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 20K to 400K. 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.

Keywords: Ant lion optimizer, Barrier height, Capacitance-voltage, Multi quantum wells, Schottky diode

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 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 20K to 400K.

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 $2x10^{+16}$ $cm^{-3}$and $1.33x10^{+16}$ cm^{-3}, respectively, at growth temperature of 630 °C.

The structure layers of the Schottky diode, starting from the substrate, are; (i) 1µm GaAs (n-type with concentration $2x10^{+16}$ cm^{-3}) buffer layer, (ii) 0.14 µm $Al_{0.33}Ga_{0.67}As$ ($n=1.33x10^{+16}$ cm^{-3}) barrier, (iii) a 60 periods of GaAs (50 A°) and $Al_{0.33}Ga_{0.67}As$ MQW's, (iiii) 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 K–400 K and 1MHz frequency, within the characterization bench (School of Physics and Astronomy, Nottingham University). Fig. 1 shows both the schematic representation of the Schottky diode and its SEM (Scanning Electronic Microscope) image.

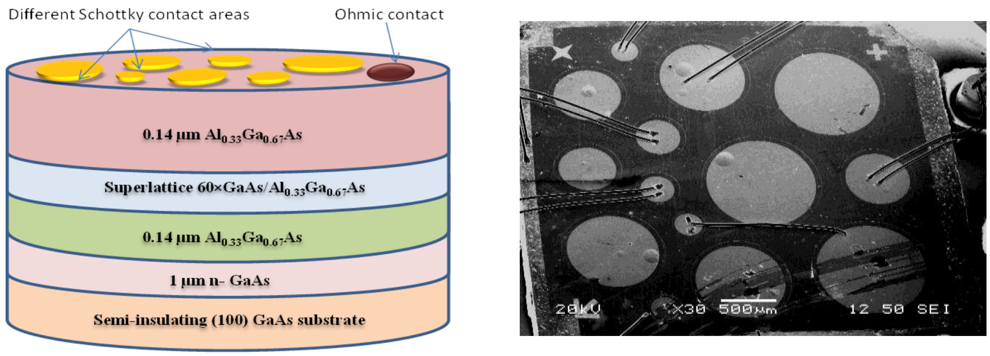

Fig. 1. Schematic representation of the NU1054 Multi-Quantum Wells (MQWs), b) Picture by SEM of NU1054 of (MQWs).

2. THE PROPOSED APPROACH OF EXTRACTION

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

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

Where the sign (+) applies for p-type and the (-) sign applies for n-type, A is the contact area, q is the electron charge, ε 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 $N_D >> N_A$).

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 ϕ_b can be determined as function of V_{bi} and N_D as given bellow [2]:

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

Where $N_c = 1.11\text{x}10^{+16}$ 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}, ϕ_b and N_D).

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].

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, (iiii) preys (ants) catching and finally (iiiii) pits re-building. The different steps of ALO algorithm are summarized in Fig. 2. For more details about ALO algorithm, see [25].

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.

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

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 (20K and 400K).

Next, the experimental measured C-V characteristics are employed to extract the barrier height ϕ_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 & $1(C/A)^2$ characteristics. Four C-V characteristics at different operating temperatures (20K, 100K, 340K and 400K) are depicted in Fig. 4. and Fig. 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 ϕ_b has been appeared (correct agreement with Eq. 2). Also, we can see that by increasing the temperature value, ϕ_b and V_{bi} will decrease. The way in which ϕ_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.

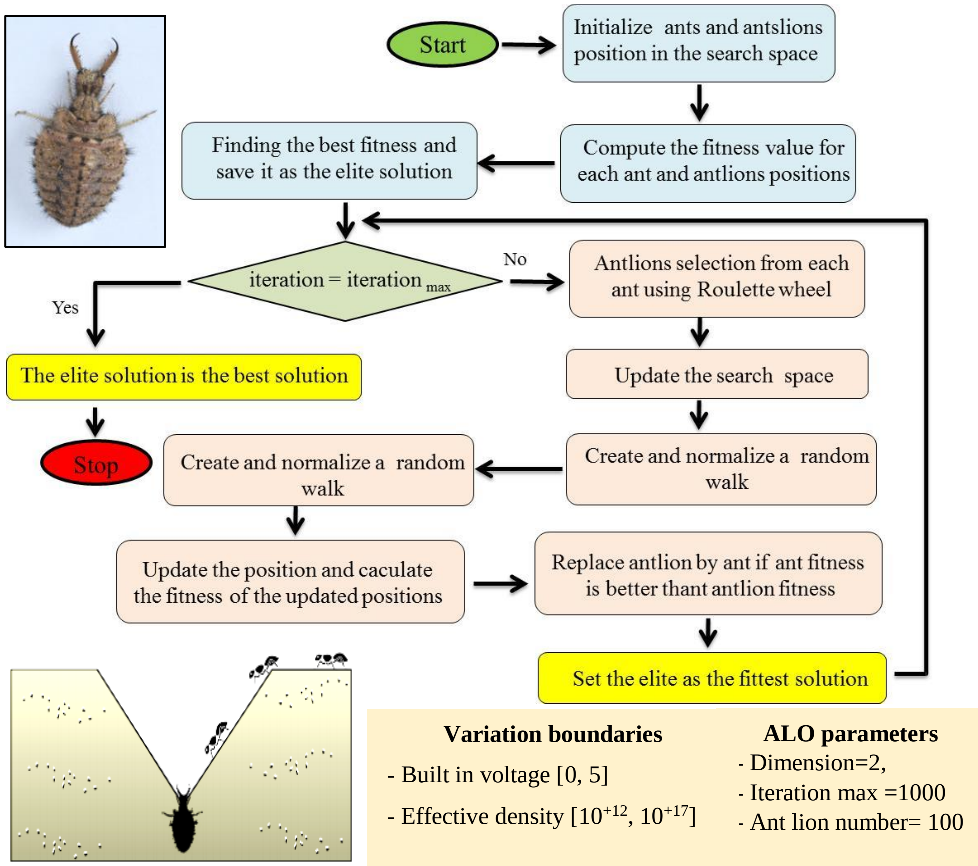

Fig. 2. Flowchart of ant lion optimizer.

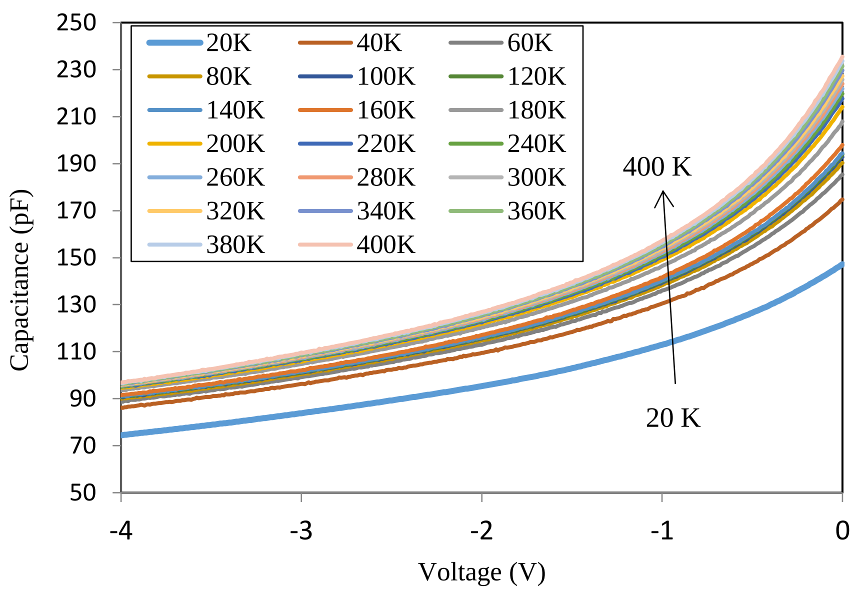

Fig. 3. The real measured C-V characteristics of the NU1054 Multi-Quantum Wells (MQWs) Schottky diode for different temperatures.

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

Temperature (Kelvin)	Buit-in volatge (V)	Effective doping (cm^{-3})	Barrier height (eV)	Root mean square error
T=20K	1.432	3.145×10^{15}	1.432	3.582×10^{-13}
T= 80K	1.172	4.22×10^{15}	1.179	3.773×10^{-13}
T=100K	1.156	4.269×10^{15}	1.147	4.195×10^{-13}
T=140K	1.145	4.289×10^{15}	1.137	4.26×10^{-13}
T=180K	1.047	4.452×10^{15}	1.033	4.253×10^{-13}
T=220K	0.971	4.51×10^{15}	0.989	4.521×10^{-13}
T=260K	0.943	4.53×10^{15}	0.960	1.054×10^{-13}
T=300K	0.915	4.54×10^{15}	0.940	4.672×10^{-13}
T=340K	0.892	4.558×10^{15}	0.865	4.406×10^{-13}
T=400K	0.859	4.604×10^{15}	0.828	4.360×10^{-13}

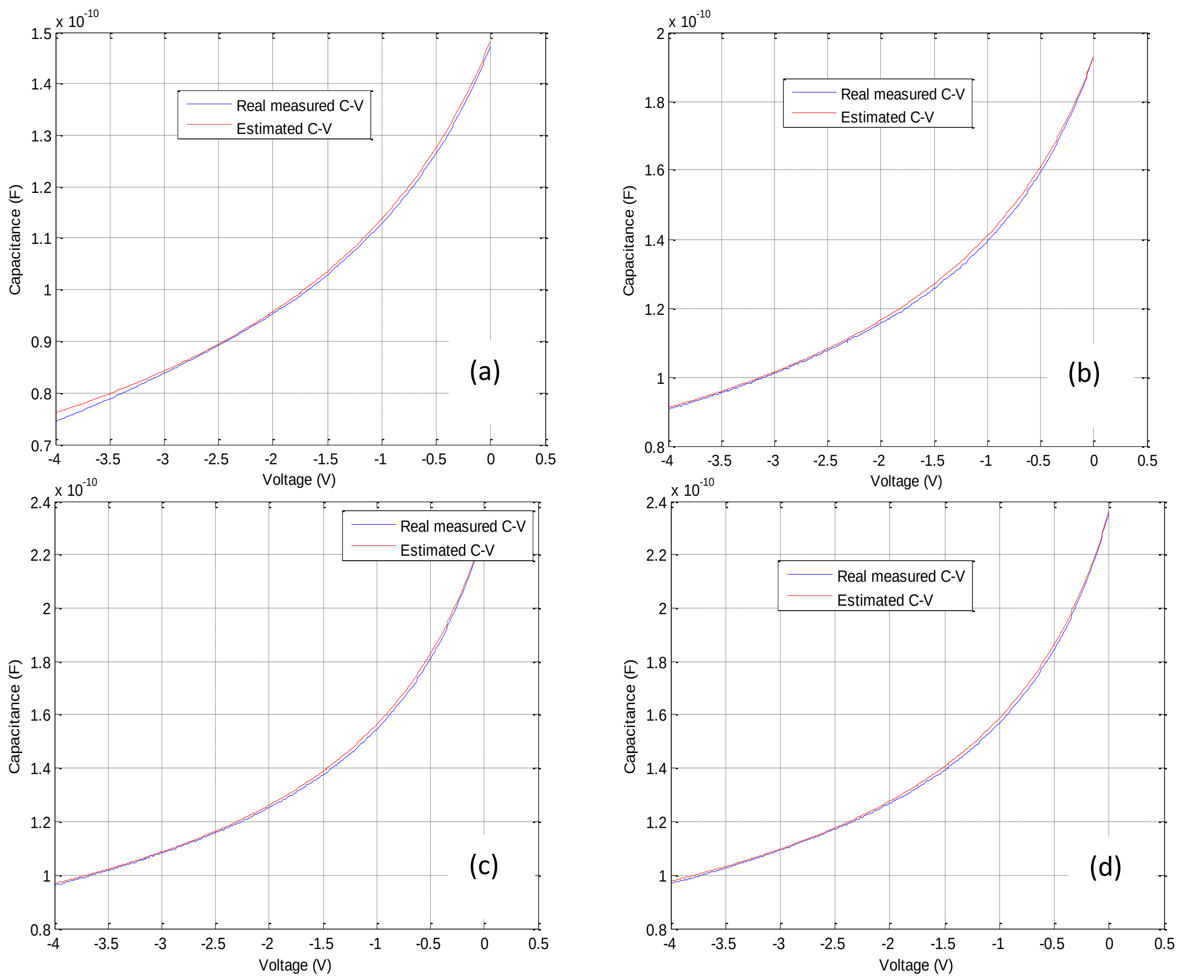

Fig. 4. Real measured and estimated C-V characteristics at a) T=20K, b) T=100K, c) T=340 K and d) T=400K.

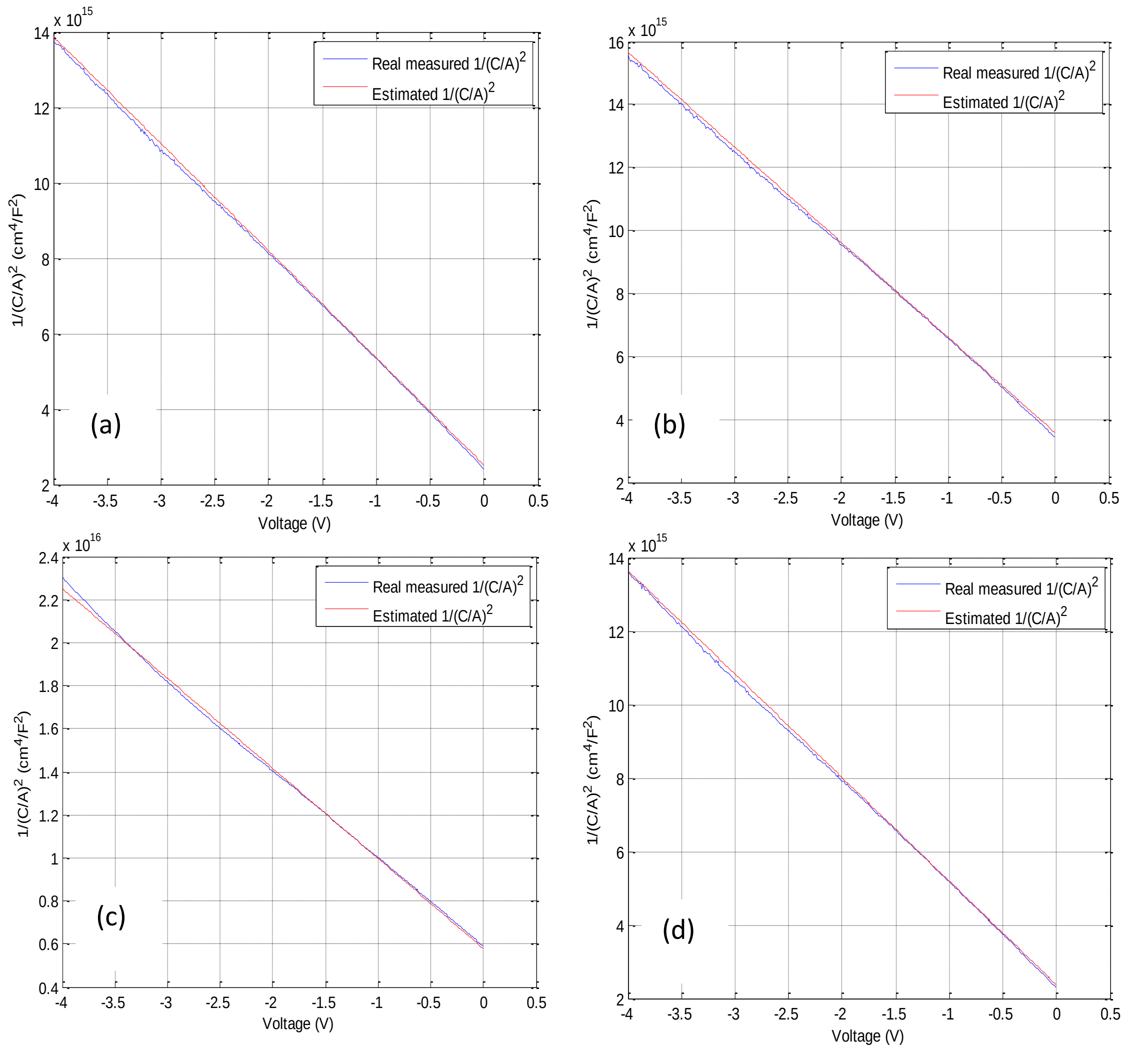

Fig. 5. Real measured and estimated $1/(C/A)^2$ plots at a) T=20K, b) T=100K, c) T= 340K and d) T=400K.

Results in Fig. 4 and Fig. 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.

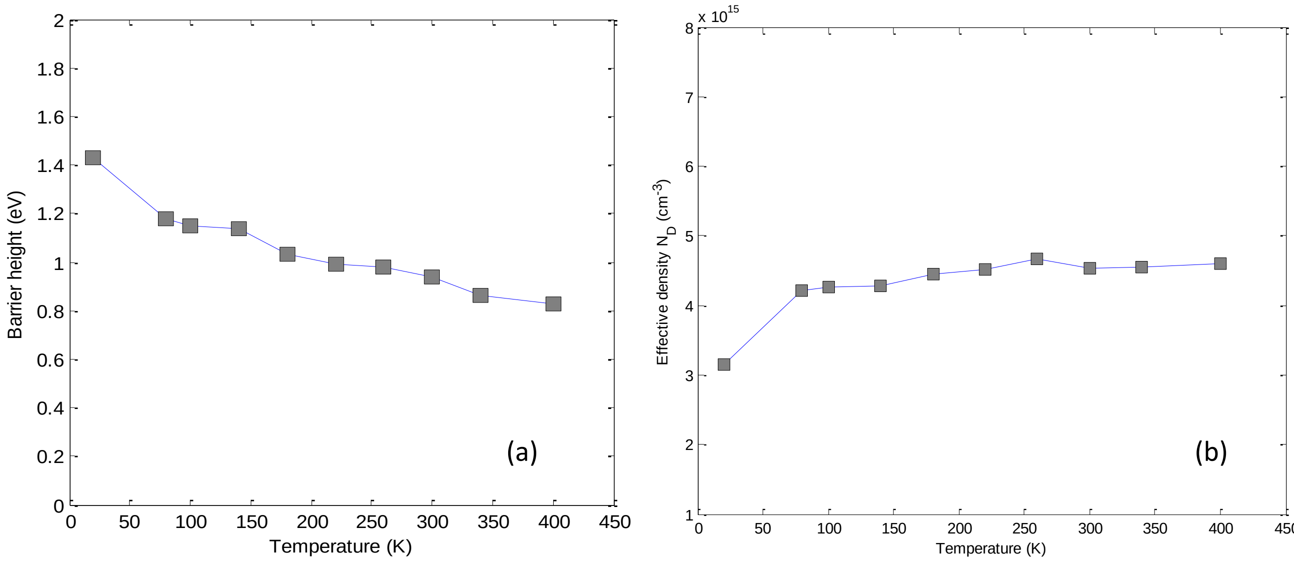

Fig. 6. The variation of a) barrier height ϕ_b and b) effective density N_D as function of temperature.

4. CONCLUSION

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.

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