Temperature dependence of InAs/GaAs quantum dots solar photovoltaic devices

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Abstract: This paper presents the temperature dependence measurements characterisation of several InAs/GaAs quantum dots (QDs) solar cell devices. The devices with cylindrical geometry were fabricated and characterised on-wafer under 20 suns in a temperature range from 300°K to 430°K. The temperature dependence parameters such as open circuit voltage, short circuit density current, fill factor and efficiency are studied in detail. The increase of temperature produces an enhancement of the short circuit current. However, the open circuit voltage is degraded because the temperature increases the recombination phenomena involved, as well as reducing the effective band gap of the semiconductor.

Key words: quantum dots; solar cells; III–V semiconductors; inter-dot doping; efficiency; temperature dependence

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1. Introduction

The analysis of photovoltaic devices under different conditions is crucial as in real operation, the environmental conditions will change according to the application. Conditions such as light power or temperature can impact negatively upon the device energy conversion performance. When solar cells are exposed to intense sun irradiance there is usually an increase in the operating temperature of the device. For some applications such as solar concentrator PV modules, solar cells need to operate above room temperature (300°K). For example, terrestrial concentrator PV modules operating above 315°K (∼40 ℃) have been reported[1]. Another example is the use of solar cells for space applications, where the operational temperature can go above 400°K depending on the mission location[2].

From the physics of the semiconductor, the strong temperature dependence of the main device metrics is evident. Temperature changes lead to recombination phenomena rates changes, which generate losses in the electrical generation of the device[3−5].

The efficiency, which is a function of the electrical properties of the material, is expected to be negatively impacted for high temperature changes. Increasing the temperature, either due to the operational environment or the light concentration, produces an enhancement of the short circuit current[6]. However, this always invariably entails open circuit voltage degradation due to the enhancement of the recombination phenomena, as well as a reduction of the effective band gap of the semiconductor[7].

Many efforts have been made in the last few decades to develop materials with minimal variations in their performance at high temperatures[8]. These efforts have led to new photovoltaic devices with higher efficiencies. Not only have structural modifications been proposed but also the addition of external thermal insulators has also been tested. In this sense, it has been found that the changes in the fill factor with temperature increases can be a consequence of the contact resistance and the collection efficiency[9].

Recently, it has been demonstrated that the introduction of quantum dots (QDs) vertically arranged within semiconductor materials have better behavior at low temperatures than other devices using a different material configuration[10]. However, it is also important to investigate the behavior of these devices at high temperatures. For example, in silicon photovoltaic devices, the effect of the temperature on the open circuit voltage has been shown to drop from 0.65 to 0.22 V[12].

In this work, we present the detailed measurement of InAs/GaAs QDs solar cells (intermediate band solar cells) performance as well as the temperature dependence of the main parameters, such as open circuit voltage, short circuit current density, fill factor and efficiency. The study includes the analysis of the effect of the inter-dot doping profile and its temperature behavior.

2. Structural details

Three different InAs/GaAs QDs structures were grown on GaAs substrates using molecular beam epitaxy. They consist of QDs arrays of 20 vertical periods. QDs are formed into InAs layers covered at the top and the bottom by 90 Å GaAs spacer layers. The three structures have as their main difference their inter-dot doping profile. Sample A (XMBE291) is undoped, sample B (XMBE293) has 8×10^{10} cm^{-2} n-type doping and sample C (XMBE294) has 16×10^{10} cm^{-2} n-type. Including the inter-dot doping has been proven to enhance the open circuit voltage[13]. 300 Å p-$Al_{0.6}Ga_{0.4}As$ layer is used as the window for surface recombination reduction purposes. The p–i–n studied structures are shown in Table 1.

A detailed optical characterization revealed two new energy states at 1.37 eV and 1.2 eV in addition to the energy state at 1.42 eV, which corresponds to the GaAs band gap. These two new energy levels occurred as a consequence of the inser-

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Table 1. InAs/GaAs quantum dot epitaxial structures details for samples A, B and C.

Top contact		
GaAs		500 Å
$Al_{0.6}Ga_{0.4}As$	p-type	300 Å
GaAs		1000 Å
GaAs		90 Å
GaAs		250 Å
Δ QD Δ	Periodicity	
GaAs	of 20	250 Å
InAs		
GaAs		90 Å
GaAs	n-type	3000 Å
GaAs		2000 Å
GaAs		Substrate
Bottom contact		

tion of QDs into the host lattice. The presence of dopants in the dots reduces the recombination. Thus, an enhancement in the open circuit voltage can be achieved, which in turn helps with the increase of the device's efficiency.

3. Experiment details

Simple devices, which consist of 250 μm cylindrical diodes, were fabricated. Au/GeAu metallization layer was used as the bottom contact. For the top contact, the metallization used consists of a Ti/Au ring and the latter is formed from two concentric circles with diameters of 50 nm and 200 nm respectively. The wafers were cut into small pieces and placed on a temperature controlled base. The devices were characterized on-wafer under 20 suns light simulator (AM1.5 Solar light model 16S-002-300 using Keithley 237 I–V test equipment).

To obtain a light intensity of 2000 mW/cm^2, the light was focused using a Fresnel lens. The temperature of the samples was controlled using a cryostat system.

4. Electrical characterisation

4.1. Room temperature measurements

The obtained I–V curves for all the samples, measured using $\sim$2 W/cm^2 light, can be seen in Fig. 1. It was found that sample A (undoped QDs) exhibited the highest current density, 283 mA/cm^2. However, the enhancement of the open circuit voltage due to the inter-dot doping insertion is also clear in the graph. The QD devices' efficiencies under 20 suns were extracted and the results are shown in Table 2. In the case of the highly doped sample (16×10^{10} cm^{-2}), the efficiency increased up to 7% and the fill factor (FF) up to 73%, which are excellent values for such simple structures.

It is clear how the insertion of the inter-dot doping n-type profile helps considerably the quality of the device in terms of shunt resistance (R_{sh}). This can be seen in the curve slope from 0 to 0.4 V approximately.

Table 2 shows the values used for the efficiency calculations. The doped samples exhibit a smaller short circuit current density compared with the one for the undoped sample. Thus, the inter dot doping does not help the solar cell generate more free carriers in the studied structures. However, the

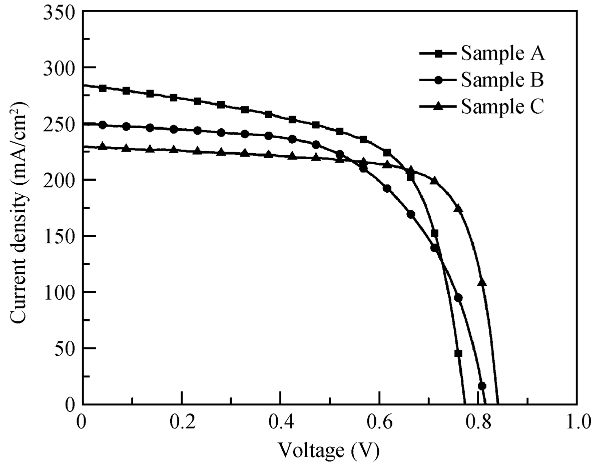

Fig. 1. J–V characteristics under 20 suns at room temperature for samples A, B and C.

Table 2. GaAs/InAs QD devices' efficiencies under 20 suns.

Sample	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	η (%)
Sample A	283.5	0.77	62.8	6.9
Sample B	249.5	0.81	58.7	6.0
Sample C	228.9	0.84	73.3	7.0

doping within the host lattice does help to reduce the recombination since the open circuit voltage is enhanced.

The J–V characteristics showed that the short circuit current density (J_{sc}) for sample A is 20 mA/cm^2 and its open circuit voltage (V_{oc}) is the lowest of all the samples at only 690 mV. The QDs can act as traps for the generated electrons. However, the probability that one electron can be trapped is reduced as doping of the dots is increased. The highly doped sample, sample C, exhibits the highest V_{oc} of 800 mV. It is clear that the insertion of doping into the QDs reduces recombination phenomena in the material.

5. Temperature dependence measurements

The devices were tested in the temperature range from 300°K to 430°K. For the undoped dots sample, as expected, the open circuit voltage is reduced by about −28 mV as the temperature increases. The short circuit current density at 430°K, for sample A, goes up to 312.3 mA/cm^2, which represents an enhancement of about 10% compared with the room temperature value. The J–V curves for sample A at different temperatures are depicted in Fig. 2.

For samples B and C, the electrical parameters degrade continuously as the temperature increases. For sample B which has an n-type doping profile of 8×10^{10} cm^{-2}, the open circuit voltage drops from 0.81 V at room temperature to 0.56 V at 430°K. This implies that the open circuit voltage drops by just −25.5 mV, a decrease of $\sim$30%. The short circuit current density increases by around 8% with the temperature, as can be seen in Fig. 3. The reduction of the open circuit voltage for sample B compared with sample A is barely noticeable, due to the effect of the doping profile introduced in the host lattice.

The smallest degradation of the open circuit voltage is ex-

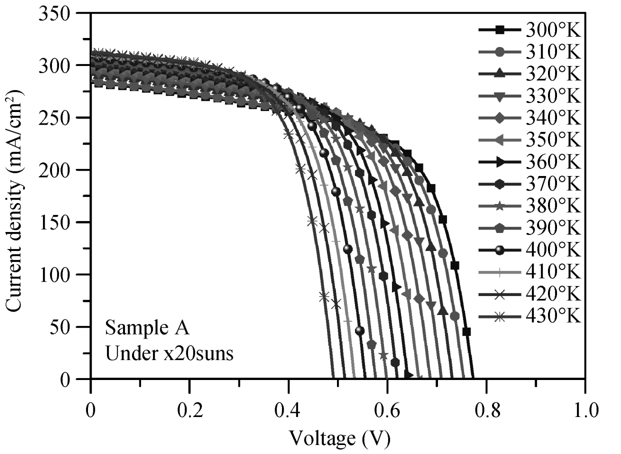

Fig. 2. J–V curve measurement for temperature range from 300°K to 430°K for sample A.

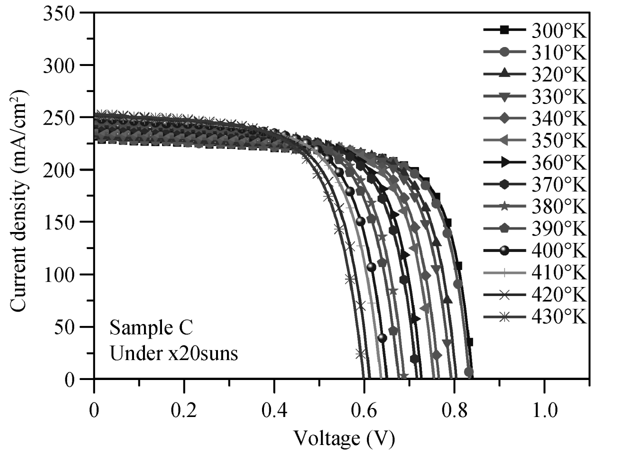

Fig. 4. J–V curve measurement for temperature range from 300°K to 430°K for sample C.

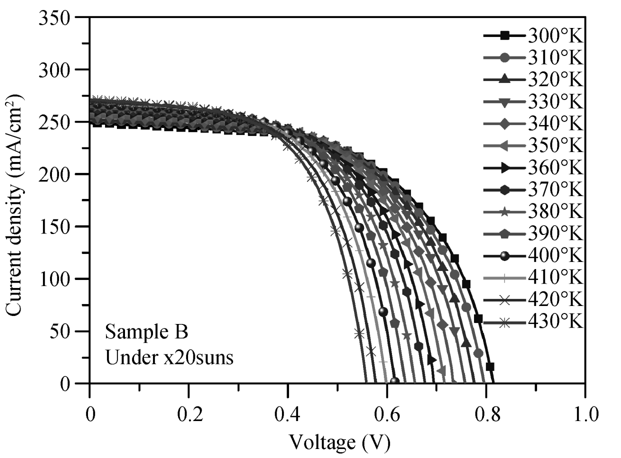

Fig. 3. J–V curve measurement for temperature range from 300°K to 430°K for sample B.

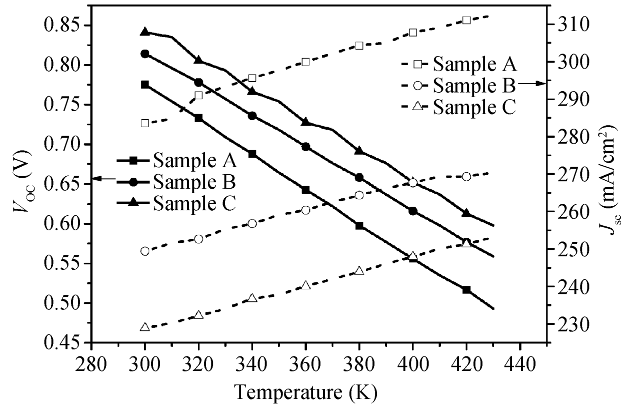

Fig. 5. Temperature dependencies characterisation of the J_{sc} and the V_{oc} for InAs/GaAs QD solar cells under 20 suns (2000 mW/cm^2).

Table 3. Temperature dependence for V_{oc} and J_{sc}.

Sample	dV_{oc}/dT (mV/°K)	dJ_{sc}/dT (mA/cm^2/°K)
Sample A	−2.18	0.21
Sample B	−1.90	0.16
Sample C	−1.90	0.19

hibited by sample C, which shows an open circuit voltage reduction of only −24 mV in the whole analysed temperature range. The open circuit voltage obtained at 430°K is 0.6 V. Furthermore, the short circuit current density increases by 10% rising from 228 mA/cm^2 at room temperature to 253 mA/cm^2 at 430°K (See Fig. 4).

It is clear from these data that the recombination phenomena can be reduced by introducing n-type dopant atoms within the QDs structure, and consequently there is an enhancement of the open circuit voltage. In this material system, the open circuit voltage drop is slower as the inter dot doping profile increases. Using inter dot doping, an open circuit voltage up to 0.6 Volts was achieved at 430°K.

The J–V curve data measurements were used to calculate the open circuit voltage and the short circuit current density rates as a function of the temperature. The trends of these parameters are shown in Fig. 5. It is evident that the recombination processes in the material increase as the temperature increases, limiting the open circuit voltage. On the other hand, the short circuit current density is enhanced with increases in the temperature. Doping effects at high temperatures for these material systems have not been reported to date.

As expected, the photovoltaic device performance is degraded when the temperature increases. In this sense, the open circuit voltage is negatively affected by the temperature rise. The calculated rates of the open circuit voltage changes are shown in Table 3. It is clear that the doped QDs samples, B and C, present the lowest coefficient of −1.9 mV/°K, while −2.18 mV/°K is obtained for the undoped QDs sample. These values are competitive with the best values for organic solar cells found to be in −1 mV/°K for bulk heterojunction (BHJ) material[14] and −1.9 mV/°K in Ref. [15].

The efficiency of the photovoltaic device, like the ones presented in this work, are strongly dependent on the material characteristics and the contacts (metallization) used. The latter gives an efficiency dependence of the open circuit voltage and the short circuit current density. These parameters directly affect the fill factor of the cell, an important device quality reference. Fill factors close to 100% are desirable, but in real de-

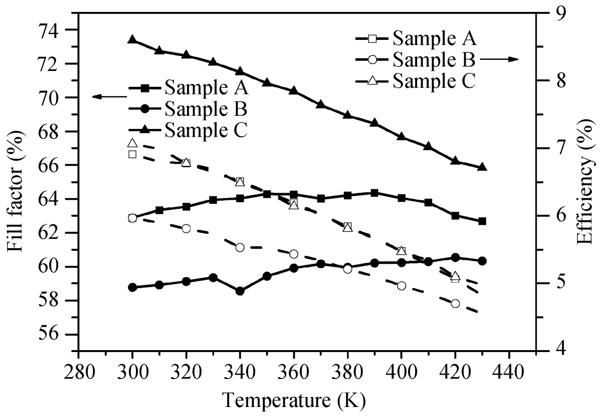

Fig. 6. Fill factor and efficiency temperature dependence measurements for InAs/GaAs QD solar cells under 20 suns (2000 mW/cm^2).

Table 4. Temperature dependence for fill factor and efficiency.

Sample	dFF/dT (%/°K)	dη/dT (%/°K)
Sample A	0.060	0.0162
Sample B	0.014	0.0106
Sample C	0.059	0.0164

vices, values above 70% are acceptable. Therefore, as the fill factor is a function of the V_{oc} and J_{sc} parameters, the efficiency of the devices will be markedly impacted by the temperature variations.

In Fig. 6, the temperature dependence curves for the fill factor and efficiency for samples A, B and C are depicted. For the undoped sample, the fill factor remains fairly constant with as the temperature increases. However, for the doped samples, the fill factor does drop with the temperature.

The efficiency for all the devices is impacted negatively with the temperature increasing as expected. The best efficiency temperature dependence coefficient (dη/dT) is displayed by sample B, which has a coefficient of −0.0106 %/°K. The obtained result implies that the efficiency, as a function of the temperature, of sample B drops at a lower rate than that of samples A and C, despite the fact that the open circuit voltage drop is faster than in the highly doped dots sample. There is thus a clear compromise between open circuit voltage and short circuit current density.

In Table 4, the temperature dependence of the fill factor and the efficiency coefficients for samples A, B and C are presented. The fill factor drops at a lower rate for sample B and as a consequence, this sample exhibits the lowest efficiency temperature dependence rate of −0.010 %/°K. These values of fill factor temperature dependence are excellent compared with the values of −0.64 %/°K found for Si devices[16]. For commercial crystalline Si solar cells, the fill factor coefficient drops at a rate of −0.2 %/°K and the efficiency at a rate of −0.53 %/°K[11].

6. Conclusions

In summary, detailed investigations of three InAs/GaAs QD samples with different doping profiles tested under 20 suns irradiation in the temperature range from 300 to 430 °K are reported. The solar cell efficiency was found to be sensitive to temperature. The efficiency is reduced as the operational temperature is increased. The obtained results indicate that an improvement of the GaAs solar cells operation at higher temperatures due to the insertion of QDs is present. The open circuit voltage temperature dependence value of −1.9 mV/°K is an excellent value compared with the one obtained on GaAs solar cells of −2 mV/°K reported in Ref. [2]. In addition, it was found that with the introduction of n-type dopants into the QDs lattice, the temperature dependence of the open circuit voltage is weaker compared with the undoped QDs structures. The latter helps to improve the working temperature, reducing the temperature coefficient of the efficiency. Even at high temperatures, the fill factor can be either kept or improved by doping the QDs, which makes this material very promising for high temperature applications.

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