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INNOVATIVE STRUCTURES FOR THIN FILM CRYSTALLINE SILICON SOLAR CELLS TO GIVE HIGH EFFICIENCIES FROM LOW QUALITY SILICON

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ABSTRACT

The multilayer cell has been specifically designed with the aim to obtain high solar cell efficiency using low quality, thin film, polycrystalline silicon material. The structure consists of multiple *p*- and *n*-type silicon layers. This paper examines the tolerance of the cell design to a range of metallic impurities and grain boundaries using computer simulations. The modelled results indicate that the device can tolerate impurity concentrations up to 250 times greater than a conventional, thick solar cell. Further, the results indicate that the structure has excellent tolerance to grain boundaries present in bulk regions of the device. The simulations indicate that grain boundaries present in depletion regions will limit efficiencies considerably if the effective recombination velocity of the grain boundary approaches 10^7 cm/s. This extreme case should be largely avoided utilizing grain boundary passivation techniques during device fabrication.

INTRODUCTION

There has been considerable research effort aimed at producing low cost, thin film polycrystalline silicon solar cells [1,2]. However, to date this goal has not been reached. For polycrystalline silicon solar cells, deposited on glass, efficiencies of only about 10% have been obtained. This is insufficiently high to allow a cost competitive PV power system to be produced using such a technology. Efficiencies would need to be of the order of 15% with costs around the $1/watt mark.

The multilayer solar cell, recently developed at the UNSW [2,3], aims to overcome the barriers which at present prohibit thin polycrystalline silicon solar cells from achieving these goals. This new design, to a large extent, overcomes traditional limitations to cell performance such as low minority carrier lifetimes, and high grain boundary density. This paper will present computer simulations which investigates the tolerance of this new solar cell structure to low quality material.

The multilayer solar cell consists of multiple, horizontal, interleaved *p* and *n* -type silicon layers (see Fig. 1). Electrical contact is made to all the horizontal layers using the patented Buried Contact approach. For the multilayer cell, the aim is to apply this approach to thin silicon layers deposited on a cheap substrate such as glass. The thickness of the substrate would be typically 300 μm, while the thickness of the silicon layers in total, *W*, would be 10 to 20 μm. The spacing between the metal contacts would be of the order of 1 to 2 mm.

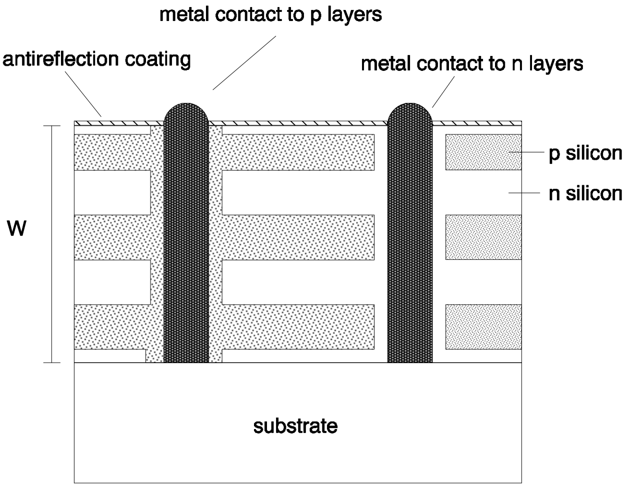

Figure 1. Multilayer solar cell structure

The basic aim of the cell design is to maximise the collection probability of photogenerated carriers throughout the device for low lifetime material or material with a high density of grain boundaries. This is achieved by the many, thin *p* and *n* layers, which ensures that a photogenerated minority carrier has only a short distance to diffuse to a collecting junction. In addition, the lifetimes in poor quality silicon is limited more by defects, grain boundaries, or contaminants rather than dopant effects. Hence, these devices can tolerate relatively high dopant concentrations (e.g., ~10^{18} cm^{-3} , approximately 100 times higher than conventional solar cell designs) without lowering the minority carrier lifetime significantly. This increase in doping means that the saturation current, arising from the bulk regions of the various layers can be lowered, allowing higher open circuit voltages to be achieved. The trade off that is incurred with this design is the increased sensitivity of the device to recombination in the depletion regions of the multiple junctions.

TOLERANCE TO IMPURITIES

In order to achieve cost effective photovoltaics it is likely that the material used will be far less pure than that used at present for silicon wafer based technologies. It is well documented that impurities in silicon, particularly metals, significantly lower the performance of silicon solar cells [4]. Shown in Figure 2a are the results of a comprehensive study by Davis et. al [4] who investigated the tolerance of conventional thick (~300 μm) single junction silicon solar cells to various impurities. Shown in Figure 2b is the performance tolerance of a thin multilayer silicon solar cell. The cell performance in both cases is represented by a normalised efficiency versus metal impurity concentration. The modelled multilayer cell consisted of a 22 μm thick cell, with 2 μm thick layers doped to 10^{18} cm^{-3}. The model used for the lifetime variation with metal impurity concentration is the same as that used for the single junction case [4]. The results were produced using a 1D analytical model of the multilayer cell taking into account Band Gap Narrowing, Auger recombination, and Junction recombination. The model uses standard material parameters for silicon in accordance with the device simulation program PC-1D [5].

The solid lines for both the single and multilayer cells are the modelled "ideal" normalised efficiencies. In their original study Davis et. al. found that certain impurities such as Cu and Fe introduced "non-ideal" components to the cells I-V characteristics [4]. That is, it was not possible to model the I-V curve of these cells with only an ideality factor *n* of unity as it was for cells with other impurities present. Instead, for these particular impurities the I-V characteristics exhibited ideality factors $n > 2$. This was attributed to "non-ideal" junction effects introduced by the formation of precipitates in the junction depletion region [4]. Hence the ideal, $n=1$ component was used to model and characterise the effect of these impurities upon cell performance to allow comparison with the cell results from other impurities. These non-ideal effects are quite dramatic and their effect can be seen for both single and multilayer cells in Figure 2a and 2b respectively (scatter plots). Although the multilayer cell is more severely affected by these "non-ideal" junction effects the multilayer cell efficiency would still be higher than a thin single junction device with similar low material quality.

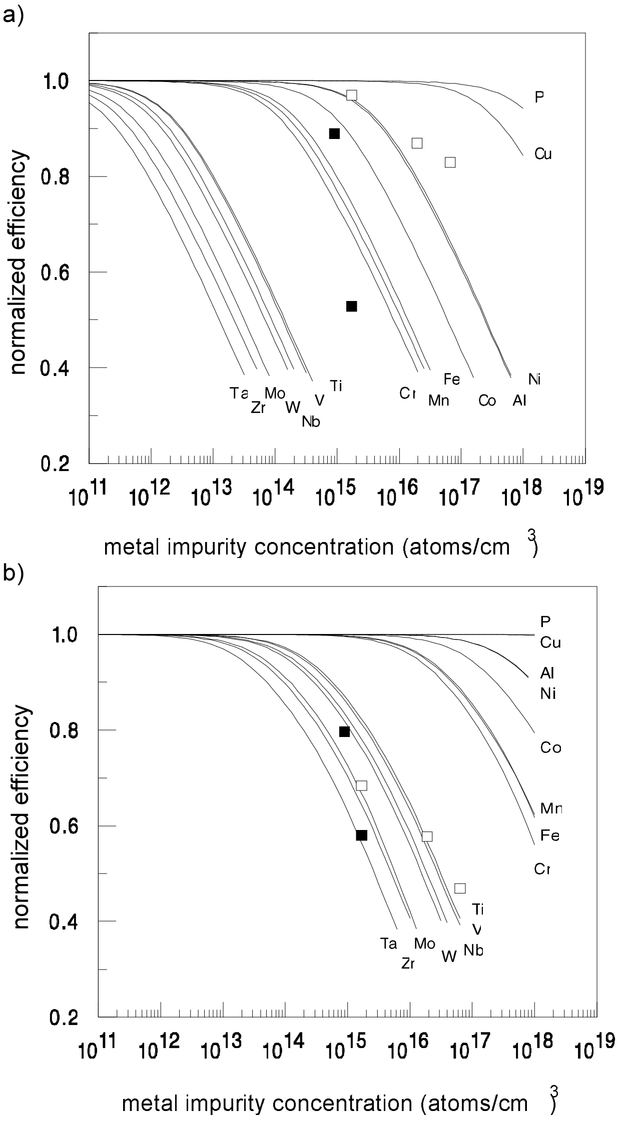

Figure 2: Normalised efficiency as a function of metal impurity concentration. Solid lines are modelled results derived from experimental data for a) a single junction cell and for b) a multilayer cell. "Non ideal' behaviour is shown by the impurities Fe (■) and Cu (□).

By comparing Figure 2a with Figure 2b (solid lines) it can be seen that the multilayer solar cell exhibits a much greater tolerance to metal impurities than the thick, single junction case. In general the decrease in solar cell performance for a multilayer solar cell for a particular impurity occurs at an impurity concentration of about 250 times greater than for the single junction case. Consider Ta for example. For the single junction case the efficiency drops to 90% when Ta is present in silicon for concentrations of approximately $3x10^{11}$ atoms/cm^3. However the multilayer cell performance is degraded to the same level when the Ta concentration is approximately $5x10^{13}$ atoms/cm^3. This is despite the additional recombination in the junction regions introduced by the multilayer approach. This is fully accounted for in the modelled results using a standard expression for recombination in a depletion region with a mid gap trap, with symmetric capture cross sections [6]. The model used here for the multilayer cell is harsher than the physically more meaningful situation of multi-level traps with energies away from mid gap. For these trap energies, junction recombination is less than the case of a trap at mid-gap. Therefore, multilayer cells could have an even better tolerance to impurities than that which is modelled here.

TOLERANCE TO GRAIN BOUNDARIES

Possibly the dominant defects present in low cost polycrystalline silicon grown on foreign substrates arise from grain boundaries. In this paper a grain boundary will be simply modelled as a plane of recombination, characterised by a recombination velocity S_g. Although this model ignores charges on the grain boundary and the subsequent band bending around the grain, these effects are considered as being secondary when considering the overall impact of grain boundaries on solar cells.

BULK EFFECTS

Horizontal Grain Boundaries

A horizontal grain boundary (HGB) in the bulk region of a solar cell can be modelled using one dimensional (1D) analytical expressions.

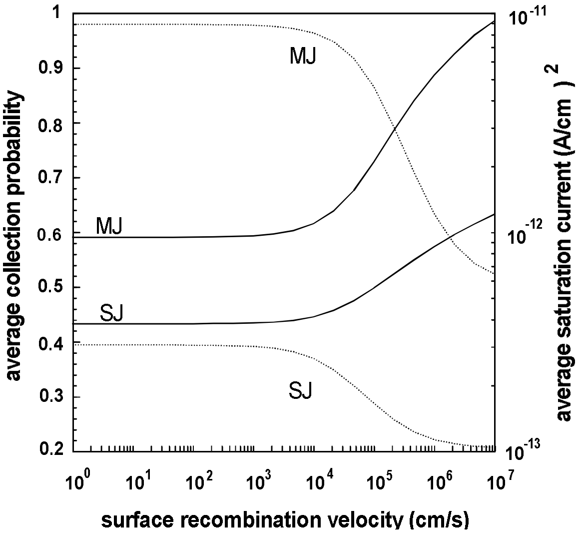

Figure 3: Tolerance of a single junction (SJ) and a multilayer (MJ) solar cell to a horizontal grain boundary in bulk regions. Average collection probability (···) and saturation current (—) are shown as a function of the grain recombination velocity.

The effect of a horizontal grain boundary is investigated here by analysing the average dark saturation current (where the average is calculated with respect to the position of the grain boundary across the width of the quasi-neutral region) and the average collection probability (the position of photogeneration is also averaged as well as the grain position). Typical results for low quality material are shown in Figure 3 for a 2 μm thick *p*-layer in a multilayer device with L ~4 μm. For comparison results are also shown for a bulk region 10 μm thick for a single junction. To compare the saturation currents 5 layers of the multilayer device are considered with only one having a grain boundary present. The doping density was 10^{18} cm^{-3} with a diffusivity of 10 cm^2/s. Regardless of the value of S_g a multilayer cell will always have a higher saturation current arising from the bulk regions than a single junction cell for the same doping. Typically the contribution to the dark saturation current from the bulk regions alone would limit open circuit voltages V_{OC} to approximately 570 to 630 mV for the multilayer case. These values are approximately kT/q less than for a single junction device. However, the collection probability for the multilayer cell is greater than 80% for $S_g < 2\times10^5$ cm/s which is about 2.5 times better than a single junction device under the same conditions.

Vertical Grain Boundaries

For a vertical grain boundary (VGB), it is necessary to use a 2 or 3 dimensional transport model. A 2D analytical solution developed for treating VGB will be discussed here. The approach used here follows that of Strollo and Vitale [7]. Basically a solution of the transport equations is found in terms of an infinite series solution for $n(x,y)$, the excess minority carrier concentration. Again in considering the results for the multilayer cell it is useful to consider a single junction case for comparison. We will consider 10 μm of *p*-type material, as above, with the multilayer cell having 2 μm layers. The grain size is 5 μm and the dopant density is as above. In this case, V_{OC} values would be limited to approximately 550 to 630 mV for the multilayer cell. These voltages are ~5 to 10% less than the single junction case. Again, however the multilayer cell has a distinct advantage in current capability with collection probabilities about 3 times that for the single junction case for such poor material.

FULL NUMERICAL SIMULATION

Vertical Grain Boundaries

Due to it's design the multilayer cell has quite good tolerance to both vertical and horizontal grain boundaries when these defects are situated in the bulk regions of the device. With low quality material the multilayer design allows good current generating capability to be maintained with moderate values for V_{OC} being achieved. In this section results are presented from a complete numerical simulation where vertical grain boundaries are present in the device. This allows the effect of grain boundaries in depletion regions to be examined. To date no completely analytical expressions have been developed for the effect of grain boundaries in depletion regions. However useful approximations for low to medium values of S_g have recently been derived [8].

Shown in Table 1 are the results for a multilayer cell using the 2D simulation package SIMUL [9]. The defect lifetime was set to 50 ns, the grain spacing was 5 μm, the device had 5 layers and was 10 μm thick, and the dopant density was set to 10^{17} cm^{-3} for the internal layers. The value of S_g was varied for three cases. The dopant density in the bulk regions and the layer widths were determined by a 1D analytical optimisation program reported elsewhere [10]. The surface recombination velocities for the front and rear surfaces were set to 2×10^4 cm/s. Lambertian light trapping was used with a perfect rear reflector.

S_g (cm/s)	0	2×10^4	10^7
J_{SC} (mA/cm^2)	38.1	37.6	30.1
V_{OC} (mV)	563.7	547	320
η (%)	16.8	15.8	6.0

Table I : Simulated cell performance for a multilayer solar cell with vertical grain boundaries with varying recombination velocities S_g.

The results indicate that the grain boundaries decrease the device performance only marginally for moderate values of $S_g \sim 10^4$ cm/s. In this case the efficiency is still above 15%. However, the results for $S_g = 10^7$ cm/s show that junction region recombination can severely limit the open circuit voltage and hence the efficiency of these devices for high values of S_g.

CONCLUSIONS

Numerical modelling has shown that the multilayer cell has good tolerance to defects. In comparison to a conventional, thick single junction cell the multilayer cell can tolerate typically up to 250 times more impurities for the same level of performance degradation. Additionally, the structure has excellent tolerance to grain boundaries present in bulk regions. For grain boundaries which cross the depletion region of a junction, efficiencies over 15% can still be obtained provided that the average surface recombination velocity of the various grains in the device is of the order of 10^4 cm/s or less.

In conclusion, from the simulations presented here, the multilayer solar cell structure appears to be capable of producing good energy conversion efficiency from low quality silicon material. This holds promise for the development of a cost effective photovoltaic technology.

ACKNOWLEDGEMENTS

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