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Observation of reduced radiative recombination in low-well-number Strain-Balanced Quantum Well Solar Cells

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Abstract

Absolute electroluminescence and photoluminescence measurements were carried out on strain-balanced quantum well solar cells Over a range of bias, a reduced radiative recombination in the wells was observed compared to a model assuming a constant quasi-Fermi level separation over the device thickness. This was interpreted as a QFLS suppression in the wells relative to the bulk of 18 and 5 meV respectively for the single and 5 well SB-QWSCs, consistent with previous results on strained Single Quantum Well and Double Quantum Well devices. The photoluminescence spectra at open-circuit voltage under illumination in the well agreed with the electroluminescence spectra in the

light in contrast to some theoretical predictions. Generation of hot carriers in the wells could be the thermodynamically compensating phenomenon for the QFLS reduction.

When a p-n junction solar cell is illuminated and/or electrically biased the Fermi level splits into electron and hole quasi Fermi levels over the depletion region of the device. The quasi-Fermi level separation (QFLS) determines the radiative recombination losses of the solar cell. Araujo and Marti [1] used a detailed balance treatment to show that in an ideal cell, the QFLS is equal to the applied bias at all points so that in the radiative limit, no higher efficiency could be achieved by a Quantum Well Solar Cell (QWSC) compared to a conventional cell of optimum band-gap. However studies carried out on strained Single Quantum Well (SQW) [2] and Double Quantum Well (DQW) [3] devices concluded that the QFLS was reduced in the wells compared to the bulk indicating promising efficiency enhancements. Since then the strain-balance concept has been introduced allowing the incorporation of a higher number of wells into the GaAs p-n junction while maintaining the materials crystalline quality [4]. Compressive strain in the low band gap $In_xGa_{1-x}As$ well material is compensated by tensile strain in the high band gap $GaAs_{1-y}P_y$ barrier material. In this paper we extend the work on QFLS studies from strained well devices to Strain-Balanced Quantum Well Solar Cells (SB-QWSCs).

Three SB-QWSC wafers were grown by MOVPE (Metal Organic Vapour Phase Epitaxy) as p-i-n structures with 1, 5 and 10 quantum wells (QWs) inside the intrinsic region. The emitter and base consisted of C-doped GaAs and Si-doped GaAs respectively. All cells were designed to have the same i-region width (~ 7800 Å). The i-region was grown with two buffer layers of intrinsic GaAs of various thickness either side of 1, 5 or 10 $In_{0.163}Ga._{0.837}As$ 95Å-thick well layers. The compressive strain of these wells is compensated by 145 Å–thick $GaAs_{0.911}P_{0.089}$ barrier layers in tensile strain, separating the wells.

Photodiode structures were processed from the wafers and the spectral response of the three cells have been measured and compared to the in-house simulation model SOL described in Ref. 5. The model solves transport equations for the minority carriers in the charge neutral regions of the cell and calculates the well absorption spectrum from first-principles calculations of the confined states in the well. By adjusting the minority carrier parameters of neutral regions and the QW dimensions in the i-region, one can obtain the best fit of the spectral response and hence set the absorption coefficients of every layer. These absorption coefficients are used by the model to predict the luminescence response of the cells.

The emission of a SB-QWSC is calculated using a detailed balance treatment, explained in detail in Ref. 2 based on the following expression for the emitted light flux U_{rad}:

$$U_{rad} = \int_0^\infty \int_S a(E,\theta,s) b(E,\Delta E_F)\, d\Omega . dS . dE \qquad (1)$$

where $a(E,\theta,s)$ is the probability that a photon of energy E will be emitted or absorbed from the point s on the surface S of the emitting volume at an angle θ and $b(E, \Delta E_F)$ is the spectral photon flux density due to spontaneous emission at that point. ΔE_F is the local QFLS. The flux density $b(E,\Delta E_F)$ is defined from the generalized Planck equation for spontaneous emission [6] as:

$$b(E,\Delta E_F) = \frac{2n^2}{h^3c^2}\frac{E^2}{e^{(E-q\Delta E_F)/kT}-1} \qquad (2)$$

where n is the refractive index of the cell, k is Boltzmann's constant, T the absolute temperature, h Planck's constant and c the speed of light. The spatial geometry of the cell is taken into account in calculating the forward emitted flux [7] which is then compared to experimental electroluminescence spectra.

To be able to compare the absolute intensities of the spectra, the experimental EL was calibrated using the method described in Ref. 8. Low temperature photocurrent and photoluminescence measurements were taken as a function of bias. The reverse bias and the photoluminescence spectra were compared with the forward bias photoluminescence (PL) spectra so that the latter could be expressed as the number of photons emitted per eV and per s.

Experimental calibrated EL spectra were taken at various forward biases for each sample. Examples at +0.87V (a) and +0.92V (b) for the single well, +0.88V for the 5 well (c) and +0.87V for the 10 well (d) SB-QWSCs are shown as circular data points in Fig. 1 where they are compared to the model (broken lines) with a QFLS equal to the applied bias.

For bulk cells with no quantum wells, for example a GaAs p-i-n cell [8] the model fits the calibrated EL closely in absolute units assuming the QFLS is equal to the experimentally applied bias throughout the cell.

For quantum well samples however the model assuming constant QFLS throughout, overestimates the well luminescence. This is seen most clearly at the main well excitonic luminescence peak at 1.285 eV for the single and the 5 well samples. The bulk peak is also overestimated due to a contribution from the quantum well, as the GaAsP barrier is higher than bulk GaAs. We find that in order to fit the EL overall, and the main excitonic peak in particular, the model requires a reduced QFLS in the wells of 18, 15 and 5 meV as shown by the full lines in Fig.1.a, b and c. The single well result is similar to the QFLS reduction of 23 meV observed in a GaAs/InGaAs strained SQW of similar well depth [2] and to the (11-18) meV reduction observed in the deeper well of AlGaAs/GaAs lattice matched DQWs over a similar voltage range [3].

Single well and 5 well SB-QWSCs therefore demonstrate similar results to strained SQW and unstrained DQWs in that radiative losses are less than predicted by assuming a constant quasi-Fermi level equal everywhere to the applied bias which is an assumption made in some models of radiatively dominated QW solar cells [1,9]. This QFLS reduction will lead to a significant solar efficiency enhancement if the dominant contribution to dark currents is radiative as has been observed in SB-QWSCs at high concentration [10].

Luque and Marti [9] have used a local thermodynamic argument to suggest that if the QFLS in a QW cell is reduced under dark conditions as observed here, then the QFLS and hence the radiative recombination will be increased under illumination. We have pointed out that the QFLS reduction could be explained by a compensating thermoelectric effect [11]. An increase of the temperature of the carriers photogenerated in the wells of only a few degrees relative to the crystal temperature (hot carriers) could create a thermal gradient that would balance the gradient of the electrochemical potential [12,8]. Our observed reduction in QFLS with well number is consistent with this picture

[11]. It has further been suggested that light concentration may amplify the phenomenon by promoting the creation of hot carriers [11].

For this reason, and to test the Luque-Marti conjecture, we have investigated the behavior of these SB-QWSCs under illumination. The three samples were illuminated with a tunable Titanium:Sapphire laser operating at 1.355 eV, i.e. carriers were excited by illumination in the QW absorption continuum. A holographic notch filter centered on 907 nm was placed in front of the monochromator slit to attenuate the laser line. Photoluminescence (PL) spectra (full lines) obtained at open circuit voltage (V_{OC}) are shown in Fig. 2 together with EL spectra (scattered points) obtained in the dark at the same bias. The EL and PL spectra are identical for all three samples. Hence the radiative recombination spectra and integrated radiative-recombination current are identical in both cases.

We conclude that the QFLS reduction deduced from the EL spectra modeling shown in Fig.1 must also be the same under illuminated conditions at the same bias. This confirms the observation on the GaAs/InGaAs strained SQW [13,14] and suggests the QWSC does not conform to the assumptions by Luque and Marti [9] of a constant QFLS separation. Work is in progress examining the temperature of carriers in the wells and shows signs of higher carrier temperatures in the well mentioned above [8, 12,]. We are also extending these QFLS measurements to higher biases where radiative recombination dominates [10].

The EL spectra at various biases were integrated to calculate radiative currents shown as scattered square points in Fig. 3.a for the single well SB-QWSC sample. The measured total dark currents are shown as dots. The radiative recombination current is proportional to $e^{qV/nkT}$, with an ideality factor n of 0.95±0.04, showing good agreement with the n = 1 expected for radiative processes. This last observation gives confidence into the procedure used to extract the radiative recombination current. The experimental radiative current was found to be significantly below the current predicted by the model assuming the QFLS was equal to the applied bias, as shown by the full line in Fig. 3.a, confirming that radiative recombination is reduced over the whole range of bias. The corresponding QFLS reduction for each applied bias is shown in Fig. 3.b and varies slightly between 15 and 19 meV depending on the applied bias. The radiative current becomes comparable with the total dark current at ~ 1.1V consistent with the change of ideality observed in SB-QWSCs at these biases which correspond to 200x concentration [10]. For terrestrial applications SB-QWSCs will be used under high light concentration to reduce costs. Hence a QFLS reduction at these biases is of great interest in the aim of minimizing dark currents and enhancing efficiencies. To exploit the QFLS observed in these low well number devices efficient forms of photon-recycling will be necessary for example by means of back surface mirrors as already under study [8].

In summary we have confirmed that the QFLS reduction first observed in SQW and DQW lattice matched and strained SQW cells is also observed in the higher material quality strain-balanced cells. We have presented evidence of a reduced radiative recombination current observed on three SB-QWSCs with 1 and 5 wells and interpreted as a reduction of the QFLS in the wells. This reduction could be explained by a temperature gradient in the nanostructures with "hot carriers" in the wells and would be a contribution to efficiency enhancement in low-well-number QWSCs. The QFLS reduction was observed in the dark with EL measurements as well as in the light with

PL/EL measurements at V_{OC} in contrast to some theoretical expectations. The reduction of the radiative losses was observed for several different biases for the single well SB-QWSC. The QFLS reduction was found to decrease with the number of wells which suggest that effective photon recycling will be necessary to fully exploit this effect. It will be important to extend these studies to higher biases and under higher light concentrations where the recombination is radiatively dominated and where hot carrier effects may be more important.

Acknowledgments

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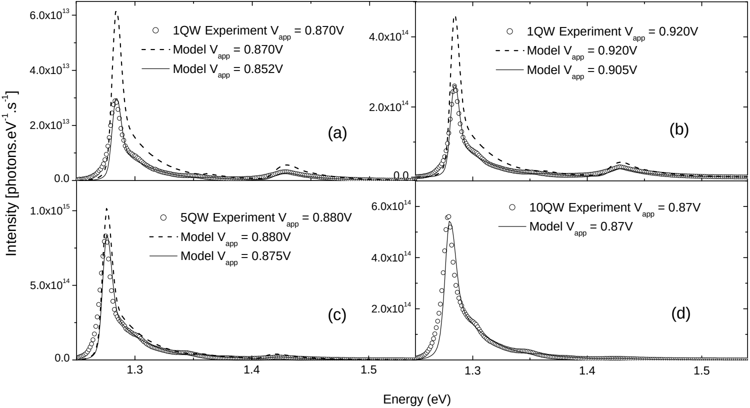
Figure captions

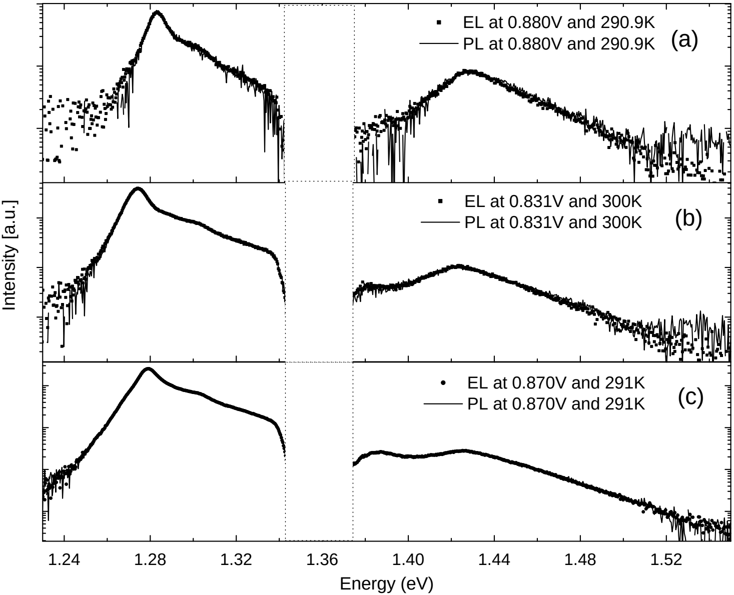
Fig. 1 Experimental (circles) and modeled EL (broken and full lines) of (a) the single well sample at 287.8K and 0.87V, (b) the single well sample at 287.8K and 0.92V, (c) the 5 well sample at 300K and 0.88V, and (d) the 10 well sample at 291K and 0.87V.

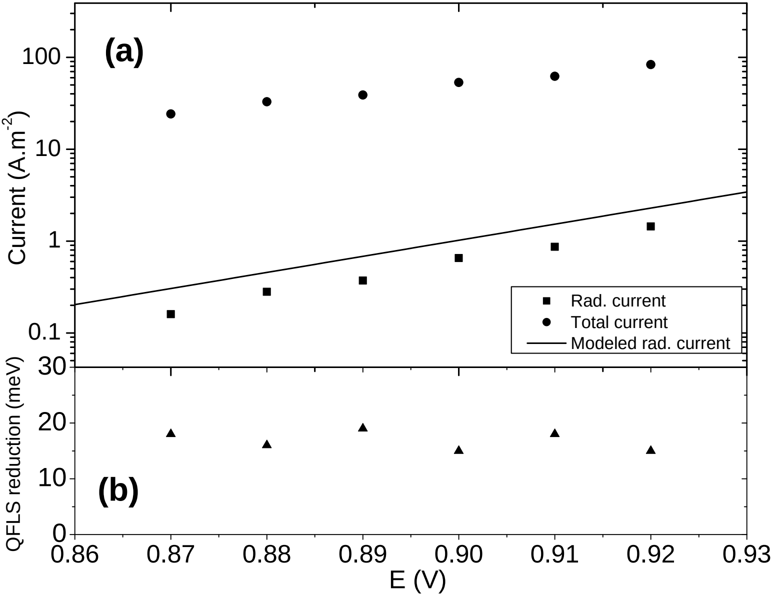
Fig. 2 Experimental photoluminescence under laser illumination at Voc (full lines) compared with measured electroluminescence in the dark (scattered points) of (a) the single well, (b) the 5 well and (c) the 10 well sample.

Fig. 3: (a) experimental radiative current (squares) and total dark current (dots) compared to the modeled radiative current assuming QFLS equals applied bias (full line) for the single well SB-QWSCs at 287.8K and (b) Experimental QFLS reduction as a function of bias.



Intensity [photons.eV^{-1}.s^{-1}]
Energy (eV)
1QW Experiment V$_{app}$ = 0.870V
Model V$_{app}$ = 0.870V
Model V$_{app}$ = 0.852V
(a)
1QW Experiment V$_{app}$ = 0.920V
Model V$_{app}$ = 0.920V
Model V$_{app}$ = 0.905V
(b)
5QW Experiment V$_{app}$ = 0.880V
Model V$_{app}$ = 0.880V
Model V$_{app}$ = 0.875V
(c)
10QW Experiment V$_{app}$ = 0.87V
Model V$_{app}$ = 0.87V
(d)
0.0
2.0x10^{13}
4.0x10^{13}
6.0x10^{13}
2.0x10^{14}
4.0x10^{14}
5.0x10^{14}
1.0x10^{15}
6.0x10^{14}
1.3
1.4
1.5


■ EL at 0.880V and 290.9K
PL at 0.880V and 290.9K
(a)
■ EL at 0.831V and 300K
PL at 0.831V and 300K
(b)
● EL at 0.870V and 291K
PL at 0.870V and 291K
(c)
Intensity [a.u.]
1.24
1.28
1.32
1.36
1.40
1.44
1.48
1.52
Energy (eV)


(a)
(b)
Current (A.m^{-2})
100
10
1
0.1
30
20
10
0
QFLS reduction (meV)
Rad. current
Total current
Modeled rad. current
0.86
0.87
0.88
0.89
0.90
0.91
0.92
0.93
E (V)