Modelling Multi Quantum Well Solar Cell Efficiency

James P. Connolly a Jenny Nelson a Ian Ballard a Keith W.J. Barnham a Carsten Rohr a Chris Button b
John Roberts a Tom Foxon c

a Blackett Laboratory, Imperial College of Science, Technology and Medicine, London SW7 2BZ
b EPSRC III-V Facility, University of Sheffield, Sheffield S1 3JD UK
c Physics Dept., University of Nottingham, Nottingham NG7 2RD UK

ABSTRACT: The spectral response of quantum well solar cells (QWSCs) is well understood. We describe work on QWSC dark current theory which combined with SR theory yields a system efficiency. A methodology published for single quantum well (SQW) systems is extended to MQW systems in the AlxGa1−xAs and InGa0.53xAs0.47P systems. The materials considered are dominated by Shockley-Read-Hall (SRH) recombination. The SRH formalism expresses the dark current in terms of carrier recombination through mid-gap traps. The SRH recombination rate depends on the electron and hole densities of states (DOS) in the barriers and wells, which are well known, and of carrier non-radiative lifetimes. These material quality dependent lifetimes are extracted from analysis of suitable bulk control samples. Consistency over a range of AlGaAs controls and QWSCs is examined, and the model is applied to QWSCs in InGaAsP on InP substrates. We find that the dark currents of MQW systems require a reduction of the quasi Fermi level separation between carrier populations in the wells relative to barrier material, in line with previous studies. Consequences for QWSCs are considered suggesting a high efficiency potential.

Key words: Quantum wells - 1: Solar Cell Efficiencies - 2: Modelling - 3

1 Introduction

The QWSC [1] is a p-i-n structure with narrow regions or quantum wells (QWs) of lower bandgap sandwiched between barrier layers with higher bandgap. Both are situated in the i region and subject to a field in the operating regime. The wells are narrow enough that carriers generated in them can only occupy discrete energy levels.

The control structures discussed here are p-i-n devices of similar material composition and dimensions as the QWSCs but with the QWs replaced with bulk material of the same composition as the barriers for barrier controls, or the barriers replaced with well material for well controls. In some cases InGa0.53xAs0.47P p-i-n heterostructures where the i region is made of material with either the confined well or the barrier bandgap are used as controls.

Experiment has shown ([2], [3]) that light absorbed in the QWs is converted to photocurrent with essentially unit efficiency, indicating good photogenerated carrier escape and collection efficiency.

Work on the efficiency of this system has raised a number of questions. It has been suggested [4] that the cell can be no more efficient than a homostructure with an equivalent bandgap in the ideal limit and that the Voc is determined by the lowest bandgap in the cell. In real structures however further work ([5], [6], [7]) has indicated that assumptions regarding a constant quasi-Fermi level separation ΔEF in the i region may not be true, in which case higher efficiencies are possible with this system.

This work investigates a QWSC dark current model dominated by Shockley-Read-Hall (SRH) recombination [8] in a number of QWSCs and control cells without wells in two different material systems with a view to exploring the efficiency of this system.

2 Model

2.1 Photocurrent

The modelling of the spectral response (SR) has been discussed previously [2] but is summarised here. It proceeds via solutions to the transport equations
Below the barrier bandgap for the quantum well levels, the absorption is calculated from first principles assuming infinite barrier thickness and using published values of well and barrier bandgaps in the bulk, and electron and hole effective masses by solution of the Schrödinger equation in the effective mass and envelope function approximations, and excitonic states are included [3].

SR theory and data for a 50 well GaAs/AlGaAs QWSC and a 30 well InGaAsP on an InP substrate are shown in figures 1 and 2 respectively. The approximations hold satisfactorily though increasing underestimation is visible near the top of the well in the region of transition from 2D to a 3D density of states (DOS). Overall the good fits show that the quantum well DOS is well described and that the assumption of unit escape efficiency for carrier escape from the wells is accurate.

2.2 Dark current

The dark current formulation used here expresses the dark current as a sum of ideal and SRH contributions. The ideal diode contribution is determined by charge transport in the neutral n and p regions which is determined by fitting the spectral response of these layers. We will see that this ideal contribution is negligible except at high forward bias in some samples.

As described in more detail in ref. [9], the SRH contribution to the dark current is the integral of the SRH recombination rate across the intrinsic region where it is non negligible because of significant populations of both electrons and holes. This method is applicable to MQW systems because the large number of wells removes the sensitivity of the dark current to well position, as opposed to the SQW case. The SRH rate for quantum wells can be expressed [10] in terms of the well understood quantum well DOS.

The SRH rate depends on the cell dimensions and material which are well known from the epitaxial growth. Given the knowledge of the DOS this leaves the hole and electron lifetimes in the intrinsic regions as free parameters in the absence of direct measurement. If electron and hole lifetimes are made significantly different in the material being considered (well or barrier), the slope of the dark current on a log-linear scale (the ideality) changes significantly in contradiction with experiment.

This leaves as two parameters the carrier lifetimes in the barriers, and in the wells. These two values are determined by fitting the dark currents of control structures made of material equivalent to wells and barriers respectively where they are the sole free parameters. Given this determination of carrier non radiative lifetimes and the knowledge of the DOS, this leaves no free parameters in fitting the dark currents of QWSC structures, as will be seen subsequently.

A further assumption we examine is that the quasi-Fermi level separation \( \Delta E_f \) is constant across the i region and determined by the applied bias. Reducing \( \Delta E_f \) implies lower carrier concentrations and hence lower recombination in the wells as investigated below.

The recombination in the wells is about two orders greater than in the barriers in this case and asymmetric due to different p and n region effective densities of states. This profile corresponds to a dark current which fits the data in figure 6 well showing a reduced \( \Delta E_f \) in SRH dominated material as discussed below.

3 Comparison with data

3.1 AlGaAs

Figure 4 shows theory and experiment for two GaAs p-i-n well controls of different dimensions from different growth runs to check repeatability. The ideal diode Shockley dark current component (dashed line) is negligible except at high bias where it starts to have an effect. The dark currents of the two cells are essentially identical within errors, but the model requires a slightly longer lifetime of 11ns in the wider cell versus 8ns in the narrower. Together the results from these different cells show a good consistency in model predictions and hence material reproducibility.
Fig. 4. Theory and experimental dark current for a GaAs MQW control with 1µm wide i region (upper figure) and 0.9µm wide i region giving non radiative lifetimes of 8ns and 11ns for undoped GaAs.

Fig. 5. Theory and experimental dark current for an Al-GaAs MQW control with 0.48µm wide i region (upper figure) and SQW 0.31µm wide i region control giving non radiative lifetimes of 0.7ns and 0.3ns for undoped Al<sub>36</sub>Ga<sub>64</sub>As.

Figure 5 shows similar results for two AlGaAs controls from different growth runs some time apart with the thicker MQW control i region 55% wider than the narrower SQW control cell. The these controls are also consistent, and determine lifetimes of 0.7ns and 0.3ns for undoped Al<sub>36</sub>Ga<sub>64</sub>As. Again the ideal component is negligible in this case and lower due to different p and n layer characteristics.

The consistency of these values gives us confidence in applying these lifetimes to material in QWSCs. We use the MQW control lifetimes (8ns for GaAs and 0.7ns for AlGas). Two examples of modelling GaAs/Al<sub>x</sub>-Ga<sub>1-x</sub>As QWSC structures are shown in figure 6. The QWSCs were again grown in different growth runs and in different institutions and have a significantly different structure. One features 50 wells and a i region 0.81µm wide, the other 30 wells in 0.48µm i region.

Fig. 6. Theory and experimental dark current for two Al-GaAs QWSCs with different i region widths and number of wells, using the same ∆E<sub>f</sub> in the wells.

The two graphs show the methodology applied to the two samples, with a fit to the data (dots) assuming a constant ∆E<sub>f</sub> (dashed line), and the same with a reduced ∆E<sub>f</sub> which agrees closely with the data. The value of ∆E<sub>f</sub> is 140meV in both cases.

This value is larger than the value reported in ref. [11] for SRH dominated SQW samples and developed in ref. [10]. A difference is not surprising given the different approaches and different MQW and SQW samples. Moreover, ref. [11] shows that the depletion approximation for SRH dominated material is good for biases up to the operating voltage, and is confirmed here since we reach the same conclusion with similar values in MQW and SQW samples. This is that the ∆E<sub>f</sub> is reduced in QWSC structures, as demonstrated in SQWs.

For this cell the constant ∆E<sub>f</sub> calculation predicts an AM1.5 efficiency 14% above what might be expected for this cell based on a constant ∆E<sub>f</sub>, in agreement with experimental. The fact that this cell does not appear to follow the constant ∆E<sub>f</sub> picture therefore yields a significant increase in efficiency in this system over what might be expected from the more simple prediction.

3.2 InGaAsP

Figure 7 shows the same analysis for the dark currents of QWSCs in InGa<sub>0.53</sub>A<sub>x</sub>P on InP substrates. The upper and lower curves are well and barrier controls, made of InGaAsP lattice matched to InP and are analogues of graphs 4 and 5.

The well control is a double heterostructure control with an i region made of material with the well effective bandgap including confinement. The barrier control is a double heterostructure control with an i region made of barrier material. In this case the bulk well control lifetime of 70ns is shorter than that of the barrier control which is 400ns, but the conclusions are the same.

The middle curves show modelling of the QWSC dark current with the lifetimes derived from the two controls. The dashed line again shows the expected dark current with a constant ∆E<sub>f</sub> given by the applied bias.

The fit requires a reduction in ∆E<sub>f</sub> level of 130meV in the well. The ideal component is again negligible.
This shows similar behaviour to the AlGaAs case with a slightly reduced $\Delta E_f$ consistent with the slightly shallower wells visible in the spectral response fits in figure 1 and 2. The sum of well depths in the GaAs/Al$_x$Ga$_{1-x}$As case is approximately 400meV versus 290meV in the InGa$_{0.53}$As$_x$P case including confinement. Furthermore, InGa$_{0.53}$As$_x$P well have different hole to electron band offsets of 16% versus about 35% in GaAs/Al$_x$Ga$_{1-x}$As and the valence well being deeper.

This shows similar conclusions in a second material despite significantly different band structures and carrier properties, and a narrower voltage range because of the lower built in voltage. Although there is uncertainty in the value of $\Delta E_f$ due to the theoretical approximations used, the reduction confirms the high efficiency potential of QWSCs.

We see a systematic overestimation of the dark current. This can be explained in terms of a smaller value of $\Delta E_f$ in the wells. This strongly suggests that these structures have the potential to be efficient solar cells. The treatment used here does not apply to SQW structures because of the approximations made. For SQW samples the position of the quantum wells and the background doping are significant and require an exact solution satisfying Poisson’s equation.

We note however that the treatment applies reliably to MQW systems studied here since dark current is determined mainly by the balance between QW and barrier material, in that on average the position of the wells is not critical. Furthermore the depletion approximation is reliable up to the operating voltage [1]. This is borne out by the range of control and QWSC GaAs/Al$_x$Ga$_{1-x}$As and InGa$_{0.53}$As$_x$P samples examined and comparison with previous exact solutions.

Finally we see consistently similar effects in two systems with very different materials parameters that can explain the higher efficiency observed in the QWSC system.

4 Conclusions

The QWSC benefits from an increase in photogeneration in the wells but suffers from increased recombination in the lower bandgap well regions. In order to study which effect is greater we study photocurrent and dark current and express the modifications to dark and photocurrent in terms of the quantum wall density of states. The photocurrent from the wells is determined mainly by the balance between QW and barrier material, in that on average the position of the wells is not critical. Furthermore the depletion approximation is reliable up to the operating voltage [1]. This is borne out by the range of control and QWSC GaAs/Al$_x$Ga$_{1-x}$As and InGa$_{0.53}$As$_x$P samples examined and comparison with previous exact solutions.

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Fig. 7. Theory and experimental dark current for a InGa$_{0.53}$As$_x$P MWQ (centre curves) and well and barrier controls showing a similar dark current reduction to GaAs/Al$_x$Ga$_{1-x}$As QWSCs

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