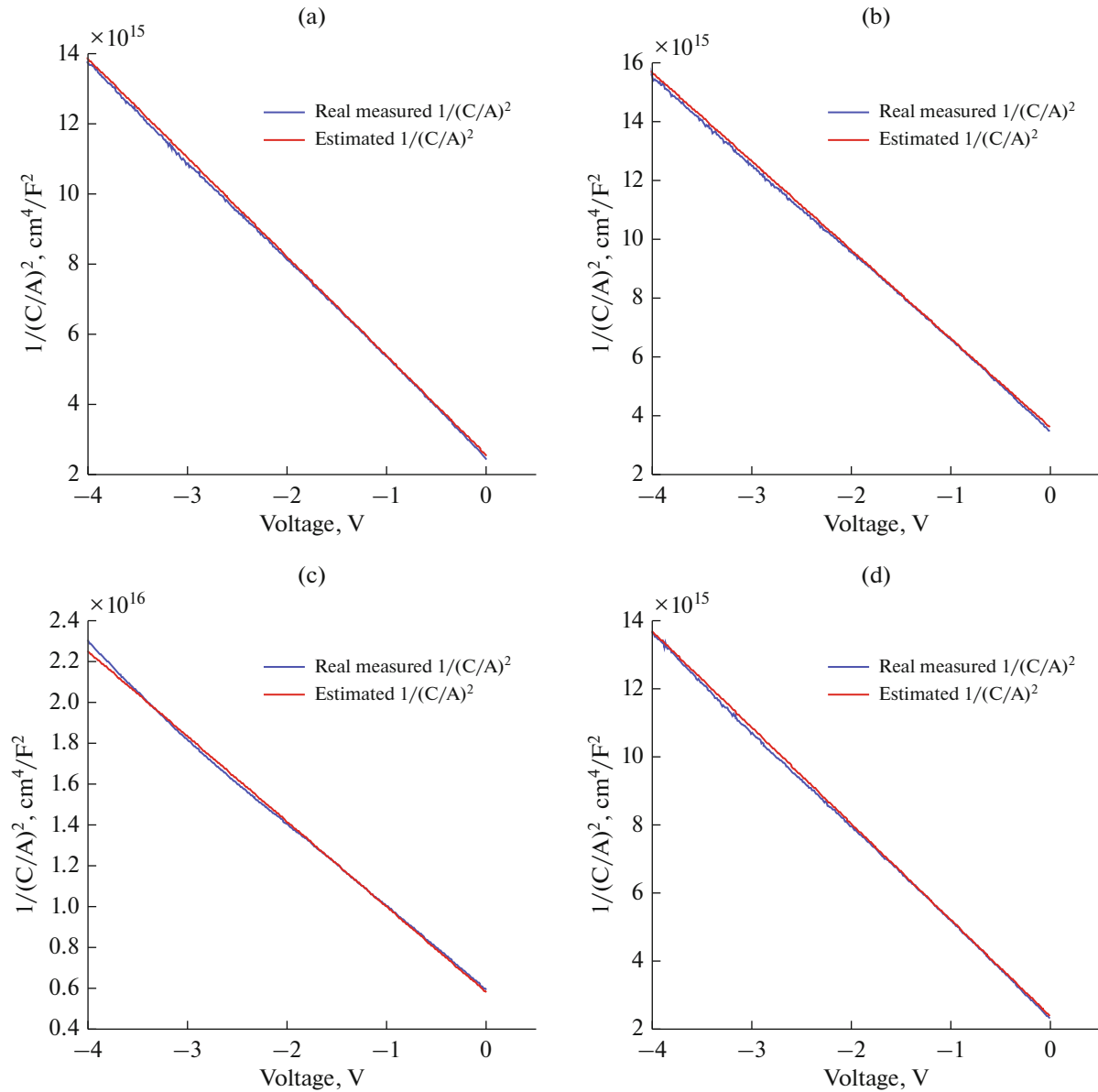
**Fig. 5.** Real measured and estimated $1/(C/A)^2$ plots at (a) $T = 20$ K, (b) $T = 100$ K, (c) $T = 340$ K and (d) $T = 400$ K.

## 3. RESULTS AND DISCUSSION

The first stage of this work was the fabrication of set of six Multi Quantum Wells AlGaAs Schottky diodes (Fig. 1), for which the authors select only one sample to validate the developed approach. Indeed, the fabrication process was successfully carried out at Nottingham University (Clean room of school of astronomy and applied physics).

The elaborated sample was afterward characterized at DLTS characterization bench of this University. The $I-V$, $C-V$ and traps characteristics are measured during this phase. More particularly, the $C-V$ characteristics have been used in this work to study the

dependence of the barrier height and effective doping density as function of temperature.

Figure 3 shows the experimental $C-V$ characteristics that have been measured at the temperature range [20 to 400 K] and voltage range [−4 to 0 V] with steps of 0.01 V.

By analyzing the obtained result, it can be seen a usual $C-V$ behavior where the capacitance value increase by increasing in temperature at reverse bias. This is mainly due to the phenomenon of carriers accumulation. Also, the Schottky diode reliability was proved by the obtained $C-V$ characteristics under high and low temperature conditions (20 and 400 K).
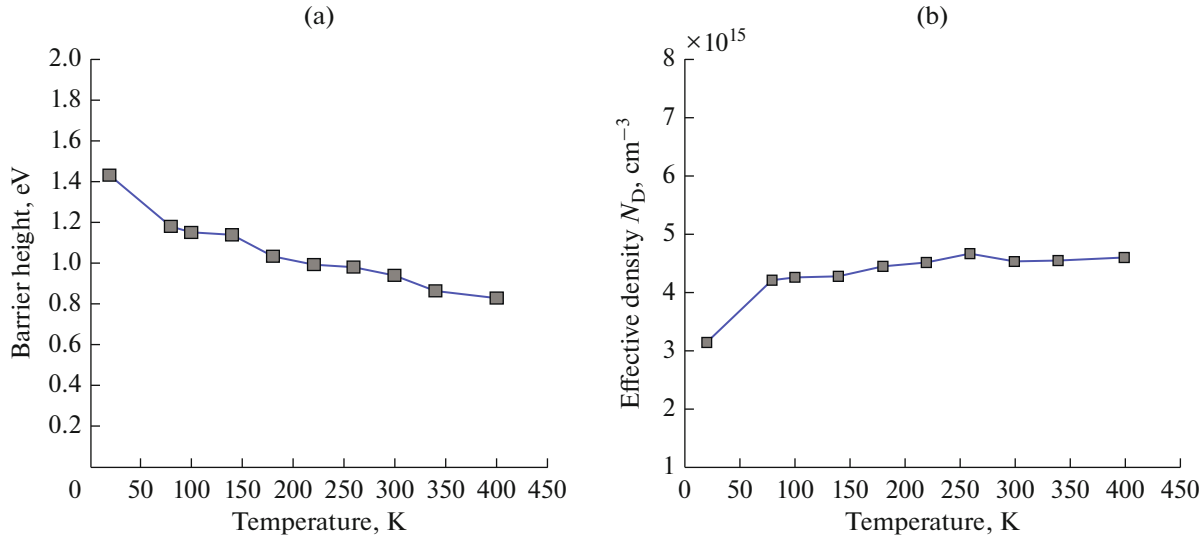
(a)

(b)



**Fig. 6.** The variation of (a) barrier height $\phi_b$ and (b) effective density $N_D$ as function of temperature.

Next, the experimental measured $C-V$ characteristics are employed to extract the barrier height $\phi_b$, effective density $N_D$ and built in voltage $V_{bi}$ by applying ALO algorithm.

The optimal values of these parameters are summarized in Table 1, where RMSE values between measured and estimated $C-V$ curves is also included.

Another criterion of parameters exactness has also been carried out by plotting both real measured and estimated $C-V$ and $1(C/A)^2$ characteristics. Four $C-V$ characteristics at different operating temperatures (20, 100, 340 and 400 K) are depicted in Figs. 4 and 5 to point out the similarity between them.

The first observation is concerning parameters values which show a normal comportment [15]. In fact, a proportional relation between $V_{bi}$ and $\phi_b$ has been appeared (correct agreement with Eq. 2). Also, we can see that by increasing the temperature value, $\phi_b$ and $V_{bi}$ will decrease. The way in which $\phi_b$ varies with temperature is attributed to the existence of trap energy levels [26] in the depletion region. Where the ionized acceptor traps reduce the capacitance of the space charge region (SCR), leading to the built in voltage increase. Therefore, the barrier height increases too.

Results in Figs. 4 and 5 show an apparent accordance between measured and estimated plots. This proves the accuracy of identified parameters where the value of RMSE is about $10^{-13}$, hence the high efficiency of ALO algorithm in parameters identification.

To better illustrate the parameters' dependency with temperature, Fig. 6 shows the thermal variation of barrier height and effective density.

## 4. CONCLUSIONS

For the first time, ALO algorithm has been applied to extract the barrier height, effective density and built in voltage of $n$-type MQW's Schottky diode from $C-V$ characteristics.

This work consists of three main phases, starting by the device fabrication, going to the characterization stage, and finishing with the parameters extraction. The device fabrication process and characterization were achieved at Nottingham University. After analyzing the obtained results, our sample has shown a usual behavior with temperature variation. Regarding the extraction results, we can see a good harmony between barrier height and built in voltage. To finish with, the achieved results prove the high efficiency of our approach. As future perspectives, the authors propose to compare the obtained results by ALO with others heuristics algorithms. And applied the approach for another type of Schottky diode.

## REFERENCES

1. *Physique des semiconducteurs et des composants électroniques,* Mathieu, H. and Fanet, H., Eds., Paris: Dunod, 2001, vol. 189.

2. *Semiconductor Material and Device Characterization,* Schroder, D.K., Ed., Chichester: Wiley, 2015.

3. *Physics and Chemistry of III−V Compound Semiconductor Interfaces,* Williams, R., Robinson, G., and Wilmsen, C., New York: Plenum, 1985.

4. Hattori, K. and Torii, Y., A new method to fabricate Au/$n$-type InP Schottky contacts with an interfacial layer, *Solid-State Electron.,* 1991, vol. 34, pp. 527−531.

5. Viktorovitch, P., Louis, P., Besland, M., and Chovet, A., Electrical characterization of metal-oxide-InP tunnel diodes based on current-voltage, admittance and low

frequency noise measurements, *Solid-State Electron.,* 1995, vol. 38, pp. 1035−1043.

6. Rami, B., Simulation of the temperature and the deep traps effect on the electrical characteristics of GaAs diodes, *Ph.D. Thesis,* Biskra, Algeria: Univ. Mohamed Khider-Biskra, 2015.

7. Filali, W., Sengouga, N., Oussalah, S., Mari, R.H., Jameel, D., Al Saqri, N.A., Aziz, M., Taylor, D., and Henini, M., Characterisation of temperature dependent parameters of multi-quantum well (MQW) Ti/Au/*n*-AlGaAs/*n*-GaAs/*n*-AlGaAs Schottky diodes, *Super-latt. Microstruct.,* 2017, vol. 111, pp. 1010−1021.

8. Mari, R.H., DLTS characterisation of defects in III−V compounds semiconductors grown by MBE, *Ph.D. Thesis,* Univ. of Nottingham, 2011.

9. Mayimele, M., van Rensburg, J.P.J., Auret, F., and Diale, M., Analysis of temperature-dependant current-voltage characteristics and extraction of series resistance in Pd/ZnO Schottky barrier diodes, *Phys. B: Condens. Matter,* 2016, vol. 480, pp. 58−62.

10. Higashiwaki, M., Konishi, K., Sasaki, K., Goto, K., Nomura, K., Thieu, Q.T., Togashi, R., Murakami, H., Kumagai, Y., and Monemar, B., Temperature-dependent capacitance-voltage and current-voltage characteristics of Pt/Ga$_2$O$_3$ (001) Schottky barrier diodes fabricated on $n$−Ga$_2$O$_3$ drift layers grown by halide vapor phase epitaxy, *Appl. Phys. Lett.,* 2016, vol. 108, p. 133503.

11. Cheung, S. and Cheung, N., Extraction of Schottky diode parameters from forward current-voltage characteristics, *Appl. Phys. Lett.,* 1986, vol. 49, pp. 85−87.

12. Karaboga, N., Kockanat, S., and Dogan, H., Parameter determination of the Schottky barrier diode using by artificial bee colony algorithm, in *Proceedings of the 2011 International Symposium on Innovations in Intelligent Systems and Applications, 2011,* pp. 6−10.

13. Zeghdar, K., Dehimi, L., Saadoune, A., and Sengouga, N., Inhomogeneous barrier height effect on the current-voltage characteristics of an Au/*n*-InP Schottky diode, *J. Semicond.,* 2015, vol. 36, p. 124002.

14. Fu, R., Grekov, A.E., Peng, K., and Santi, E., Parameter extraction procedure for a physics-based power SiC Schottky diode model, *IEEE Trans. Ind. Appl.,* 2014, vol. 50, pp. 3558−3568.

15. Naik, S.S. and Reddy, V.R., Electrical transport characteristics of Pd/V/N-InP Schottky diode from IVT and CVT measurements, *J. Nano Electron. Phys.,* 2011, vol. 3, pp. 1048−1055.

16. Jayawardena, A., Ahyi, A.C., and Dhar, S., Analysis of temperature dependent forward characteristics of Ni/β-Ga$_2$O$_3$ Schottky diodes, *Semicond. Sci. Technol.,* 2016, vol. 31, p. 115002.

17. Ferhat-Hamida, A., Ouennoughi, Z., Hoffmann, A., and Weiss, R., Extraction of Schottky diode parameters including parallel conductance using a vertical optimization method, *Solid-State Electron.,* 2002, vol. 46, pp. 615−619.

18. Toumi, S. and Ouennoughi, Z., A vertical optimization method for a simultaneous extraction of the five parameters characterizing the barrier height in the Mo/4H−SiC Schottky contact, *Indian J. Phys.,* 2019, pp. 1−8.

19. Wang, K. and Ye, M., Parameter determination of Schottky-barrier diode model using differential evolution, *Solid-State Electron.,* 2009, vol. 53, pp. 234−240.

20. Garoudja, E., Kara, K., Chouder, A., and Silvestre, S., Parameters extraction of photovoltaic module for long-term prediction using artifical bee colony optimization, in *Proceedings of the 2015 3rd International Conference on Control, Engineering & Information Technology (CEIT), 2015,* pp. 1−6.

21. Mirjalili, S., The ant lion optimizer, *Adv. Eng. Software,* 2015, vol. 83, pp. 80−98.

22. Mirjalili, S., Jangir, P., and Saremi, S., Multi-objective ant lion optimizer: a multi-objective optimization algorithm for solving engineering problems, *Appl. Intell.,* 2017, vol. 46, pp. 79−95.

23. *Properties of Aluminium Gallium Arsenide,* Adachi, S., Ed., London: IET, 1993.

24. Garoudja, E., Chouder, A., Kara, K., and Silvestre, S., An enhanced machine learning based approach for failures detection and diagnosis of PV systems, *Energy Convers. Manage.,* 2017, vol. 151, pp. 496−513.

25. Guha, D., Roy, P.K., and Banerjee, S., Ant lion optimization: a novel algorithm applied to load frequency control problem in power system, in *Proceedings of the International Conference on Frontiers in Optimization: Theory and Applications, 2016,* pp. 195−210.

26. Fritah, A., Extraction des paramètres électrique d'une diode à barrière de Schottky (SBD) à base de phosphure d'indium de type *n* (*n*-InP) par IVT et CVT, *Ph.D. Thesis,* Biskra: Univ. Mohamed Khider-Biskra, 2017.