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The Effect of Quantum Dots on the Performance of the Solar Cell

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Abstract
Quantum dot solar cells are currently the subject of research in the fields of renewable energy, photovoltaics and optoelectronics, due to their advantages which enables them to overcome the limitations of traditional solar cells. The inability of ordinary solar cells to generate charge carriers, which is prevents them from contributing to generate the current in solar cells. This work focuses on modeling and simulating of Quantum Dot Solar Cells based on InAs/GaAs as well as regular type of GaAs p-i-n solar cells and to study the effect of increasing quantum dots layers at the performance of the solar cell. The low energy of the fell photons considers as one of the most difficult problems that must deal with. According to simulation data, the power conversion efficiency increases from (12.515% to 30.94%), current density rises from 16.4047 mA/cm2 for standard solar cell to 39.4775 mA/cm2) using quantum dot techniques (20-layers) compared to traditional type of GaAs solar cell. Additionally, low energy photons' absorption range edge expanded from (400 to 900 nm) for quantum technique. The results have been modeled and simulated using (SILVACO Software), which proved the power conversion efficiency of InAs/GaAs quantum dot solar cells is significantly higher than traditional (p-i-n) type about (247%).

Keywords
Solar Cells, Quantum Dots, Intermediate Band, Multi-exciting Generation, Nanoparticles.

I. INTRODUCTION

The self-assemble structure is based on the development of coherently strained islands and managing the transition from 2D to 3D growth, both of which are brought about by an unfit strain in the epitaxial structure [1]. One of the most intriguing topics in science during the last ten years is self-assembled nanostructures. Numerous extraordinary features can be attained if the dimensions of a semiconductor are shrunk to the nanoscale scale. These nanoparticles behave significantly differently from normal materials. Many nanomaterials have been created in the previous 20 years, including quantum wells, quantum wire, and quantum dots. Quantum dots (QDs), a type of nanostructure, are said to have three-dimensional dimensions that are less than the wavelength of the Do-Broglie exciton [2]. A performance that is superior to single-gap solar cell technology is achieved using the photovoltaic ideas of solar cells with the intermediate band and many exciton generations. The basic principles of its operation center on creating a semiconductor material with an electronic band inside the band gap, for the purpose of capturing and using photons with energies below the bandgap, carrier recombination between bands should be much slower than relaxation within the bands. Alternatively, a semiconductor could be synthesized with inetraband transitions equivalent to the semiconductor's bandgap for increased benefit and use of photons with energies above the bandgap [3]. The notion of the intermediate band solar cell (IBSC), first put forth theoretically by Luque and Mart, has revolutionized the traditional single junction and multiple

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junction solar cell technologies [4]. The great majority of QD-IBSC prototypes created up until this point have utilized type - I QDs. Many materials have a two-step absorption mechanism, including the InAs/GaAs QD system [5], GaAs/AlGaAs [6], and InAs/AlGaAs [7], has been extensively studied experimentally. Recently, one single InAs/GaAs QD with the same method was reported [8–12]. The most crucial characteristic that provides measured energy levels is the quantum effect. This type of material's dimensions and form can be altered to customize its electrical and optical characteristics. The distinction between these sorts is the quantity of the limited directions. Utilizing quantum dot solar cells is one of the strategies used most frequently to improve the effectiveness of photovoltaic conversion in solar cell technology. among the most energetic study areas when it comes to third-generation solar cells at the moment is quantum dot solar cells. When compared to a quantum well, a quantum dot has stronger 3-dimensional quantum confinement effects [13].

II. THE LITERATURE REVIEW

V. Aroutiounian created the p-i-n quantum dot model in 2001. To enhance the current, Inside the i-layers, he produced several layers of quantum dots. Quantum confinement phenomenon quantizes the energy level in quantum dots, which has been crucial to understanding quantum dots [14]. It would seem fair to think about whether a low dimensional structure, such a quantum dot p-i-n structure, could offer a fresh method for solving the challenge of high-efficiency solar cells [15]. These solar cells' drawbacks include inter dot gaps' effects on electrical states, transportation properties, array shape, order and disorder, and quantum dot orientation [16]. Actually, the existence of very few atoms in a quantum dot, where excites are restricted to a considerably smaller space on the order of the exciting Bohr radius of the material, which causes quantum confinement. Charge carriers (holes and electrons) are quantum-confined in the variable-size quantum dots that make up the i-layer, which increases the material's effective band gap [17]. Numerous studies have focused on type-I InAs/GaAs QD solar cells, which can extend the spectral response to longer wavelengths beyond the GaAs absorption edge [18, 19]. The type-I QDs feature strong carrier recombination in addition to high optical absorption due to the significant electron-hole wave function overlap. Nanoscale solar cells consisting of various components and structures have been the subject of numerous studies, with a variety of study findings being given. The behavior of nanoscale and faults in this category of substances have been the subject of numerous investigations, however the highest converted with a documented efficiency of manufactured nanoscale solar cell has only been 19.4%, it has two times of illumination [20]. The shapes of the inter-dot space, the cubic, spherical, and cylindrical dots, as well as the alloy composition, are taken into consideration as we analyze the behavior of various characteristics and features of a multiple quantum dots solar cell (MQDSC) structure in this work [21].

III. RESEARCH METHODOLOGY

A. *Mathematic Theory Approach*

Basic semiconductor equations had to be solved in order to assess the performance of the solar cell; these equations have a real-valued function. The following equations, which explain the physical models utilized for this simulation, can be used to describe solar cell operation [22]:

The Poisson equation, which connects charge to electrostatic potential, is the governing equation. Equation (1) contains the Poisson Electrostatic Potential equation [23].

$$\frac{d^2E}{dx^2} = \rho/\varepsilon \tag{1}$$

where rho being the charge density (C.cm-3), and epsilon is the substance permittivity. Equation (2), which is derived from the charge neutrality equation, can be written as the dopant fully ionized.

$$\rho = q(p - n + N_D^+ - N_A^-) \tag{2}$$

Equation (2) yields equation (3) when it is combined with equation (1) [23]

$$\frac{d^2E}{dx^2} = q(p - n + N_D^+ - N_A^-)/\varepsilon \tag{3}$$

The second equation is a continuity equation, which is also known as a governing equation because it considers generation, recombination, drift, and diffusion simultaneously. The continuity equation for the change in electron and hole concentration is represented by equations (4) and (5) [23]:

$$\frac{\partial n}{\partial t} = G_n - R_n + \frac{1}{q}.\frac{\partial J_n}{\partial x} \tag{4}$$

$$\frac{\partial p}{\partial t} = G_p - R_p + \frac{1}{q}.\frac{\partial J_p}{\partial x} \tag{5}$$

Where the current density of the electrons is Jn, while the current density of the holes is Jp, Gn and Gp represent the rates of creation of electrons and holes, respectively, and Rn and Rp represent the rates of recombination of electrons and holes.

In semiconductors, electric currents are produced as a result of the movement of charges by electrons and holes. A solar cell simulator's capacity to calculate the current and characteristics requires the ability to solve the drift-diffusion equation for current in a solar cell as illustrated below.

Drift parameter: is the electric field proportional to the velocity of charged particles. The carrier's acceleration is frequently destabilized by collisions with ionized impurity atoms and thermally vibrating lattice atoms. The drift-current densities for electrons and holes Jn and Jp drift are described by equations (6) and (7), respectively, and the overall drift current is described by equation (8).

$$J_{ndrift} = -qnv_d n = qn\mu_n E \tag{6}$$

$$J_{pdrift} = qpv_d p = qp\mu_p E \tag{7}$$

$$J_{drift} = J_{ndrift} + J_{pdrift} = q.E.(n\mu_n + p\mu_p) \tag{8}$$

Where μn and μp represent the mobility of the electron and hole, respectively.

Diffusion parameter: is a phenomenon in which, result of irregular thermal motion, particles tend to spread from high to low regions concentration particle. Equations (9) and (10) are used to express the diffusion-related currents that are relative to the gradient in particle concentration, while equation (12) are used to define the total diffusion current [24].

$$J_{ndiff.} = qD_n \nabla n \tag{9}$$

$$J_{pdiff.} = qD_p \nabla p \tag{10}$$

$$J_{diff.} = J_{ndiff.} + J_{pdiff.} \tag{11}$$

$$J_{diff.} = q(p\mu_p + n\mu_n)E + q(D_n \nabla n - D_p \nabla p) \tag{12}$$

B. Modeling and Simulation of Standard Solar Cell:

Fig.1 depicts the p-i-n structure utilized in this simulation as a representation of a solar cell. This model has six layers, the first and fifth of which are InGaP and are referred to as the field layer on the rear surface and the window layer, respectively. Utilizing these two layers has the advantages of lowering surface recombination at the solar cell's top and bottom and blocking minority carriers [6]. GaAs makes up the second, third, fourth, and sixth layers, which are the epitaxial seed layer (n-type), the base region, i-region, and the emitter region (p-type), respectively. First and fifth layers were doped with (2x1018 / Cm3) p-type and (1x1018 / Cm3) n-type, respectively, with (50 nm) thickness. The following levels of doping and thicknesses were utilized for the second, fourth, and sixth layers: (500 nm) for p-type doping, (1960 nm) for n-type doping, and (250 nm) for p-type doping. The i-region layer was used, and its thickness was 410 nm. SILVACO TCAD was used to create and simulate the solar cell model.

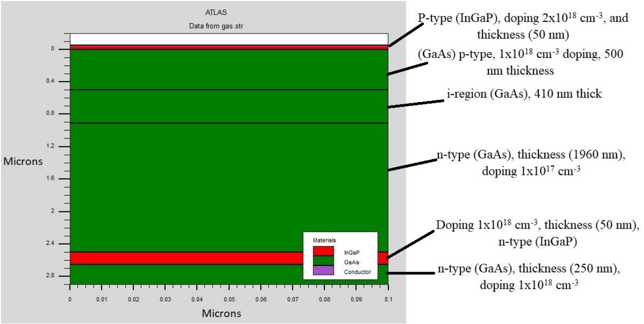

Fig. 1. Structure of standard p-i-n solar cell.

C. Modeling and Simulation of Quantum Dots Solar Cell:

The influence of quantum dots on the performance of the solar cell was investigated using the same p-i-n structure as before. InAs (QDs) were used to fill the intrinsic layer, which is located between the p-region and the n-region. The structure of p-i-n QDs is shown in Fig. 2, Fig. 3, and Fig. 4. It is seen that the barrier layers are made of GaAs, and the inserted quantum dots layer is made up of multiple InAs QDs. The purpose of the quantum dots utilized is to produce numerous electron-hole pairs within the intrinsic region, which will enhance the parameters that determine the features of the solar cell.

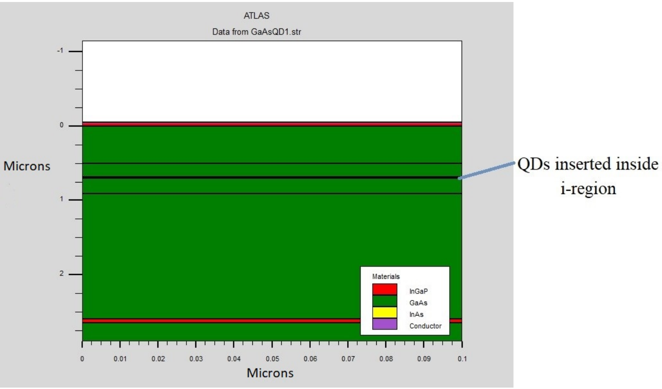

Fig. 2. ATLAS model of an InGaP/GaAs InAs quantum dot solar cell.

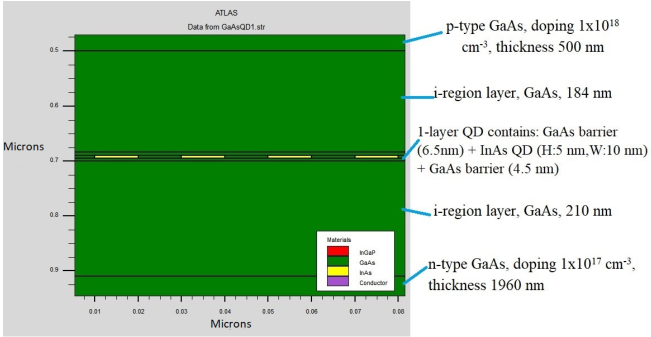

Fig. 3. Quantum dot area in the modeled device, zoomed in.

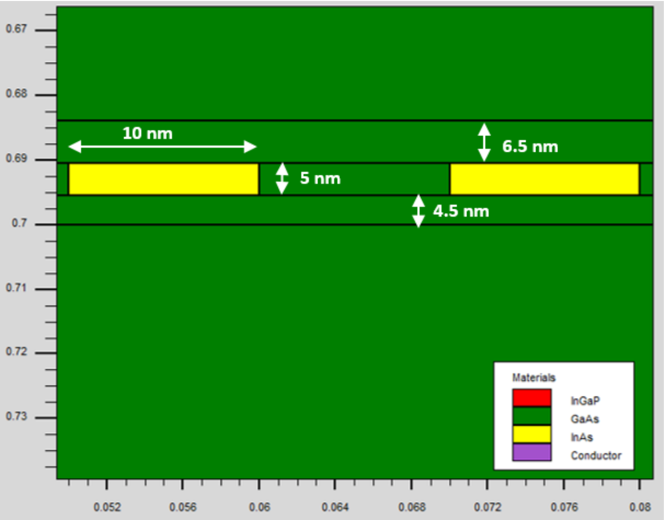

Fig. 4. Quantum dot sizes and one-layer QD barriers.

IV. RESULTS AND DISCUSSION

The solar cell was replicated in this work at 300 K solar cell and an AM1.5 light source based on (SILVACO Software). The results are compared with a previous study for Boqun Dong [25]. Where the same structure is used, but the i-region at the previous study was variable with increasing the number of quantum dots layers that were inserted into this region. While in this work the i-region is kept constant with increasing quantum dots layers. In the beginning, a typical p-i-n GaAs solar cell was simulated, and the outcomes were noted. The findings for the different added layers (1,5,10,15, and 20) are then recorded for a p-i-n InAs/GaAs quantum dot solar cell simulation. To determine the degree of improvement happened by the addition of quantum dots layers, a significant solar cell parameters recorded of several parameters, including a short circuit current, open circuit voltage, fill factor, and conversion efficiency, are measured and compared.

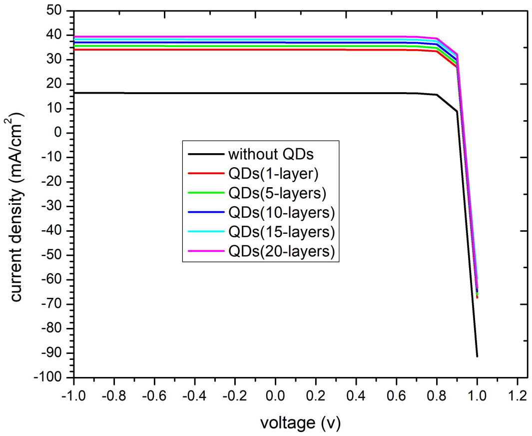

Fig. 5. Standard J-V curve with InGaP solar cell and various InAs QD layer counts.

Table I displays the outcomes of the simulation for six different solar cells, where it can be seen that the efficiency, FF, and Jsc value for all poor. When one layer of InAs QD is inserted in the i-region, the values of Jsc, FF, and efficiency rise with a minor increase in Voc. As the number of QD layers increased to (5, 10, 15, and 20), the Jsc and efficiency rise as well. The FF rises to 84.213% at QDs with 1-layer and keeps increasing at 5, 10-layers while at 15, 20-layers, it decreases to 83.93% and 83.97%.

The J-V curves of both conventional solar cells and quantum dots solar cells are displayed in Fig. 5 based on the outcomes of the simulation. The device's absorption is increased with the addition of more QDs layers, which accounts for the improvement's significance, especially in current density.

Fig. 6 shows the electrical power of standard p-i-n solar cell and multi-layers (up to 20-layers) QDs solar cell. It can be seen that standard solar cell provides an electrical power of 12.52 pW/cm2. When starting to insert the first layer of QDs in the i-region, the electrical power will increase to 26.714 pW/cm2. It continuous to increase until it reaches 30.95 pW/cm2 at 20-layers of QDs solar cell.

While Fig. 7 illustrate increasing in power conversion efficiency (PCE) from (5-20 layers), which values starts at (27.8457%) for (5- layers) and still increased to be (30.94025%) for (20-layers).

The spectral response via wavelength are measures using simulation capabilities as shown in Fig. 8. Fig 8 demonstrates that the conventional p-i-n solar cell's spectral response does indeed converge to zero at wavelengths around 900 nm. Regarding the solar cells that contain 1, 5, 10, 15, and 20-layers of quantum dots. Through Fig. 8, it can be noticed that the re-

TABLE I.
RESULTS OF SIMULATIONS OF KEY CHARACTERISTICS OF CONVENTIONAL SOLAR CELLS AND INAS/GAAS QUANTUM DOTS SOLAR CELLS WITH VARIOUS NUMBERS OF QD LAYERS

Device	p-i-n without QD	1-layer QD	5-layers QD	10-layers QD	15-layers QD	20-layers QD
Jsc(mA/cm2)	16.4047	34.1625	35.5917	37.1026	38.3309	39.4775
Voc (volts)	0.908847	0.928569	0.93004	0.931544	0.93456	0.933705
FF (%)	83.977	84.21370	84.1527	84.07935	83.9353	83.97019
PCE(%)	12.51586	26.7046	27.8457	29.0493	30.0569	30.94025

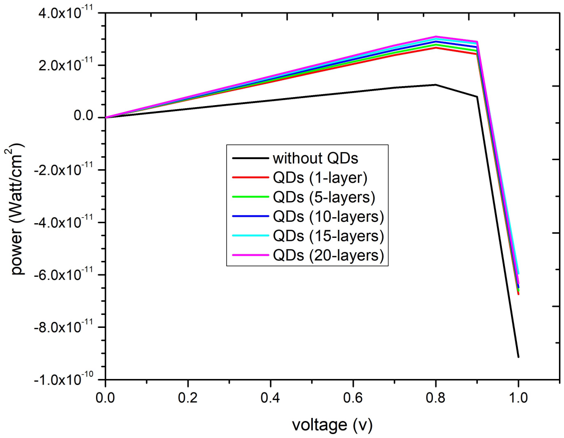

Fig. 6. Typical power curve with InGaP solar cell with various InAs QD layer counts.

sponse of standard solar cell is low compared to the response of the solar cell in the presence of QDs layers.

V. CONCLUSIONS

In this study, the capabilities of (SILVACO Software) are employed to modeled and simulated of InAs quantum dots material to improve the characteristic parameters. The creation of a comprehensive data library of material parameters, models with various settings are generated and simulated. Several outcomes that attained are displayed and discussed. First, inserting (1, 5, 10, 15, and 20 layers) of InAs/GaAs QDs into the p-i-n GaAs increases the power conversion efficiency from 12.515% to 30.94%. Second, the absorption range edge of photons with low energies is extended from (400 nm to 900 nm) by inserting multiple layers of InAs/GaAs QDs inside the i-region of p-i-n GaAs. However, the results explained that (QDs) technique give a significant value for different parameters (FF, Jsc, Voc, and PCE) that increased and improve solar cell operation. This study shows that (QD) solar cell are still have some deficiencies and more advances are needed.

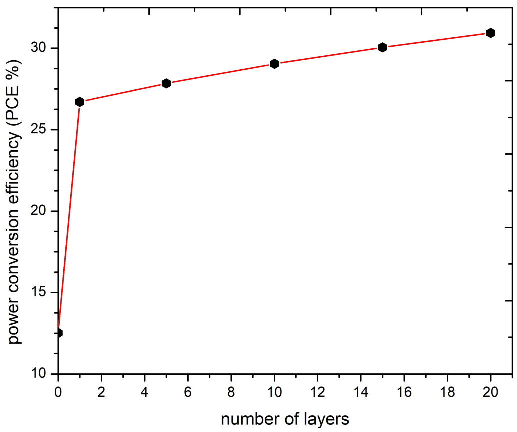

Fig. 7. Power conversion efficiency (PCE) of InAs/GaAs QD solar cells as function of the number of QDs layers.

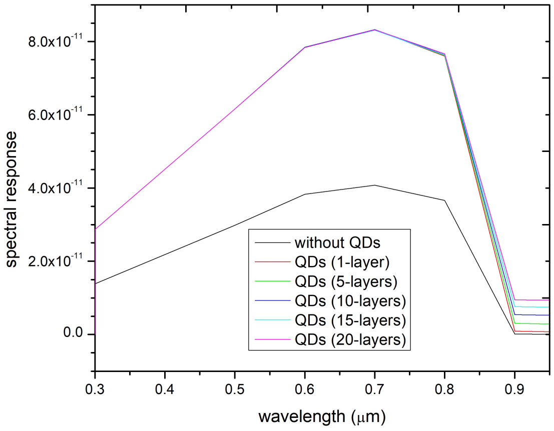

Fig. 8. The spectral response as a function of wavelength.

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

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