2017

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Publication Details

Humayun, M. A., Khan, S., Alam, A. H. M. Z., Yaacob, M., AbdulMalek, M. & Rashid, M. A. 2017, 'Improvement of temperature dependence of carrier characteristics of quantum dot solar cell using InN quantum dot', International Journal of Renewable Energy Research, vol. 7, no. 1, pp. 330-335.

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Improvement of Temperature Dependence of Carrier Characteristics of Quantum Dot Solar Cell Using InN Quantum Dot

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Received: 07.11.2016 Accepted: 29.12.2016

Abstract- Improvements of temperature dependence of certain characteristics of quantum dot solar cell using InN as active material of the device structure has been reported in this paper. A numerical analysis of temperature dependence of different parametric characteristics related to carriers within a quantum dot solar cell has been carried out in this research work. Numerical analysis of these solar cell features have been performed using Group-III Nitride trios namely GaN, AlN and InN quantum dot as active layer material of solar cell structure. Among different parameters of quantum dot solar cell drift length and the diffusion length have been analyzed along with the power loss of the carriers to complete the whole process. In this present research work effect of temperature on the characteristics of these parameters has been analyzed using mathematical approach. Numerical results obtained are compared for preferential outcomes. It is revealed from the comparison results that only the drift length of the carrier has been increased but the diffusion length and the power loss of the carriers have been minimized using InN quantum dot in the active layer of solar cell. Hence InN is the auspicious material to fabricate solar cell in upcoming decades.

Keywords Diffusion length, drift length, power loss, quantum dot, solar cell.

1. Introduction

Modern civilization has been fundamentally formed by using fossil fuels. Therefore the development of human civilization is very much dependent on the conventional sources like coal, gas, biomass and so on to fulfil our daily energy needs, maintain our growth and look forward to the prosperity in the industrial sectors. However fossil fuels are limited in existence and dwindling day by day. The contrasting scenario of scarcity of the existing energy sources and the ever increasing demand of energy sources are forcing researchers to be worried about the alternative sources of energy to accomplish the cumulative requirement of energy for the human being to exist. Furthermore, fossil fuel based energy generation has been polluting our environment in an alarming rate ever [1]. Even though the United States of America achieved considerable advancement in protecting the environment since the electricity generation plants are quite responsible for more than seventy percent of overall Sulphur di-Oxide emissions as well as almost one third of overall Nitrogen Oxide emissions around the globe [2-4]. Therefore the issues regarding public health and safety has been raised enormously due to the environmental pollution caused by the electrical energy production systems such as Hydro-electric power plant cause sound and water pollution, Coal based power stations cause sound, air and water pollution and the Nuclear power plant cause a serious ecological pollution. Hence it is clear that electrical energy production system related pollutions have become a serious challenge to the researchers. In addition to that more than three-fourth of Carbon di Oxide is emitted from ceaseless consumption of natural energy resources required to full-fill our everyday needs. Therefore, environment pollution has become one of the major issues all over the globe nowadays [5]. Consequently, researchers are entangled from three different aspects such as: (i) scarcity of existing sources of energy, (ii) mitigating continuously increasing demand and (iii) the environment issues. Therefore it is the demand of the era of technology to resolve all the issues by implementing an environment friendly sources of energy and abundant in nature. The researchers reported that the solar energy is the most suitable one that can resolve all the issues by replacing the existing classical fossil fuels.

On the other hand use of electrical energy is considered as the indicator of the development of a country as it is the heart of industrialization in the modern world. Hence undoubtedly electrical energy has become the most important among all the types of energies we consume for our everyday needs. Considering the overall scenario researchers have devoted their research towards the development of photovoltaic (PV) panels. Consequently installed PV power capacity is experiencing almost exponential growth over the last decade with the world's first solar powered airport has started faring in India. From the rapid growth of PV panels it is revealed that among the existing renewable energy potential contenders solar energy has been proving to be next that from wind, providing in abundance the cleanest form of energy [6].

Every PV panel is an array of identical modules and each module is formed with the array of identical solar cells (SCs). Usually PV panels are built in the zones with temperatures ranges from 15^0C to 50^0C in terrestrial applications. The solar panels are also used in astronomical and concentrator systems where the temperature is higher than the earth. Therefore, temperature is assumed as the most important parameter which possesses adverse effects on the performance of SCs [7].

2. Recent Development of Quantum Dot Solar Cells

A Radiation response of SC has been evaluated by Kang through AM-241 source at variable operating temperature range by applying a doped semi-insulating GaAs wafer in the SC structure [8]. In the same year, Saikia and others performed a research on characterization of multi junction SC using various binary materials such as ZnSe, ZnTe, CdTe and HgTe. The researchers reported that single junction ZnSe/CdTe SC possess inferior efficiency than that of multi junction ZnSe, ZnTe, CdTe based SCs [9]. Hence from the outcome of their research it is greatly acknowledged that efficiency of SC decrease with the increase of number of layers of quantum dot (QD) materials in the active region to fabricate quantum dot solar cell (QDSC). In addition to that Rostami and others studied the performance of QDSC using multi-stacked different-sized InGaN QDs on GaN substrate. In this study researchers calculated the efficiency and Current-Voltage phenomena of QDSC. They have embedded QDs of different sizes in intrinsic region of a p-i-n type of SC structure. This type of SC is composed of various layers in order to utilize the confinement states of QDs. This leads to Rainbow SCs, which is composed of multi-layers of semiconductor materials with different band gaps able to absorb wide range of lights of different frequencies in order to increase the amount of output power from the SC [10]. Appropriate numbers of the QD layers required to improve the maximum energy conversion efficiency has been determined by Rostami and his research group [11]. However temperature dependence of carrier characteristics still need to be investigated, which strongly depends on the quality of the materials used to fabricate the device. Therefore it is revealed that the material quality of the active layer of the SC structure plays an important role to improve the device characteristics.

3. Materials and Method

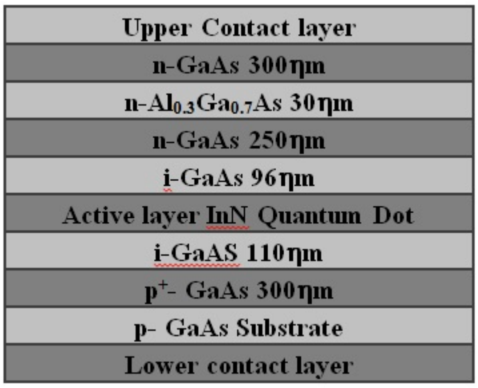
This section is composed of three different folds. The first subsection highlights a brief over view of the group-III nitride based semiconductors, which has been used as active layer material of QDSC for this research work. The second subsection highlights a detailed description of the device structure. Finally the third subsection presents the mathematical relationships used for the numerical analysis of drift length, diffusion length and the power loss of the carriers with temperature.

3.1 Group-III Nitride Materials

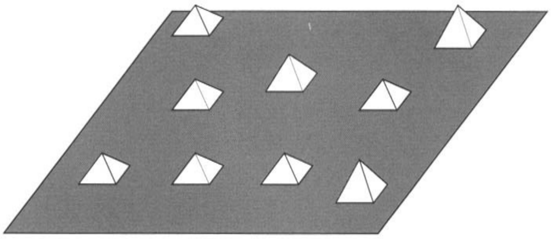
Material quality of the Group III-V semiconductors and the possibility to tune the light absorption range make these compounds attractive for SC applications. Therefore, among the available materials, group III-V materials furnish the state of art approach for achieving high performance of the SCs. Recent reports show that the preeminent mono-crystalline SCs have achieved conversion efficiency up to 24.7%, compared with the theoretically obtained maximum value of 30% [12]. The open circuit voltage, fill factor, short circuit current as well as the tilt angle have also been improved significantly over the last decade [13-15]. Hence, our current research is devoted to the effect of temperature on some of the important characteristics of the carriers within QDSC.

3.2 Device Structure

This section presents a QDSC structure composed of InN QD in the active layer of the device structure, which is shown in Fig. 1(a) and the QD array used in the active layer is shown in Fig. 1(b).



(a)



(b)

Fig. 1. (a) Schematic layer structure of InN QDSC (b) InN QD array

Schematic structure of InN QDSC presented in Fig. 1(a) is composed of a upper contact layer and a lower contact layer. In between these two layers there exist a few semiconductor layers, which form a wafer of semiconductors to form the SC. These layers consist of: p- GaAs Substrate; p+ -GaAs layer with the thickness of 300 nm; intrinsic GaAS layer with the thickness of 110 nm; 2.7 nm thick active layer with undoped InN QD; 96 nm thick intrinsic GaAs; 250 nm thick n-GaAs; 30 nm n-$Al_{0.3}Ga_{0.7}As$ and a 300 nm n-GaAs layer. Fig. 1(b) presents the schematic view of the formation of self-assembled QD, which is used to form active layer of the QDSC. Self-assembled QDs with mean diameter d = 6 nm and mean height h = 2.7 nm are used here, which are typically grown by molecular beam epitaxy in the Stranski–Krastanov growth mode.

4. Mathematical Mode

In this section mathematical relationship of the device parameters considered in this research work with temperature has been presented. The parameters considered in this research work are: drift length of the carriers, diffusion length of the carriers and the power loss due to the movement of carriers within a QDSC to complete the electron-hole recombination process.

4.1 Drift Length

Carrier transportation within the SC depends on drift in the depletion region and diffusion in the quasi-neutral region of the device structure. Flow of carriers in the existence of electric field is referred as "Drift transport". Drift transportation of carriers within a SC takes place due to the presence of electric field. In the case of drift conveyance of carriers, carriers move in the opposite path to applied electric field. Hence the drift length travelled by the carriers has a notable influence on the performance of SC. Drift length depends on the carrier mobility, built-in-field and carrier lifetime. This relationship can be described mathematically as follows [9]:

$$L_{drift} = \mu E \tau \quad (1)$$

where L_{drift} is Drift length, E is Built-in field, μ is Carrier mobility and $\boldsymbol{\tau}$ is Carrier lifetime.

4.2 Diffusion Length

Number of minority carriers within a SC increases due to the incident of light. It is expected that the surplus minority carriers will be dwindling back to the equilibrium carrier concentration. This equilibrium condition will be achieved by the means of recombination process. The rate at which recombination of electrons and holes take place is usually referred as "Recombination Rate". The recombination rate is governed by the number of surplus minority carriers. The recombination rate is also governed by the minority carrier lifetime and the minority carrier diffusion length. Hence the minority carrier diffusion length is one of the major parameters that has significant effect on the device performance. Minority carrier lifetime of a semiconductor material is the mean time that a carrier takes to recombine after the generation of electron-hole pair before the recombination process to take place. Sometime the term "Minority carrier lifetime" is referred as "Carrier lifetime", which has a direct relationship with the parameters considered in our current study. Usually minority carriers are generated in the bulk region of the sandwich by the incident light. The minority carriers persist for a long time before recombination process to take place. Carrier diffusion length is given by the following equation [16].

$$L_{diffusion} = \sqrt{D\tau} \quad (2)$$

Again, the Einstein relationship shows the relationship between diffusion coefficient and carrier mobility. The relationship is as follows [7]:

$$\frac{D}{\mu} = \frac{KT}{q} \quad (3)$$

Where D is Diffusion coefficient and K is Boltzmann's constant and T is the temperature in K.

Using equations (1) and (3), relationship between drift length of the carrier and the temperature is derived as follows:

$$L_{drift} = \frac{E\tau q D}{KT} \quad (4)$$

The temperature dependence of diffusion length of the carrier is determined by using equations (2) and (3) as follows:

$$L_{diffusion} = \sqrt{\frac{KT\tau\mu}{q}} \quad (5)$$

4.3 Power Loss of Electron

The processes of photon absorption, carrier relaxation and recombination in the SC results the loss of energy of the electrons [11]. Now the rate of change of energy, that is, the power loss of electron due to the above mention processes will be calculated. The power loss of electron is given by the following equation [17].

$$P = \frac{h\upsilon}{\tau_{avg}} e^{-\frac{h\upsilon}{KT}} \quad (6)$$

where h is Planck's constant = 6.63×10^{-34} Js, ν= frequency of the light and τ_{avg} is the photon life time.

5. Result and Discussions

A detail description of the numerical analysis of the temperature dependence of drift length, diffusion length and the power loss of the electrons within a QDSC has been presented in this section. QD considered in this research work are equal in size. The outcomes of the numerical analysis are presented graphically in Fig. 2-4 using Eq. 4-6.

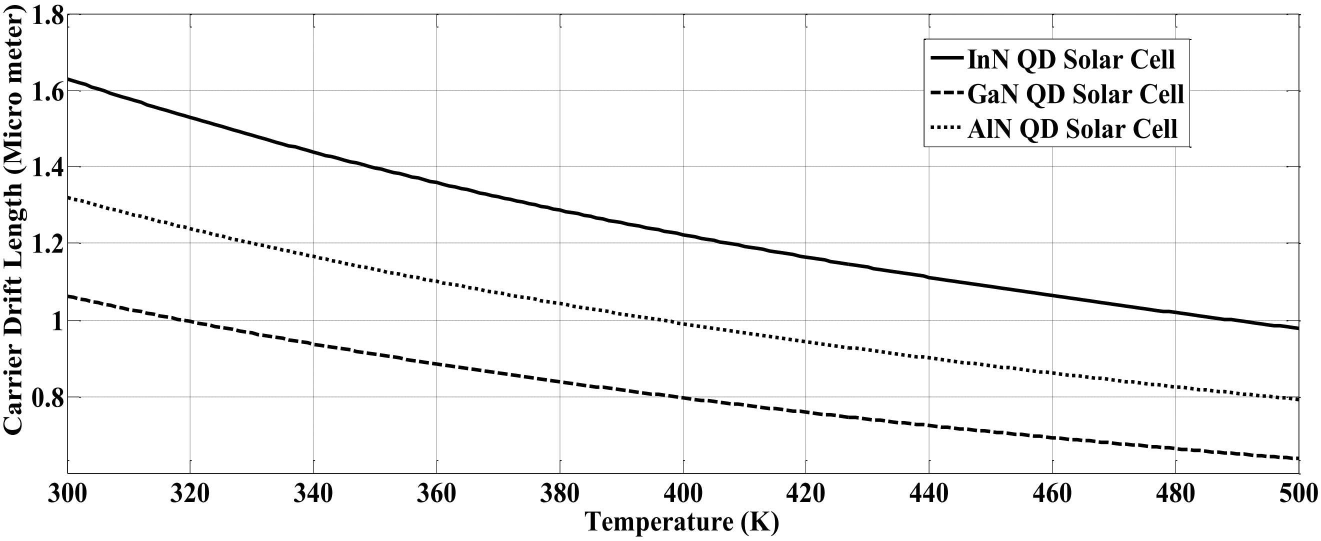


Fig. 2. Temperature dependence of drift length of carriers in QDSC using InN (Solid curve), GaN (Dashed curve) and AlN (Dotted curve) QD in the active layer.

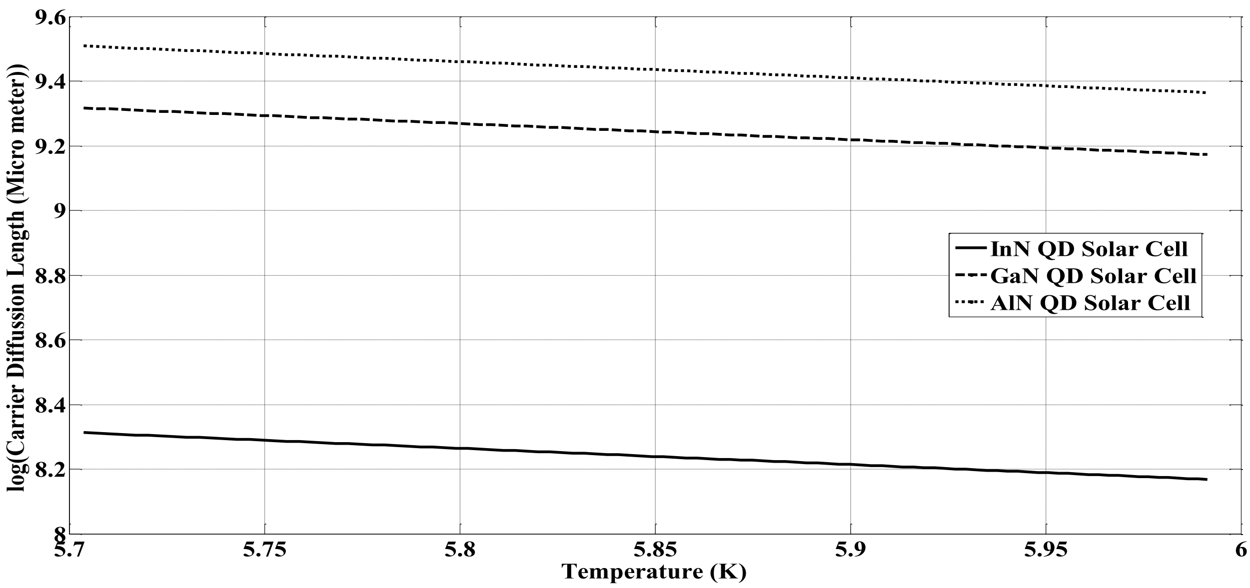


Fig. 3. Temperature dependence of diffusion length of carriers in QDSC using InN (Solid curve), GaN (Dashed curve) and AlN (Dotted curve) QD in the active layer.

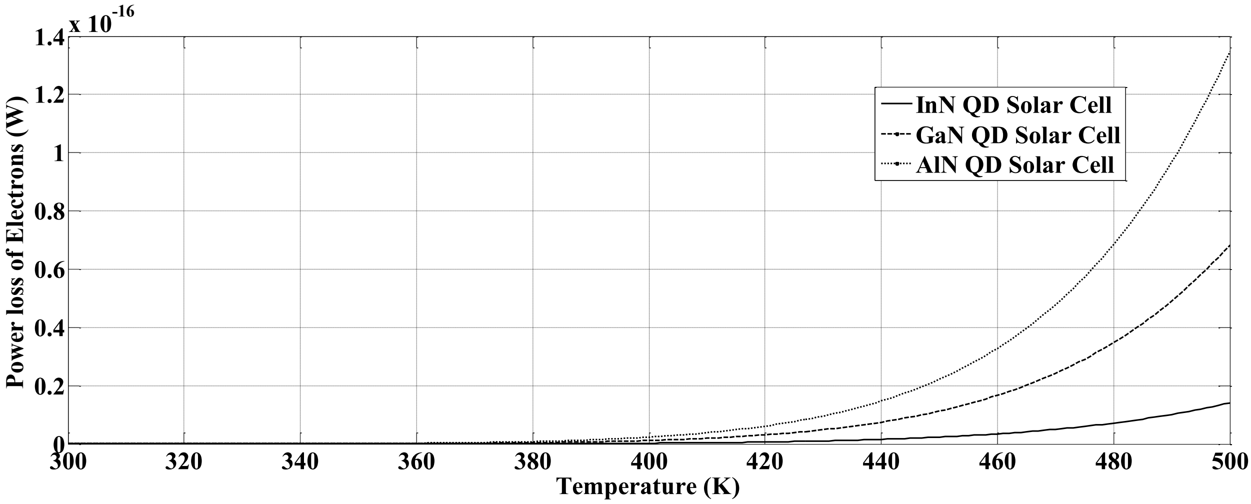


Fig. 4: Power loss of electrons in QDSC at different temperature conditions using InN (Solid curve), GaN (Dashed curve) and AlN (Dotted curve) QD in the active layer

Figure 2 presents the temperature dependence of drift length of carriers in QDSC. From the plot of Fig. 2 using equation (4) it is revealed that drift length of carriers reduces nonlinearly due to the linear rise in environmental temperature. While analyzing the variation of carrier drift length with temperature is as per equation (4), τ at room temperature has been considered. Again the drift velocity is proportional to the drift length; hence, the drift velocity of the carrier decreases with the increase of temperature. Yet again, drift current is directly proportional to the drift velocity so it can be concluded that the drift current within the QDSC will correspondingly decrease with the rise of temperature. The carrier characteristics of SC using InN, GaN and AlN QDs in the active layer has been presented by solid curve, dashed curve and dotted curve correspondingly. It is ascertained from the numerical comparison of Fig. 2 that the drift length of InN QDSC is higher than the drift length of the GaN and the AlN QDSC under a given temperature condition. Consequently, the drift current has been increased notably using InN QD as the active layer material of the QDSC structure.

Figure 3 has been plotted using equation (5). While analyzing the variation of carrier diffusion length with temperature is as per equation (5), τ and μ have been considered at room temperature. Figure 3 presents the temperature dependence of carrier diffusion length of QDSC at logarithmic scale. From the comparative analysis presented in Fig. 3 it is clear that the diffusion length is decreasing exponentially with the rise in temperature for every type of QDSC. Again diffusion velocity is proportional to diffusion length. Hence, diffusion velocity reduces with the rise in temperature. Furthermore, diffusion current is directly proportional to the diffusion velocity. Therefore, it can be concluded that the diffusion current will reduce with the rise in temperature. The solid curve, dashed curve and dotted curve indicates the diffusion length characteristics of InN, GaN and AlN QDSC correspondingly. From numerical analysis presented in Fig. 3 it is ascertained that diffusion length of InN QDSC is lower than that of GaN and AlN QDSC at any temperature. As a result, the diffusion current has been decreased expressively using InN QD in the active layer of the QDSC.

Figure 4 shows the temperature dependence of the net power loss due to the whole process of generation of electricity by absorbing light. The whole process includes: capture of electron by the QD, escape of electron from the QD recombination and optical generation. From the assessment of the outcome shown in Fig. 4 it is ascertained that the power loss occurred from the electrons participating in this process is increasing exponentially with the increase in temperature, which reduces total power output of QDSC using any QD material in the active region. The solid curve, the dashed curve and the dotted curve characterize the characteristics of InN, GaN and AlN QDSC respectively. From the plot it can be concluded that the power loss of the electrons in the InN QDSC is lower than that of GaN and AlN QDSC for any temperature. Therefore it is discovered that the power loss of the electron has been minimized notably by applying InN QD as the active layer material of the QDSC.

Finally a summary of improvements of temperature dependence of carrier characteristics of QDSC using InN QD can be observed at a glance from the Table1.

Table 1. Numerical Comparison of the drift length, diffusion length and power loss of electron of InN, GaN and AlN QDSC (at T=400K)

Sl. No.	Parameters	InN QDSC	GaN QDSC	AlN QDSC
1	Drift Length (μm)	0.8	1	1.21
2	Diffusion Length (Logarithmic Scale)	8.19	9.19	9.39
3	Power loss of Electron (Watt)	2.4×10^{-19}	1.2×10^{-18}	2.3×10^{-18}

6. Conclusion

The temperature dependence of the different characteristics of QDSC has been investigated through mathematical approach in this research work. We have analyzed the temperature dependence of drift length, diffusion length and the power loss phenomena of the carriers using InN, GaN and AlN QD in the active layer of the QDSC structure. Then the numerical results were compared. The outcomes of the numerical analysis show that drift length of carriers within a QDSC reduces with the increase of temperature for using any QD material of the SC structure as shown in Fig. 2. It is revealed from the solid curve of the graph that the highest carrier drift length has been achieved for InN QDSC. Similarly, from Fig. 3 it is ascertained that diffusion length of the carrier reduces with the rise in temperature for any material in the active layer of the QDSC structure. The lowest diffusion length has been achieved for InN QDSC as indicated by the solid line curve of the graph in Fig. 3. As a result, drift current is expected to be increased and the diffusion current of InN QDSC is expected to be decreased with respect to GaN and AlN QDSC. Further, the lowest power loss of the electrons participating in the overall process has also been reported for InN QDSC. Therefore, from our comparison of numerical analysis it is ascertained that InN QD is an auspicious candidate to fabricate high performance QDSCs in the very near future as it offers lowest loss of electrons within the QDSC hence it will boost up the efficiency as well.

Acknowledgements

This post-doctorate fellowship supported by the International Islamic University Malaysia for this work is gratefully acknowledged.

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