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Spectral response and I-V characteristics of large well number multi quantum well solar cells

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The inclusion of quantum wells in p-i-n solar cells leads to both an increase in photocurrent and a reduction in open circuit voltage. It has been shown that up to 50 shallow strain-balanced GaAsP/InGaAs quantum wells can be inserted into a GaAs cell resulting in an increase in photocurrent that is greater than the reduction in V_{oc}, leading to higher cell efficiency [1]. We present an investigation into the effects of a further increase in well number. The spectral response and IV characteristics of a 65 well quantum well solar cell and an otherwise identical 50 well cell are presented and compared. In addition, the ideality $n = 1$ dark currents obtained from these samples at concentrator current levels are studied. The predicted and measured light current densities under forward bias are compared at one sun illumination and demonstrate additivity to a good approximation. The results obtained suggest that cell efficiency decreases as well number increases from 50 to 65. Additionally, a 65 well cell of reduced exciton wavelength is also considered and found to demonstrate additivity at AM1.5 g short-circuit current levels and projected efficiency equal to that of the 50 well cell. *© 2005 Springer Science + Business Media, Inc.*

1. Introduction

The enhancement in spectral response caused by the addition of quantum wells to the intrinsic region of a p-i-n solar cell allows quantum well solar cells to make better use of the incident solar radiation and thus produce a higher photocurrent than conventional GaAs solar cells. However the inclusion of quantum wells also leads to an increase in dark current and a reduction in open circuit voltage, although it is possible to minimise this effect using strain balanced [2, 3] materials. Previous studies [1] suggest that for cells containing up to 50 strain-balanced wells the cell dark current increases less strongly with increasing well number than the photocurrent, causing overall cell efficiency to increase with rising well number. In order to produce quantum well solar cells (QWSCs) of maximum possible efficiency it is necessary to investigate whether these trends continue as well number is increased beyond fifty, or if there is an optimum well number beyond which efficiency decreases. Even if the photocurrent continues to increase faster with well number than the dark-current, efficiency may not continue to increase if there is a loss of field across the wells at the cell operating point as this will cause reduced carrier collection and therefore lower device efficiency. We investigate this experimentally, in the cells to be discussed, by testing *additivity*. This involves comparing the measured current-voltage curve under illumination with the difference between the short-circuit photocurrent and the dark-current.

2. Sample description

In order to examine the effects of continued increase in well number two strain compensated samples, differing only in well number, were grown using Metal-Organic Vapour Phase Epitaxy (MOVPE) at the EPSRC National Centre for III-V Technologies at the University

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TABLE I Wafer composition

Wafer name	No. of wells	Well width (nm)	Barrier width (nm)	Well In fraction	Barrier *P* fraction	Exciton wavelength (nm)
Qt1840	50	8.3	17.4	0.11	0.090	932
Qt1838R	65	8.3	17.4	0.11	0.090	932
Qt1858D	65	8.3	17.4	0.10	0.089	924

of Sheffield [3]. The composition of these wafers is detailed in Table I. In particular, it is important to note that the first two wafers possess the same exciton wavelength, making them directly comparable. Additionally, a second 65 well wafer with shallower quantum wells and an exciton wavelength of 924 nm was also grown (see Section 4.3).

Each sample was processed as both a 1 mm diameter test photocell with a SiN_3 anti reflection (AR) coating and a fully metalised device to assess the dark current.

3. Cell characterisation

The dark currents of the fully metalised samples were measured and fitted using the equation

$$J_d = J_{01}\left(e^{\frac{-qV}{n_1 kT}} - 1\right) + J_{02}\left(e^{\frac{-qV}{n_2 kT}} - 1\right) \qquad (1)$$

where J_d is the total dark current density and J_1 and J_2 the reverse saturation currents of the $n_1 = 1$ and $n_2 \sim 2$ current densities [4]. The mean value of J_{01} was calculated for each wafer from fits to approximately 18 fully metalised devices with n_1 fixed at unity and n_2 allowed to vary.

The internal quantum efficiencies of the solar cells were determined using external quantum efficiency and reflectivity measurements. This was then used to predict external quantum efficiencies for a sample with an ideal SiN_3 AR coating by combining the internal quantum efficiencies with calculated reflectivities of an idealised SiN_3 coat, thus removing any effect on the samples of differences in the anti reflection coating.

The light current densities of each photocell were measured in a 3000 K black body spectrum with the light intensity adjusted so the device short-circuit current J_{sc} was equal to the predicted short circuit current in an AM1.5 g spectrum using the theoretical external quantum efficiency discussed above (5% metallization is assumed). Efficiencies and other parameters predicted in this way for quantum well solar cells have subsequently been shown to agree well with measurements obtained when the same wafer has been processed as a solar cell and measured in the appropriate simulator [3]. However, here the aims of these measurements are to test if additivity holds at the relevant current level and to be able to make comparisons between cells measured under the same conditions. The fill factors, open circuit voltages and projected AM1.5 g cell efficiencies obtained from this measurement were compared to predicted values obtained from the subtraction of J_d from J_{sc}. As discussed above, the comparison of the measured light IV with the prediction obtained from the subtraction of the measured J_d and the J_{sc} fixed as above is a test of *additivity*. This is an important test for quantum well cells which will fail if the electric field is not maintained across the i-region [5].

4. Experimental results and discussion

4.1. Dark currents

The dark currents of Qt1838R and Qt1840 are shown in Fig. 1. At low bias the dark current of the 65 well sample is around an order of magnitude higher than that of the 50 well sample although at higher bias the dark currents of the two cells start to converge. The dark current densities at 0.9 V for the 65 and 50 well sample are 479.3 and 430.4 Am^{-2} respectively.

The $n = 1$ reverse saturation current density J_{01} (shown in Table II) of Qt1840, determined from the fits to approximately 18 devices in each case, is significantly lower than that of Qt1838R, demonstrating an increase in recombination with increasing well number.

4.2. Photocurrents

The photocurrent of Qt1838R is only slightly higher than that of Qt1840 (Table III). This suggests that the

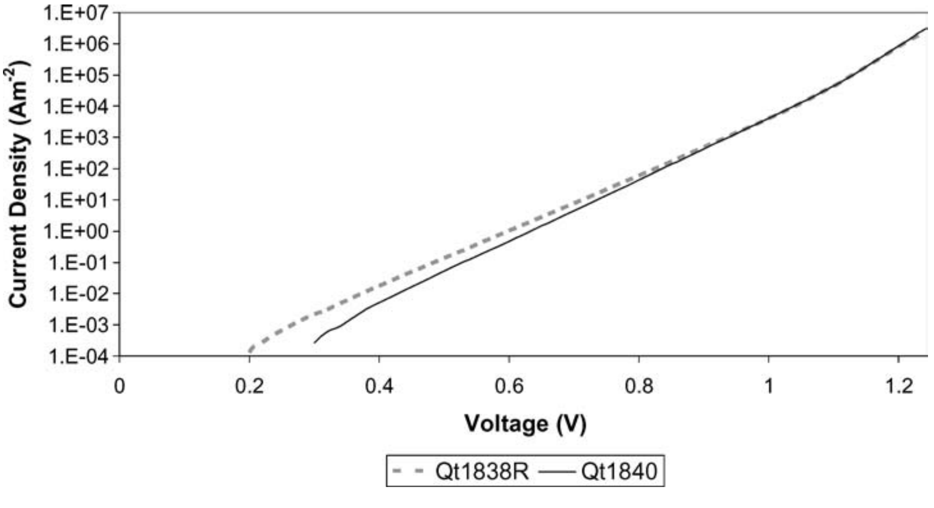

Figure 1 Dark current densities of 65 well Qt1838R (65 wells) and Qt1840 (50 wells).

TABLE II Ideality $n = 1$ reverse saturation current densities of Qt1838R and Qt1840

Sample name	No. of wells	Ideality $n = 1$ reverse saturation current densities (Am^{-2})
Qt1840	50	$(2.8 \pm 0.3) \times 10^{-15}$
Qt1838R	65	$(3.8 \pm 0.2) \times 10^{-15}$

TABLE III Predicted AM1.5 g photocurrent densities of Qt1838R and Qt1840

Sample Name	No. of wells	Predicted AM1.5 g photocurrent densities (assuming 5% shading) (Am^{-2})
Qt1840	50	280
Qt1838R	65	281

increased absorption due to the larger number of wells in Qt1838R is compensated for by a slightly lower absorption at short wavelength, i.e. lower absorption in the p-region (see Fig. 2).

4.3. Reduced wavelength 65 well cell

In addition to Qt1840 and Qt1838R, a second 65 well sample, Qt1858D, with an exciton wavelength of 924 nm was also characterised. The composition of this cell is also detailed in Table I.

The dark current density of Qt1858D is 193.3 Am^{-2} at 0.9 V, significantly lower than that of both Qt1840 and Qt1838R, as expected for a cell of lower exciton wavelength [5]. The predicted AM1.5 g photocurrent of Qt1858D is 284 Am^{-2}, higher than the photocurrent of Qt1840. This is partly due to the position of the exciton peak of the reduced wavelength sample, which corresponds to a region of higher intensity in the AM1.5 g spectrum (see Fig. 3). Also, additivity is very well maintained throughout the light IV plot of this sample although there is a small difference between predicted and measured maximum power point photocurrent for samples Qt1838R and Qt1840, suggesting a slight loss of field across the i region of these devices (see Fig. 4).

4.4. Projected cell efficiencies

It is possible to use the experimental data to accurately calculate the efficiency of the cells when illuminated by an AM1.5 g spectrum provided the quantum efficiency of the devices does not change with bias and the dark current densities of the devices do not change significantly with increasing cell size [3]. These are both reasonable assumptions given the good agreement between predicted and measured light currents shown in Fig. 4 and the fact that the dark current density measured in small devices is likely to be higher than that obtained from large area devices due to edge effects. For the samples with an exciton wavelength of

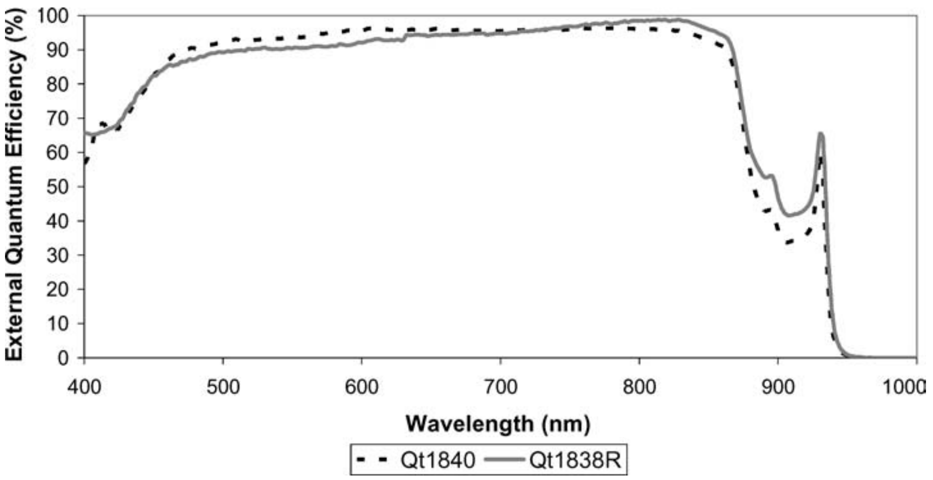

Figure 2 Ideal external quantum efficiencies of Qt1838R and Qt1840.

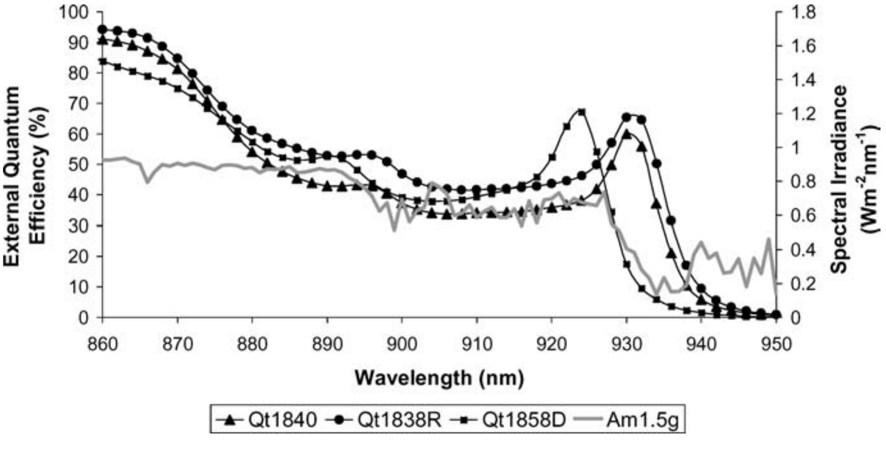

Figure 3 Detail of the sample exciton peaks and the AM1.5 g spectrum [6].

TABLE IV Measured and predicted open circuit voltages, predicted short circuit currents, measured and predicted fill factors and projected AM1.5 g 1 sun efficiencies of all samples, determined as described in the text

Sample	Measured V_{oc} (V)	Predicted V_{oc}(V)	Predicted J_{sc} (Am^{-2})	Measured fill factor (%)	Predicted fill factor (%)	Projected AM1.5 g η (%) (assuming 5% shading)
Qt1838R (65 wells)	0.868	0.881	281	79.1	79.7	19.2
Qt1840 (50 wells)	0.914	0.923	280	80.9	81.1	20.7
Qt1858D (65 wells reduced wavelength)	0.910	0.913	284	79.9	80.3	20.7

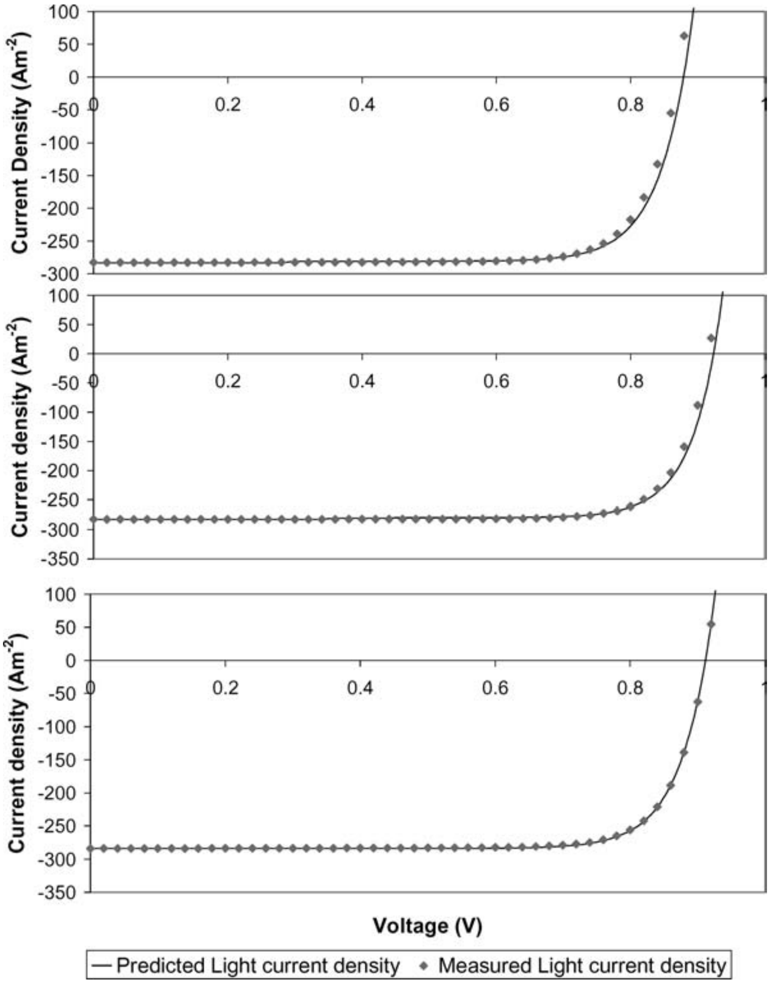

Figure 4 Predicted and measured light current densities for Qt1838R (top), Qt1840 (middle) and Qt1858D (bottom).

932 nm (Qt1840 and Qt1838R), the projected AM1.5 g efficiency of the 65 well sample is lower than that of the 50 well sample (see Table IV). It would appear that the slight increase in photocurrent caused by the inclusion of more quantum wells does not compensate for the increased dark current the 65 well sample possesses. The projected efficiencies of the 50 well sample and the reduced wavelength 65 well sample (Qt1858D) are equal, due to both the low dark current of the reduced wavelength sample, caused by its shorter exciton wavelength, and its increased photocurrent caused by more wells and better utilization of the solar spectrum.

5. Conclusions and further work

The photocurrent of a 65 well sample with an exciton wavelength of 932 nm is slightly higher than that of an otherwise identical sample containing only 50 wells, but is insufficient to compensate for the higher dark current the 65 well sample possesses. This leads to the 65 well sample having a lower projected AM1.5 g efficiency than the 50 well cell. A sample with 65 wells and a reduced exciton wavelength of 924 nm has an equal projected efficiency to the 50 well sample, despite containing more wells, due to its low dark current and high photocurrent resulting from its shorter exciton wavelength which makes better use of the AM1.5 g spectrum. Also additivity is demonstrated in the reduced wavelength sample, suggesting that this wafer maintains the field across the i-region at 1-sun intensities despite having 65 wells. More cells of the same exciton wavelength as this sample with varying well numbers are planned to allow further study of large i region strain balanced QWSCs.

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Acknowledgments

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