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***Abstract* — We report on the fabrication of InAs/GaAs quantum dot solar cells with high open circuit voltage by molecular beam epitaxy. ‘Shallow’ and ‘deep’ junction architectures were compared. The highest open circuit voltage of 0.94 V was obtained for the ‘shallow’ junction configuration. The open circuit voltage of InAs quantum dot solar cells decreased only by ~40 mV compared to GaAs reference cells for both junction architectures indicating high quality quantum dots. The open circuit voltage of InAs/GaAs quantum dot solar cells was also found to be dependent on the size of quantum dots.**

***Index Terms* — III-V semiconductors, molecular beam epitaxy, photovoltaic cells, quantum dot.**

I. Introduction

InAs/GaAs quantum dots (QD) have been proposed to provide enhanced photocurrent for GaAs solar cells without reduction in the open circuit voltage (V_{oc}) of the devices. Such solar cells would have potential as sub-junctions of very high efficiency multi-junction solar cells in space applications due to their enhanced radiation resistance when compared to standard GaAs-based solar cells [1]. Also, very thin GaAs-based QD solar cells (QDSCs) with high efficiency could be utilized in unmanned aerial vehicles such as planes and drones, which require solar cells with high power-to-weight ratio [2]. Obtaining a high V_{oc} for InAs/GaAs QD solar cells has been a challenge until recent years because the QDs exhibit a small bandgap and induce a rather large electrical confinement for electrons and holes, which easily leads to enhanced carrier recombination. The published V_{oc} values for InAs/GaAs QDSCs are typically about 0.2 V smaller than those of standard GaAs solar cells. Recently, however, it has been demonstrated that by using metal-organic chemical vapor deposition it is possible to fabricate InAs/GaAs QDSCs in which the V_{oc} values are close to 1 V and only marginally decrease from the V_{oc} of the GaAs reference solar cell [3], [4]. However, with molecular beam epitaxy (MBE), such high V_{oc} has not been obtained so far. Several ways have been suggested to improve the V_{oc} and short-circuit current density (J_{sc}) of the InAs/GaAs QDSCs. The methods include using an electric field to enhance the extraction of electrons and holes from QDs [5]. Thin layers of GaP or GaAsP have also been used for strain compensation or at least to partially accommodate the compressive strain induced by the InAs QD sheets [3], [4]. Also, doping of the QDs has been shown to improve the carrier extraction and thus the photogeneration in InAs QD solar cells [6].

In this communication, we demonstrate that high quality InAs/GaAs QDSCs with high V_{oc} can be fabricated by MBE. In addition, we investigate the effect of the p-n junction position in ‘deep’ (DJ) and ‘shallow’ (SJ) architectures – referring to position of the physical p-n junction measured from the sample surface – as well as the influence of InAs/GaAs QD size on ability to obtain high V_{oc}.

II. Experimental

The InAs/GaAs QD test samples and solar cell structures were grown on exactly cut p-GaAs(100) substrates using a V90 MBE system with standard conical effusion cells for group-III elements and dopants, and valved cracker sources for group-V elements. Silicon and beryllium were used as n-type and p-type dopants, respectively.

The structures of the DJ and SJ architectures are shown in Fig. 1. The growth temperature for the p-GaAs, n-GaAs, and p-AlGaAs BSF layers was about 580 °C, whereas the InAs QDs were grown at 465-475 °C. The n-AlInP window layer was grown at 490 °C. Thin, 2-monolayer-thick, GaAsP strain-balancing layers were grown within the undoped GaAs barrier layers between the QD sheets. The number of QD sheets was 0, 10 or 20.

The wafers were processed to 6×6 mm^2 solar cells by dicing and using a shadow mask for front-side grid metal deposition in an electron beam evaporator. No anti-reflection coating was deposited onto the cells.

The QD and non-QD structures were characterized by photoluminescence (PL), x-ray diffraction, and atomic force microscopy (AFM). The electrical parameters of the solar cells were measured using light-biased current-voltage (*I*-*V*) and external quantum efficiency (EQE) measurements.

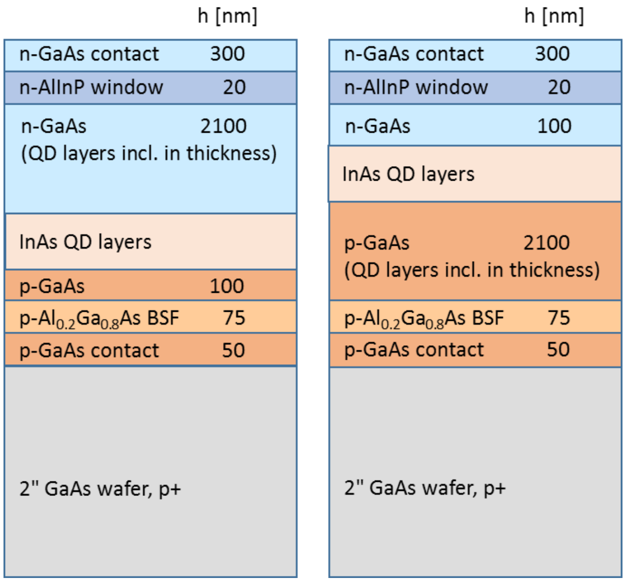

Fig.1. The schematic layer structure of the DJ (left), and SJ solar cells (right).

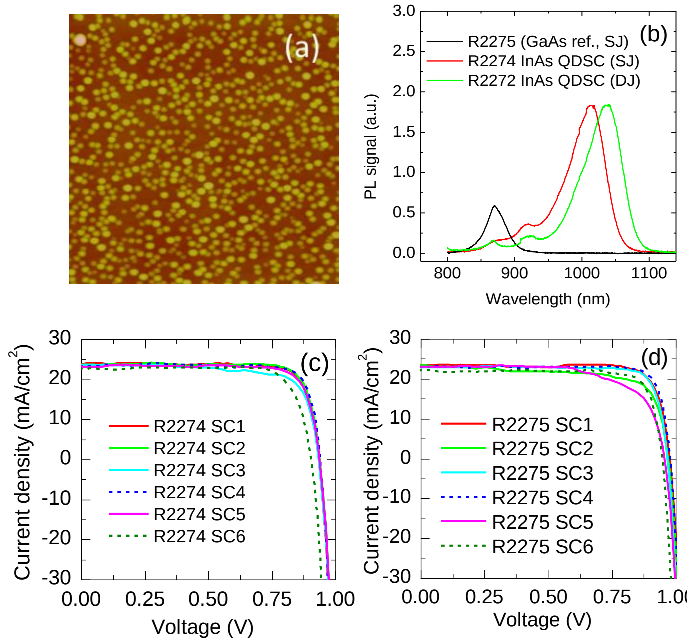

Fig. 2. (a) AFM image of 1.9 monolayers of InAs grown onto GaAs. The QD density is about ~7×10^{10} cm^{-2}. (b) PL spectra of GaAs (black) and InAs/GaAs QD solar cells: SJ (red) and DJ (green). *I-V* characteristics of SJ InAs/GaAs QDSC (c) and SJ GaAs SC (d).

III. Results and Discussion

Fig. 2a shows an AFM image of a sample with InAs/GaAs QDs grown onto GaAs substrate. It is apparent that the QDs have size variation and at least bimodal size distribution. This is reflected into the PL spectrum of the QDSCs shown in Fig. 2b. The full-width-at-half-maximum values of the PL peaks for SJ and DJ were 63.6 nm and 67.3 nm, respectively. The wetting layer peak is clearly visible at ~920 nm. Also, the PL emission intensity corresponding to GaAs layers is reduced for the InAs/GaAs QDSCs.

Table 1 lists the electrical parameters determined from the *I-V* measurements. When the DJ and SJs are compared to the GaAs SCs it is seen that V_{oc} and J_{sc} of the SJ are 62 mV and 2.2 mA/cm^2 higher, respectively, than those of the DJ. This can be explained by the fact that in the DJ there is increased recombination in the thick n-GaAs layer when compared to thick p-GaAs of the SJ. Nevertheless, it is interesting to compare how the addition of the QD sheets into these structures affects the electrical parameters.

For the DJ approach, SCs with 10 and 20 QD sheets were compared to GaAs SCs. The analysis of the electrical parameters reveals that there is a loss in V_{oc} of ~3.25 mV per each QD sheet with respect to the GaAs reference cell. Comparing SCs with 10 and 20 QD sheets, the V_{oc} decreases about 2.5 mV per QD sheet, which is not far from the extrapolated theoretical value of 26 mV × ln(20/10), i.e. 1.8 mV per QD sheet [7]. The highest J_{sc} of 22.6 mA/cm^2 was obtained for the QD SC with 10 QD sheets. The FF values are rather similar for all the DJ structures. Although the GaAs DJ has higher V_{oc}, the active area efficiency of the QDSC with 10 QD sheets is 1.9 %-points larger than that of the GaAs cell.

TABLE I
Summary of The Best Room Temperature (25 °C) I-V Measurement Results on SCs Without AR-Coating. Measurements Were Performed Using AM1.5D (1000 W/cm^2) Spectrum.

Sample	**Structural elements**			**Electrical Parameters**			
	Material	QD sheets	Junction type	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	Active area Efficiency (%)
R2262	GaAs	0	deep	0.917	19.5	80.2	14.3
R2270	InAs QD	20	deep	0.852	21.9	79.2	14.8
R2272	InAs QD	10	deep	0.877	22.6	81.7	16.2
R2274	InAs QD	10	shallow	0.940	22.1	83.9	17.4
R2275	GaAs	0	shallow	0.979	21.7	83.8	17.8

The difference in efficiencies between the samples with 10 and 20 QD sheets mainly arises from the higher J_{sc} and higher FF. Most likely, the 20 QD sheets for the DJ start to affect the crystal quality as the accumulating compressive strain induced by the InAs QDs is not completely removed by the GaAsP strain balancing layers.

For InAs QDSC with SJ architecture, the loss of V_{oc} is only 39 mV when compared to the GaAs reference. This is almost the same value as was obtained for the DJ approach (40 mV) for the same number of QD sheets. Again, QDs slightly increase the J_{sc} from 21.7 to 22.1 mA/cm^2 and FF remains the same in both samples, which leads to very similar conversion efficiencies with only ~0.4 %-points difference. The results indicate that for both structural architectures the quality of the QDs is high and that any improvements in the quality of the thick n-GaAs for the DJ variant would improve its electrical characteristics.

To distinguish the photoresponse from the InAs/GaAs QD sheets in the SJ structures, the measured EQEs are shown in Fig. 3a. The EQEs of both devices are almost identical from 400 nm up to ~870 nm above which the sample with QDs has higher EQE due to wetting layer and bound QD states.

The V_{oc} values of a larger set of InAs QDSCs are plotted as a function of the PL peak wavelength in Fig. 3b. The graph suggests that V_{oc} is dependent on the size of the QDs. Larger QDs induce larger electrical confinement of carriers, and thus, the carrier escape from the QDs is hindered and recombination is increased at the QDs leading to lower V_{oc} [8–10].

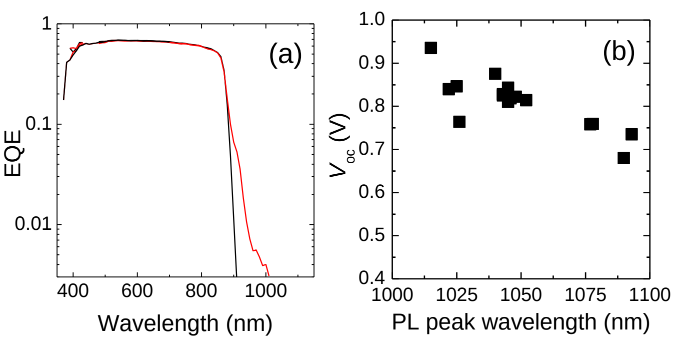

Fig. 3. (a) The EQEs of uncoated SCs with SJ architecture: GaAs reference (black) and InAs/GaAs QD (red). (b) The V_{oc} values of InAs/GaAs QDSCs as a function of the PL peak emission wavelength.

IV. Conclusion

In summary, deep and shallow architectures of MBE-grown InAs/GaAs quantum dot solar cells were compared. The highest V_{oc} of 0.94 V was obtained for the shallow variant in which thin GaAsP strain balancing layers were grown into GaAs barriers between the QD sheets, and in which the QD sheets were placed in the undoped GaAs layer between the thin n-GaAs emitter and the thick p-GaAs base. Only 40 mV loss of V_{oc} was measured for both QDSC variants due to insertion of ten InAs QD sheets.

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