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Effect of Inserting Quantum Wells on Electrical Parameters of Microcrystalline-Silicon Photovoltaic Cell

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Abstract

The effect of inserting hydrogenated microcrystalline-silicon (μc-Si:H) quantum well layers with Raman crystallinity of 0.07, in the intrinsic region of a p-i-n configuration of thin film μc-Si:H photovoltaic cell with a Raman crystallinity of 0.01, is investigated with the help of theoretical modeling. The dependence of open-circuit voltage, short-circuit current density, fill factor, and conversion efficiency over the band offset of well and barrier layers is studied. Partial correlation of the study with experimental results is established. This work provides an exclusive method to enhance the efficiency and FF of μc-Si:H silicon photovoltaic cell. The efficiency could be increased by nearly 10% of the efficiency value of μc-Si:H photovoltaic cell without quantum wells.

Keywords: Quantum wells, photovoltaic cell, Raman crystallinity, micro-crystalline Si

Introduction

The concepts of quantum wells and quantum dots have been subject of extensive studies in the recent years in context with third generation photovoltaic cell. Third generation concepts include the use of quantum wells and quantum dots to boost the efficiency of a photovoltaic cell. Groups from the globe have been working on various ways to introduce quantum wells or quantum dots in the silicon thin film solar cell using wide band gap barrier layer, e.g., SiO_2 and Si_3N_4 [1]. Here, an attempt is made to design μc-Si:H quantum well photovoltaic cell by using thin silicon films of different 'Raman crystallinity'. To differentiate one layer from another a parameter known as 'Raman crystallinity factor (ϕ_c)' indicative of the crystalline volume fraction (i.e. Raman crystallinity) is used throughout this paper [2]. The model is founded on following simplifying assumptions:

(i) Minority carrier forward injection (diffusion) and reverse extraction (drift) currents are treated as in the ideal theory of quantum well photovoltaic cell [2] based on depletion approximation. Bias dependence of the depletion region width is neglected.

(ii) Radiative and non-radiative recombination is considered.

(iii) Carrier distributions throughout the structure are described by non-degenerate Maxwell-Boltzmann statistics and quasi-Fermi levels. This presumes scattering processes sufficiently efficient to keep the carrier subsystems in the wells and barriers in quasi-equilibrium with themselves as well as capture and emission rates sufficiently rapid to keep the two subsystems in quasi-equilibrium with one another [3].

(iv) The ϕ_c of hydrogenated amorphous silicon semiconductor material is considered as zero, and ϕ_c of mono-crystalline silicon is considered to be one.

(v) Amorphous silicon being perfect imperfect semiconductor material is direct band gap and same is assumed for nearby microcrystalline-silicon (i.e. silicon thin film with $\phi_c \leq 0.1$). Ohmic losses are assumed negligible, with quasi-Fermi levels assumed to be flat throughout the intrinsic region and separated by the terminal voltage.

(vi) The doping of the n- and p- regions are assumed to be equal and the conduction band structure is assumed to be a mirror image of the valence band structure about the middle of the gap at every point in the cell.

(vii) All the broken bonds or dangling bonds and interface states are well-passivated.

Based on these assumptions the results are out lined in the following paper.

Model of μc-Si:H quantum well photovoltaic cell

In this section the model of μc-Si:H quantum well photovoltaic cell along with the associated parameters that are used in modeling are mentioned. Any equivalent discussion for the electrode layers is not presented and it is assumed that these layers are ideal and have no effect on the behavior of the cell.

The model of μc-Si:H quantum well photovoltaic cell is based on current voltage relationship of ideal quantum well photovoltaic cell [3]. The relationship is mentioned hereunder:

$$J_{QW}(V) = J_0(1 + r_R\beta)[\exp(qV/k_BT) - 1] + r_{NR}\alpha[\exp(qV/2k_BT) - 1] - qr_G\Phi_B \quad (1)$$

where, r_R is radiative enhancement ratio, β is the ratio of the current required to feed radiative recombination in the intrinsic region at equilibrium to the usual reverse drift current resulting from minority carrier extraction, r_{NR} is the non-radiative enhancement ratio, α represents the ratio of current required to feed non-radiative recombination in the intrinsic region at equilibrium, r_G is the generation enhancement ratio, Φ_B is the net flux of incident photons with energies greater than or equal to bandgap of base material (i.e. here μc-Si:H with $\phi_c = 0.01$) and all remaining symbols have their usual meanings. Some of these parameters are material specific and need to be calculated for the material of interest.

To calculate various material parameters of microcrystalline-silicon, concept of "equivalent average" was utilized. The concept was used for calculating band gap of microcrystalline silicon by somewhat arbitrarily weighting the bandgap of a-Si:H ($E_g^{a-Si:H} = 1.75\,\text{eV}$) and c-Si ($E_g^{c-Si:} = 1.1\,\text{eV}$) materials with the equation for "equivalent average bandgap" given as [2]:

$$E_g^* = \phi_c \cdot 1.1 + (1-\phi_c) \cdot 1.75 \qquad (2)$$

where, ϕ_c is the Raman crystallinity measured for the given μc-Si:H thin film. Similar "equivalent average" expressions were derived for other material related parameters such as effective masses, carrier mobility, density of states and carrier lifetimes.

The low band gap μc-Si:H thin layer (i.e. a layer with high ϕ_c) is considered as well layer and high band gap μc-Si:H thin layer (i.e. a layer with low ϕ_c) is considered to be barrier layer. Since the goal of this work is investigation of broad trends due to insertion of quantum well rather than the detailed properties of specific structure, a single set of representative parameters is thus used in the studies. The thickness of intrinsic layer was considered to be 450 nm (nearby values being reported by various authors for modeling of a-Si:H photovoltaic cell [4]). A well width of 5 nm is taken to have an effective quantum confinement. In order to avoid quantum mechanical tunneling barrier width has to be five-six times of the well width so a barrier layer of 30 nm is considered. Using the assumed thicknesses of well and barrier layers 12 wells could be incorporated in the intrinsic region (i - Layer). The schematic diagram of the model is shown in the figure (See Fig. 1 & Fig. 2).

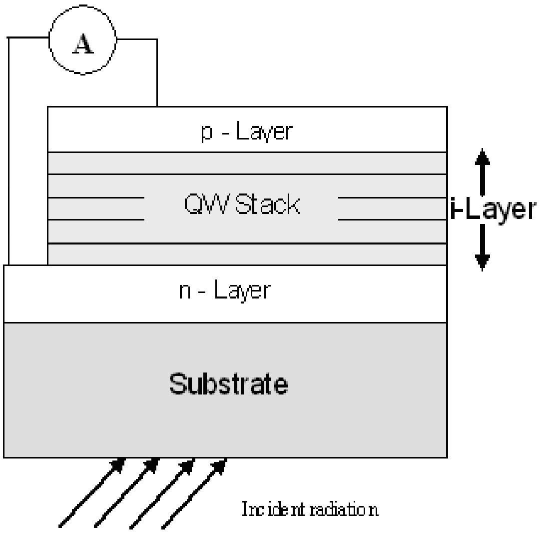

Figure 1: Schematic diagram of a stacked μc-Si:H quantum well photovoltaic cell.

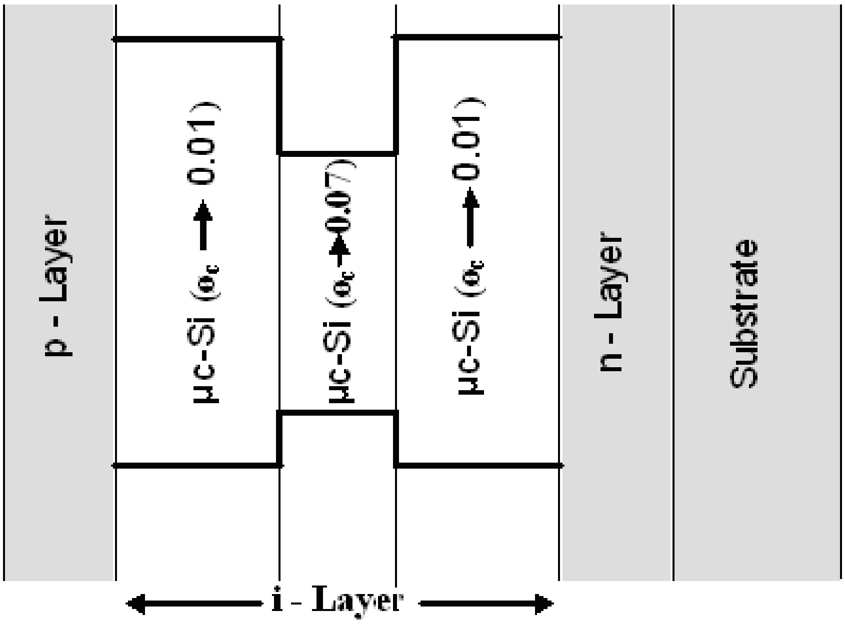

Figure 2: Schematic band diagram of the Raman crystallinity based µc-Si:H photovoltaic cell. The band offset is seen in conduction band and valence band.

Simulation Results

The theoretical simulation is done to study the dependence of electrical parameters over the "band offset". When the smaller bandgap layer (i.e. the higher ϕ_c layer) is sandwiched between two higher bandgap layers (i.e. the smaller ϕ_c layer) then the conduction band minima of the sandwiched layer lies below the conduction band minima of other two layers (See Fig. 2). The difference in the two minima is called here the "band offset". In this way, the study performed here relates the Raman crystallinity with electrical performance parameters of a thin film microcrystalline silicon photovoltaic cell.

Dependence of open circuit voltage (Voc) over band offset

It is observed that for band offset values of 0.00-0.05 the Voc remains almost constant (See Fig.3). After that Voc starts decreasing for higher band offset values. Since the higher band offset signifies higher ϕ_c layers so this study is in accordance with the experimental finding that 'Voc linearly decreases as the ϕ_c increases [5]'.

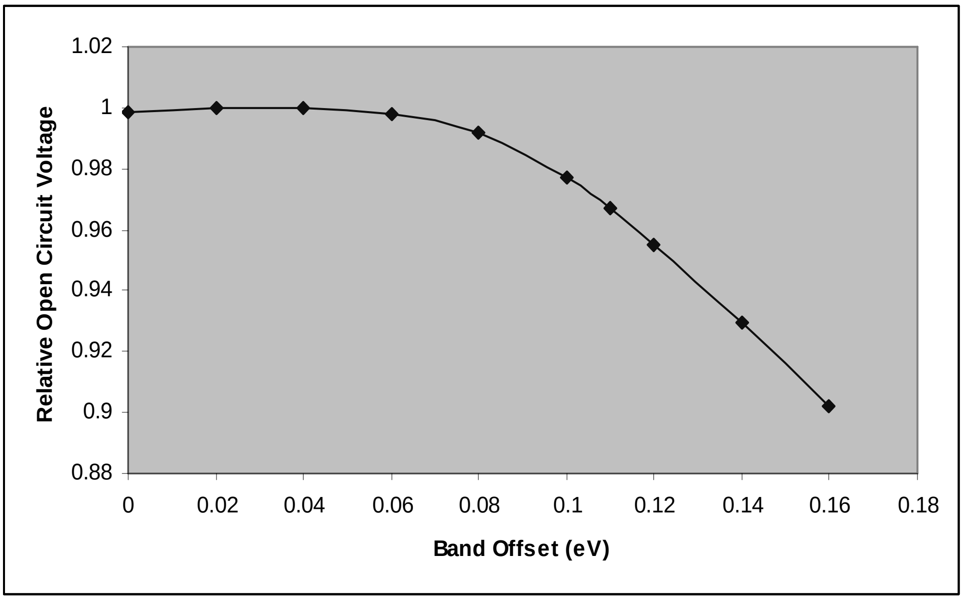

Figure 3: Variation of relative open circuit voltage with respect to band offset.

Dependence of short circuit current (Isc) over band offset

Figure (See Fig. 4) shows that the Isc is linearly increasing (with a small slope value) with band offset. This also confirms that with increasing crystalline fraction the transport properties of the material improve which, in fact, increases the short-circuit current.

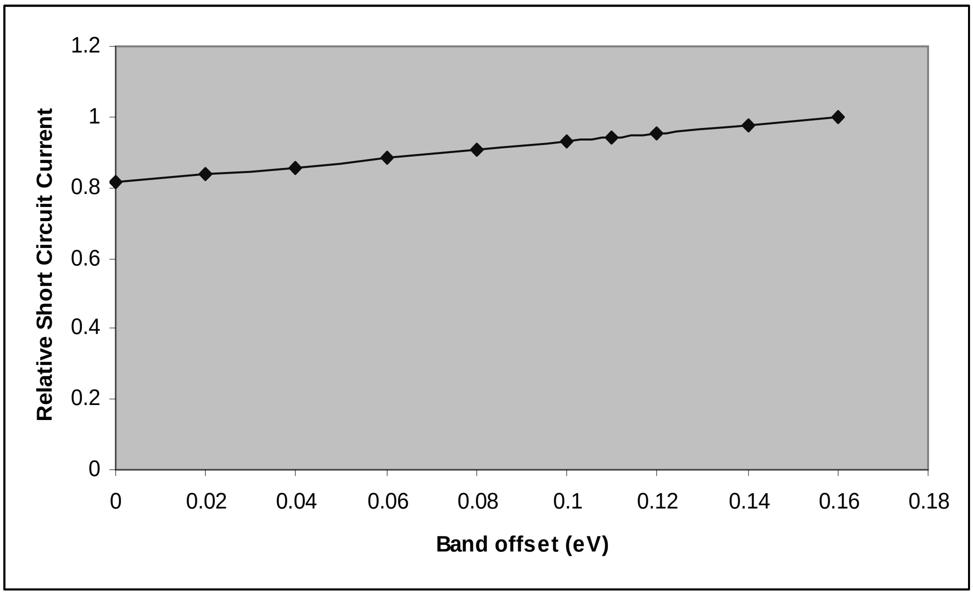

Figure 4: Variation of relative short circuit current with respect to band offset.

Dependence of fill factor(FF) over band offset

The FF shows first an increase with respect to band offset and further decreases slowly and then rapidly (See Fig. 5). As FF is a derived term from the I_{sc}, Voc and P_{max} (i.e. maximum power) it includes the trend of I_{sc} and V_{oc} variation. It is observed that V_{oc} almost remains constant for low band offset values and I_{sc} starts increasing from a minimum value at no offset. So, FF increases up to a certain limit and with the sharp decrease of V_{oc}, FF starts decreasing which shows dominance of V_{oc} in that region. This shows that higher is the ϕ_c lower will be the Voc and it will return a low FF.

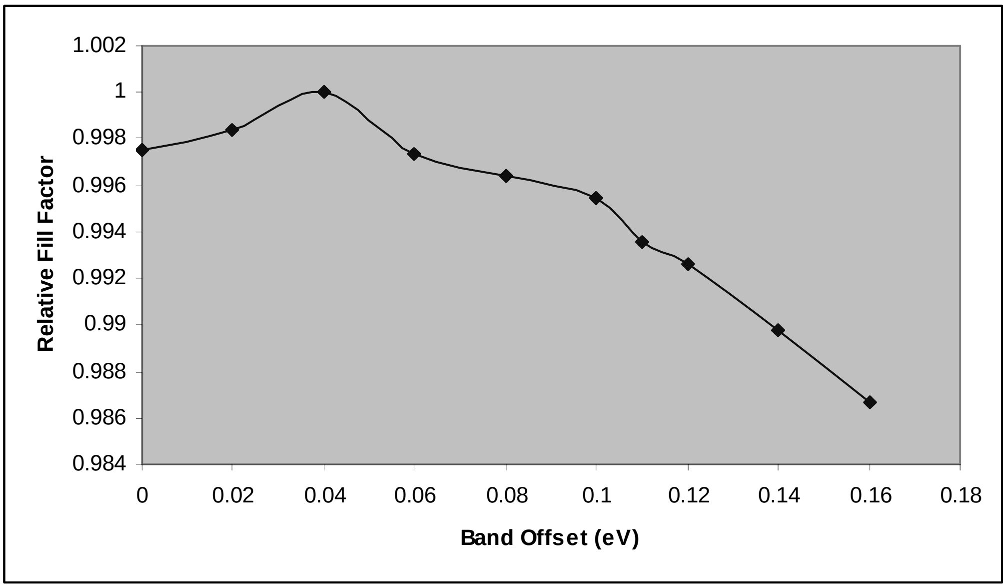

Figure 5: Variation of relative fill factor (FF) with respect to band offset.

Dependence of efficiency over band offset

The relative efficiency is plotted with respect to band offset as shown in the figure (See Fig. 6). It could be observed that the efficiency increases due insertion of quantum wells and reaches a maximum value for a band offset value of 0.11 eV and further start decreasing with respect to higher band offset values. The increase in the efficiency could be observed because of additional e-h pair generation taking place due to insertion of quantum well layers. At the specified band offset of 0.11 eV the generation seems to be dominant over the recombination.

The band offset value of 0.11 eV corresponds to a layer with $\phi_c = 0.07$ sandwiched between two layers with $\phi_c = 0.01$ as shown in figure (See Fig. 2).

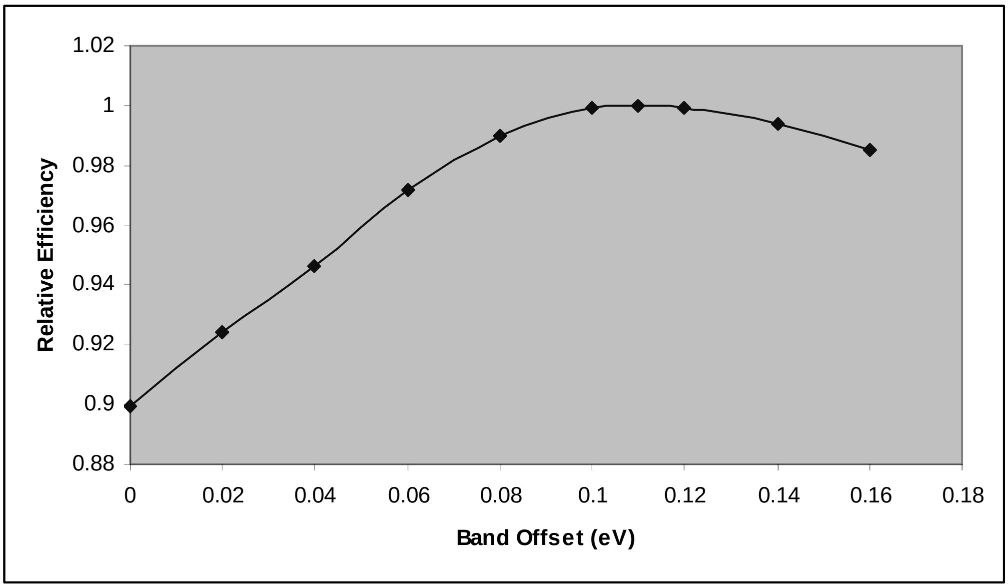

Figure 6: Variation of relative efficiency with respect to band offset.

Dependence of maximum power (P_{max}) over band offset

The maximum power delivered by a photovoltaic cell depends on the actual experimental conditions and the FF values. But while calculating theoretically the ideal situation is considered. It was observed that the quantum well insertion increases the P_{max} with respect to the band offset up to a certain limit and then it starts decreasing with increase of the band offset value (See Fig. 7).

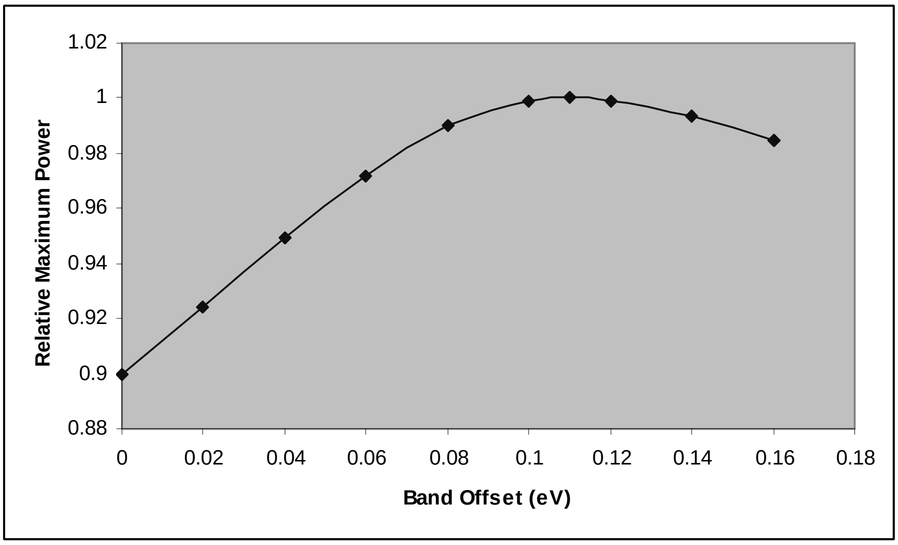

Figure 7: Variation of relative maximum power (P_{max}) with respect to band offset.

Conclusions

The effect of inserting hydrogenated microcrystalline-silicon (μc-Si:H) quantum well layers in the intrinsic region of a p-i-n configuration of thin film μc-Si:H photovoltaic cell through numerical modeling is investigated in this paper. It could be observed that insertion of quantum well layers enhances the electrical performance of μc-Si:H photovoltaic cells considerably. An increase in P_{max} and efficiency of 10% of the P_{max} and efficiency values of the μc-Si:H photovoltaic cell without quantum wells is recorded due to insertion of quantum well layers. After all it has been predicted that the electrical and overall performance of the μc-Si:H photovoltaic cells could be improved by introducing μc-Si:H quantum well layers of higher Raman crystallinity compared to the base material which acts as barrier layer.

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References

[1] Green, M. A., 2003, Third Generation Photovoltaics, Springer.
[2] Droz, C., 2003, “Thin Film Microcrystalline Silicon Layers and Solar Cells: Microstructure and Electrical Performance”, Ph.D. Thesis, University of Neuchatel, Switzerland.
[3] Anderson, N. G., 1995, “Ideal Theory of Quantum Well Solar Cells”, J. Appl. Phys., 78(3), pp. 1850-1861.
[4] Meftah, A. F., Meftah, A. M. and Belghachi, A., 2006, “Computer simulation of the a-Si:H p-i-n solar cell performance sensitivity to the free carrier’s mobilities, the capture cross sections and density of gap states”, J. Phys: Condens. Matter, 18, pp. 9435 – 9446.
[5] Droz, C., Vallat-Sauvain, E., Bailat, J., Feitknecht, L., Meier, J. and Shah, A., 2004, “Relationship between Raman crystallinity and open-circuit voltage in microcrystalline silicon solar cells”, Solar Energy Materials and Solar Cells, 81, pp. 61-71.