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# Effects of Temperature on I-V Characteristics of InAs/GaAs Quantum-Dot Solar Cells

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**Abstract.** The current-voltage (*I-V*) characteristics of quantum-dot (QD) solar cells under illumination at various temperatures are presented. High-density self-assembled InAs/GaAs QDs were incorporated into the solar cell structure. The *I-V* characteristics reveal that both short-circuit current and open-circuit voltage of the QD solar cell reduce when the measurement temperature increases. This result is unexpected and inconsistent with a basic solar cell theory where the temperature is believed to cause the enhancement of the short-circuit current. By analysis, we can explain the obtained *I-V* curves by high series resistances and low shunt resistances of the cell structure.

## Introduction

Semiconductor quantum dot (QD) is a nanostructure that can be engineered in various aspects. Nowadays, QDs have been demonstrated as an efficient photon-absorbing material in solar cell structures. Because QDs have bandgaps that are tunable across a wide range by changing the size, incident photons can be more effectively absorbed. Understanding basic properties of these devices are necessary in order to properly utilize them in realistic environment.

Self-assembled QDs are of considerable interest due to their atomic-like properties and defect-free nanostructure. They are attractive for studying physics in zero-dimensional system and offer many opto-electronic device applications including photovoltaic application. The technology and physical parameters have been studied intensively during the past thirty years. QDs are also proposed for using as intermediate band in novel solar cell [1,2]. Although there are many QD growth techniques nowadays, the Stranski-Krastanow growth mode is still the most widely used method for producing QD structure [3-7]. Fabrication of QD arrays with narrow size distribution, high QD density, or large QDs for long emission wavelengths have been demonstrated [3,4,6-8]. Self-assembled InAs QDs can formed on GaAs substrates by the Stranski-Krastanow growth mode due to the 7% lattice mismatch between InAs and GaAs. The growth of self-assembled InAs QDs on a GaAs substrate in standard molecular beam epitaxial (MBE) process results in a dot density in the range of $10^9 - 10^{10}$ cm$^{-2}$. These as-grown QDs have a too low dot density and the expected benefits of photon absorption at long wavelengths are minimal. Many techniques for improving QD quality have been proposed. For example, buffer layers with different composition like InGaAs or GaAsSb [6] have been used to increase the QD density or the QD size. Generally, the QD structures grown by MBE are preferred due to the higher quality of the interfaces between QDs and the buffer and the covering layers [9].

Although there exist techniques to improve the QD quality, there are other external factors that may cause defects and those can reduce the efficiency of a QD solar cell. Operating temperature is one important external factor. Analysis of this factor is important because it can affect the cell performance. For instance, increasing temperature may reduce open-circuit voltage ($V_{oc}$) then the maximum power point (MPP) is also changed [10,11]. Typically, the steady-state current-voltage (*I-V*) characteristics of a solar cell are often described based on one diode model [12] as given in

$$I_{cell} = -I_{ph} + I_o\left[\exp\left(\frac{q}{nkT_{cell}}\left(V_{cell} - I_{cell}R_s\right)\right) - 1\right] + \frac{\left(V_{cell} - I_{cell}R_s\right)}{R_{sh}}, \qquad (1)$$

where $I_{ph}$ is the light-generated current, $q$ is electron charge, $k$ is Boltzmann constant and $T_{cell}$ is the cell temperature, $R_{sh}$ is the shunt resistance, $R_s$ is the series resistance, $n$ is the diode ideality factor and $I_o$ is the reverse saturation current of the cell. This equation is typically useful to describe the *I-V* characteristics of a solar cell when parameters ($R_s$, $R_{sh}$, $n$ and $I_o$) are typical.

Four major parameters: series resistance, shunt resistance, diode ideality factor, and reverse saturation current of Eq. (1) are important parameters that can be varied because of internal and external device design. They can strongly affect the solar cell efficiency. The series resistance is a parasitic -- power consuming parameter [13] because it decreases the maximum achievable output power. Lindmayer and Allison [14] have reported the fill factor decrement by about 2.5% for each 0.1 Ω increment in series resistance. The shunt resistance represents a current leakage (power loss) in the solar cell. The standard solar cell has usually $R_{sh}$ of more than $10^3$ Ω [15]. Low $R_{sh}$ due to crystal damage and impurities in and near the junction will give rise to a high shunt current [13]. Therefore cell efficiency will be reduced by these factors. Controlling these parameters is important to enhance the cell efficiency. Many researchers have studied the effects of temperature on general solar cells but it has not been reported for QD solar cells.

This paper aims to present and discuss the effects of temperature on QD solar cells. It is divided into two sections: Section I is an introduction and details of the investigated cell structure. Section II consists of experimental procedures, results and discussion on the tested QD solar cell at various controlled temperatures.

## QD Solar Cell Structure

Stacks of high-density self-assembled InAs/GaAs QDs were incorporated into the QD solar cell sample structure as shown in Fig. 1(a). The samples were fabricated by using an MBE and a metal evaporator [3]. P-type GaAs substrates were used as the starting material. After the growth of 500-nm GaAs layer, as-grown InAs QDs were formed. A Si-doped (n-type) AlGaAs heterojunction was formed for next layer. Finally, a 20-nm thin $n^+$-GaAs layer was grown in order to achieve a good ohmic contact (AuGe/Ni). AuZn was grown on the back in order to form an ohmic contact to the p-GaAs substrate. Figure 1(b) shows a QD solar cell used in this experiment. The cell surface area is about $5\times10$ mm$^2$.

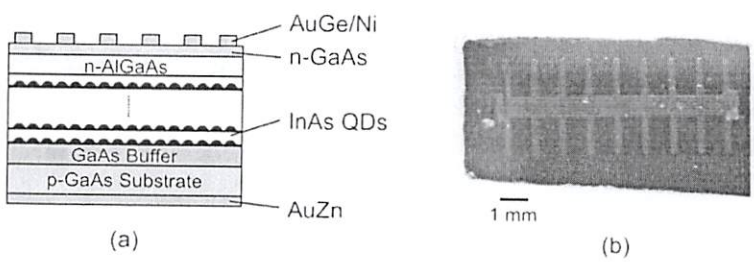


Fig. 1 (a) QD solar cell structure with stacked of high density self-assembled InAs/GaAs QDs and (b) a photograph of QD solar cell sample used in this experiment.

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## Experimental Procedure

*1. Experimental Setup*

The 24V 300W tungsten lamp was used as an artificial light source. It provides a low level of long-wavelength radiation compared to the actual solar source [3]. We used Agilent E3633A DC power supply as voltage source, Agilent 34401A digital multimeter as voltmeter and Keithley 6485 picoammeter as ammeter. The temperature variation of QD solar cell is observed by Agilent U1186A K-type thermocouple used with Agilent U1233A multimeter. The 5.5V 0.5W commercial solar cell is used as a reference cell to accurately calibrate with QD solar cell at various temperatures.

*2. Measurement circuit*

The circuit used for evaluating the *I-V* characteristics of tested solar cell is shown in Fig. 2. The left-hand side of figure is a solar cell equivalent circuit; it essentially consists of a current source shunted by a diode. These two elements correspond to generation and loss of photocurrent in the device [12]. The $R_s$ and $R_{sh}$ are also included and they directly affect the *I-V* characteristics [13,15]. A relation between $I_{cell}$ and $V_{cell}$ can generally be described based on the diode model as given in Eq. (1). The right-hand side is a group of measurement devices. The group consists of a voltmeter which measures $V_{cell}$, an ammeter which measures $I_{cell}$ and a voltage source which generates voltage $V_S$, respectively. When light (photons) with energy more than the band gap of the absorber material hits p-n junction, it creates electron-hole pairs. Due to the built-in electric field, photon produced carriers are transported to the electrodes [16], generating electricity. The voltage source will distribute a constant voltage step. The measurement devices will simultaneously measure current and voltage at controlled temperature.

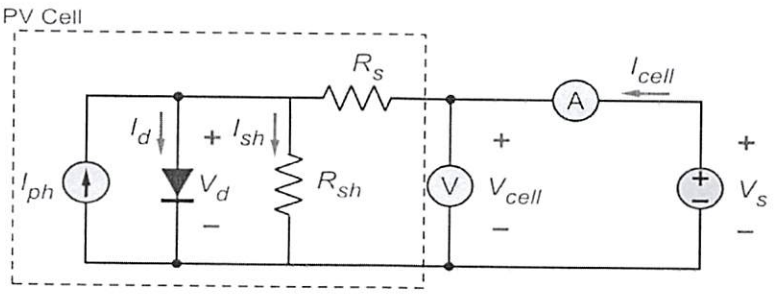


Fig. 2 The *I-V* characteristic measurement circuit

*3. Experimental Steps*

In case of the measurement with light illumination, we started by shining light to the tested cell. After that, a constant voltage is applied. The receiving data, which are cell current and voltage, were kept for subsequent analysis. In case of dark condition, we put the tested cell into a black box. This measurement procedure was similar to the measurement with light illumination.

We separated the data into 3 groups. They are (i) *I-V* data of QD solar cell, (ii) *I-V* data of QD solar cell when temperature is varied and (iii) *I-V* data of reference cell.

(i) *I-V* data of QD solar cell

The QD solar cell described above is measured in the case where the temperature effect is ignored. The measurement confirms the solar cell properties as shown in Fig. 3 and discussed below.

(ii) *I-V* data of QD solar cell when temperature is varied

Temperature was varied between 30 °C and 60 °C to study the effects of temperature. During the *I-V* measurement, a thermocouple was also used to monitor temperature.

(iii) $I$-$V$ data of reference cell

The reference cell is used to prove a basic solar-cell theory and compare it with the QD solar cell. The temperature observation was done as before. The results are not shown in this paper.

The (i) and (ii) are plotted while only data from (ii) were fitted for finding $I_{ph}$, $n$, $I_o$, $R_s$, and $R_{sh}$ The plotted and fitting data are showed in the next section.

## Result and Discussion

The measurement taken in the dark showed that the $I$-$V$ characteristic of QD solar cell behaves like a typical diode (see Fig. 3(a)). Under illumination, a large leakage current affects a low open-circuit voltage $V_{oc}$ closed to 0.4 V and it has a short-circuit current $I_{sc}$ of approximately 2 mA. The very low $I_{sc}$ value is inconsistent with the report in Ref. [3] because the light source used provided low light intensity in this experiment. It has 0.15 mW of maximum power at the maximum power point (MPP); approximately 0.9 mA and 0.17 V. This result therefore confirms that this device has solar-cell characteristics.

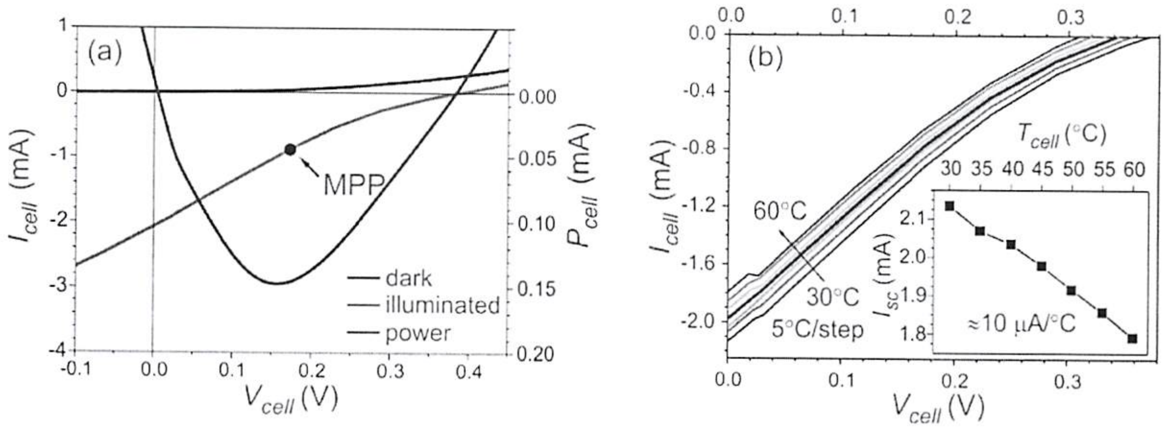


Fig. 3 (a) The $I$-$V$ characteristics of QD solar cell with (red line) and without (black line) illumination at $T_{cell}$ = 30 °C and power-voltage ($P$-$V$) characteristics of same structure under illumination (blue line) and (b) the $I$-$V$ characteristics of QD solar cell at various temperatures (30 °C to 60 °C). Inset shows the variation of short-circuit current as a function of temperature.

Prior to the measurement of the QD solar cell, a reference cell was measured (The $I$-$V$ characteristic is not shown here). The result from the measurement at various temperatures (between 30 °C and 60 °C) confirms a basic solar cell theory [10,11,17]. When light illuminates over a reference cell, its $I_{sc}$ always slightly increases and $V_{oc}$ is decreased when cell temperature increases. The next step was to change the measurement temperature in 5 °C per steps for the QD solar cell. Figure 3(b) shows the $I$-$V$ characteristics at various cell temperatures. $V_{oc}$ is decreased from 0.37 V to 0.31 V and $I_{sc}$ is decreased from 2.1 mA to 1.8 mA. The characteristic of $I_{sc}$ variation with the temperature is different from that of the reference cell. The decrease of this current is quite linear. The rate of change is approximately 10 μA per °C as shown in the inset of the Fig. 3(b). This behavior of a QD solar cell is unexpected and inconsistent with a basic solar cell theory where the temperature is believed to cause the enhancement of the short-circuit current.

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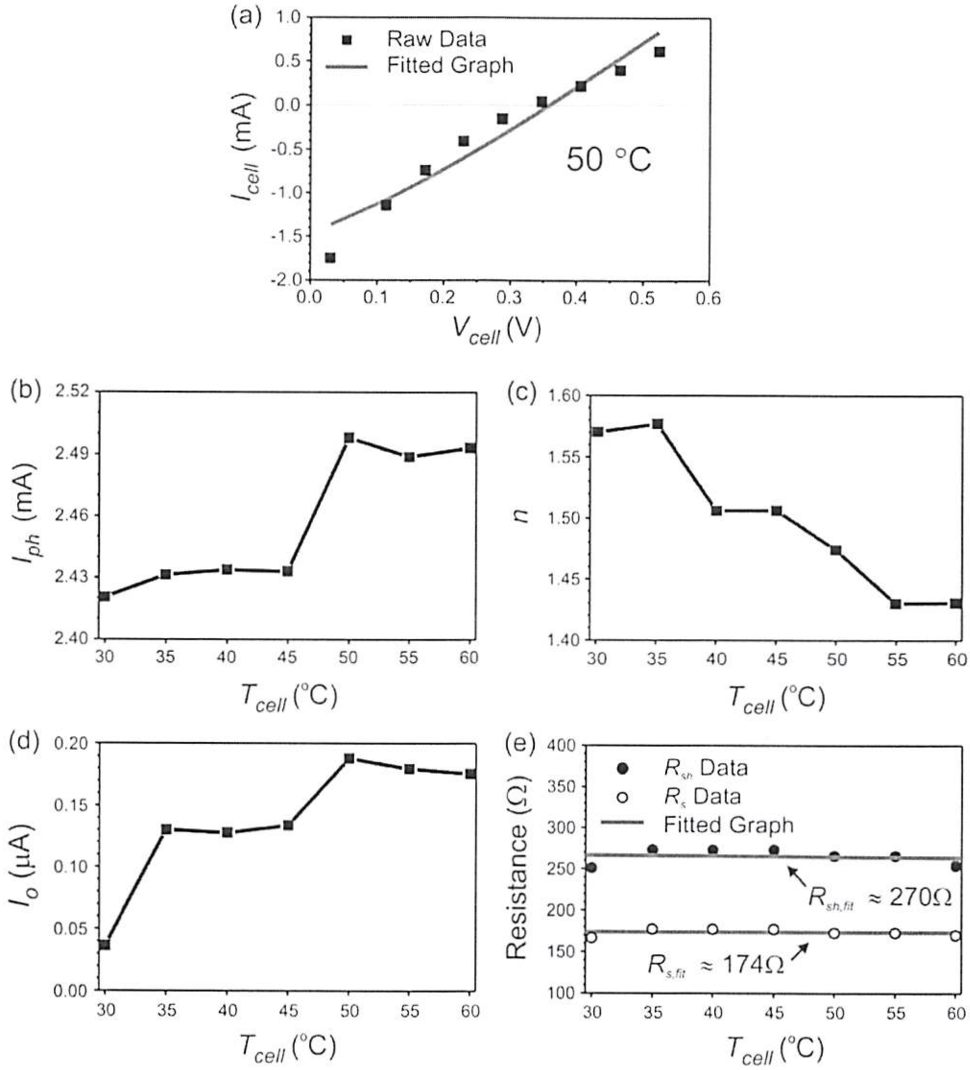


Fig. 4 (a) *I-V* characteristics of QD solar cell: raw experimental data (scatter) and the fitted graph (line). Solar cell parameters: (b) $I_{ph}$, (c) $n$, (d) $I_o$ and (e) resistance as a function of $T_{cell}$.

There are many techniques for extracting circuit parameters of a solar cell such as a non-interactive technique [12], transformation method for explicit approximate solutions [18] and polynomial fitting [19]. Here we transform the implicit function in Eq. (1) to explicit function by using Lambert $W$ function [18]. According to Eq. (1), the cell current can be written as:

$$I_{cell} = \frac{nkT_{cell}}{R_s q} lambertW\left\{\frac{qI_o R_s}{nkT_{cell}\left(1+R_s/R_{sh}\right)}\exp\left[\frac{qV_{cell}+qR_s\left(I_o+I_{ph}\right)}{nkT_{cell}\left(1+R_s/R_{sh}\right)}\right]\right\}+\frac{V_{cell}/R_{sh}-\left(I_o+I_{ph}\right)}{1+R_s/R_{sh}} \qquad (2)$$

We find the circuit parameters by using *lsqcurvefit* function in MATLAB program [20]. A typical fitted curve is shown as an example in Fig. 4(a). The raw experimental data (scatter) and the fitted graph (line) of QD solar cell are plotted together. In Fig. 4(b), we show the fitted $I_{ph}$ since it has a clear tendency with the temperature. The $I_{ph}$ increases with the temperature [21]. In Fig. 4(c), we show the fitted $n$ as a function of $T_{cell}$. The $n$ tends to decrease when the temperature increases. This result is similar to Sharma *et al.* [22]. In Fig. 4(d), the fitted $I_o$ is shown since it has some tendency with the temperature too. Our observations are similar to the results reported by Triphathi *et al.* [17]. They have shown that the effects of temperature on $I_o$ tend to increase when temperature increases. Finally, Fig. 4(e) shows the fitted resistances of the solar cell ($R_s$ and $R_{sh}$). For the fit, we found that series resistance and shunt resistance were about 174 Ω and 270 Ω, respectively. They were quite constant (no clear tendency) with temperature.

Increasing temperature will narrow the material band gap. Due to this fact the light absorption will be increased by the additional absorption at longer wavelengths. The number of photo-generated electron-hole-pair (current) is therefore increased at higher temperatures. As shown in Eq. (1), the increment of $I_{ph}$ will enhance the magnitude of $I_{sc}$. This phenomenon always happens in a solar cell with very low $R_s$ and high $R_{sh}$ [13]. This is different from our QD solar cell sample which has high $R_s$ and low $R_{sh}$ values. Van Dyk *et al.* [13] reported that both parameters will detract *I-V* shape from the standard *I-V* characteristics. The MPP is moved to the lower point. The fill factor and cell efficiency is then dropped.

We believe that excessively high series resistance and low shunt resistance has adverse effects on the *I-V* characteristics of QD solar cells. This means our QD solar cells deviate from a conventional solar cell behavior. However, we were not able to clearly suggest how to experimentally improve our QD solar cells. By decreasing $R_s$ and increasing $R_{sh}$ to ideal values (equal to zero and infinity, respectively), the *I-V* characteristics will therefore improve and cell efficiency will increase. We will do more analysis on this case in future work.

## Conclusions

We present the effects of temperature on the *I-V* characteristics of the QD solar cell. We found that its characteristics are different from a conventional solar cell where rising temperature causes the enhancement of the short-circuit current. We found that the excessively high series resistance and low shunt resistance of the QD solar cell is the factor responsible for the observed the *I-V* characteristics. We believe this work enhances the understanding of photovoltaic device incorporating nanostructures.

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