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Electric Field Optimisation by Graded Low-Level Doping in Amorphous Silicon P-I-N Diodes

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ABSTRACT: Low-level graded doping of the intrinsic layer is applied to compensate the i-layer space-charges due to light-induced defects, and thus to optimise the electric field distribution within the i-layer of amorphous silicon thin film p-i-n solar cells. The bifacial DICE method is employed to monitor the collection in the solar cell i-layer. Numerical modelling, and recovery effects for the case of boron doping indicate that is the positive space-charge at the p-i interface that governs the electric field distribution in light-soaked p-i-n solar cells. The compensation of this positive space-charge by a linearly decreasing boron doping profile is shown to yield p-i-n solar cells with an homogeneously distributed, and on the average increased collection from the i-layer. Such optimally compensated cells show an improved conversion efficiency for red light, and have therefore the potential to be beneficially employed as bottom cells in double-stacked, identical band-gap amorphous silicon tandem solar cells.

Introduction

Amorphous silicon thin film p-i-n diodes are currently being used for a variety of large area photo-electric devices, such as solar cells, light and ionising particle detector arrays, and LED displays. The p-i-n diode structure has proven to be the most advantageous device for detector, power-conversion, and light-emitting applications. This is due to the generally low carrier mobilities and life-times in amorphous materials, a fact that requires the use of an electric field in assisting the carrier transport (drift) so as to achieve functional devices. On the other hand, an electric field is most easily created in an intrinsic (i-) layer. The electric field in the i-layer of the p-i-n diodes is not constant, but ionisable defects in the i-layer cause important distortions of the electric field, and electronic transport is correspondingly hampered. To counteract the effects of the i-layer space-charge, one may compensate the defect charges by local, low-level doping in the i-layer, and thus homogenise the electric field distribution, as proposed in [1, 2] (see Figure 1).

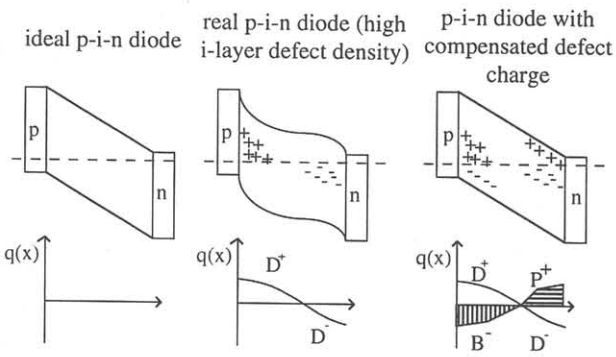

Figure 1: Band diagram (top), and space charges in different amorphous silicon p-i-n solar cells, schematically illustrating the defect space-charge compensation method. Left: ideal diode, without electric field distortion; centre: diode with the i-layer electric field distorted by charged defects, and right: diode with the defect space-charge compensated by graded doping, yielding a homogenous electric field distribution.

In the thick i-layer of detector devices (5-100 μm), the magnitude of the i-layer space-charge determines the external bias voltage required to fully extend the electric field over the whole i-layer (depletion). By compensation of an assumed homogeneous, positive i-layer space-charge with low-level boron doping in the i-layer, an experimental study [1] was successful in homogenising the electric field, and lowering the depletion voltage in 5 μm thick p-i-n detectors.

In thin solar cell devices only a fixed internal barrier voltage is available to drive the carrier collection; the minimum value of the electric field required for transport limits thus the maximal solar cell thickness (typical i-layer thicknesses are < 0.5 μm). Further, under light-exposure the defect density is largely increased through the light-induced degradation effect to a range of 10^{16}-10^{17}cm^{-3} (Staebler-Wronski-Effect). These defects not only reduce the solar cell performance by acting as recombination centres, but again they significantly distort the i-layer electric field, and thus cause additional collection losses. Compensation of this defect space-charge, as proposed in [2], would allow to improve the degraded state performance of a-Si:H solar cells without an actual reduction of the density of light-induced defects. Previous experimental implementations of i-layer compensation did not result in improved a-Si:H solar cells [e.g. 3]. But in the present work, we demonstrate that there is indeed a considerable potential for space-charge compensation in thin a-Si:H solar cells, if one considers in detail the shape of the i-layer space-charge distribution, and also the specific require-

ments for the conversion of different illumination spectra.

Electric field optimisation in p-i-n solar cells

To compensate the detrimental space-charge effects of light-induced defects, and thus to optimise the electric field distribution in a-Si:H p-i-n solar cells in the light-soaked state, one has first to know the polarity and exact profile of the i-layer space-charge. The charging of the i-layer defects follows in principle the sign of the local majority carriers (Figure 1, centre). Thus, the defects tend to charge positively towards the p-side, and negatively towards the n-side. This yields a concentration of the electric field towards the interfaces, and a low electric field in the centre of the i-layer. There are, however, several indications that it is the positive space-charge that dominates the i-layer electric field:

Figure 3, top, shows the i-layer collection profile before and after light-soaking in a standard p-i-n solar cell. The collection at the p-side is found to remain very high after light-soaking, whereas the collection strongly degrades towards the n-side. The stable p-side collection can be understood as the effect of positively charged defects that concentrate the electric field at the p-i interface, and thereby balance the degradation induced lifetime losses. As the collection reaches its lowest value right at the n-i interface, there is, on the other hand, no indication of any substantial negative n-side space-charge.

Also the differing degradation behaviour of p-i-n cells with low-level boron or phosphorus i-layer doping indicates a dominant positive defect charge [4]: During light-soaking, solar cells with low-level boron doping are generally found to exhibit increasing collection effects (recovery). These effects can only be understood as the result of positive charged defects that gradually counteract the electric field shift brought about by the boron-doping (see e.g. the boron doped cells of Figure 3, middle and bottom). For phosphorus-doping of the i-layer, on the other hand, no similar recovery effects, which would indicate the presence of negative defect space-charges, are observed [4].

Numerical modelling (Figure 2) can explain an asymmetric defect charging through a difference in the band-mobilities of holes and electrons: Since both carriers must support the same photo-current, the lower value of hole mobility results in the hole concentration in the i-layer being on an average higher than the electron concentration. This leads to a much larger positive defect charge, gradually tailing far into the centre of the i-layer, and dominating the whole electric field distribution. This, in its turn, leads to a concentration of the electric field at the p-i interface, and a low electric field region in the whole back half of the i-layer.

In line with the above discussion, the compensation of the defect space-charge in p-i-n solar cells requires the application of boron doping that gradually decreases from the p-i interface. Figure 3 shows the measured collection in p-i-n cells with a linearly decreasing boron doping extending over 2/3 of the i-layer thickness. Cells with two different boron doping strengths are compared to an undoped reference cell. Towards the p-side, the boron doped cells show strongly decreased

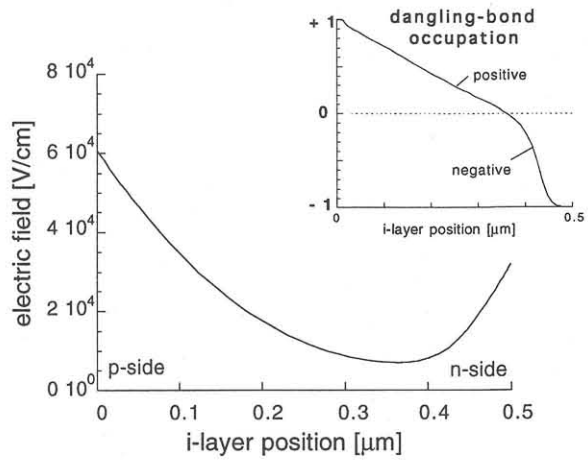

Figure 2: Numerically simulated dangling-bond occupation (inset) and electric field as a function of the i-layer position, under illumination with homogeneously absorbed (red) light. The external voltage is 0V. The total density of amphoteric dangling-bonds is $2 \cdot 10^{16}$ cm^{-3} (constant in the i-layer), electron and hole mobilities are 10 and 1 cm^2/Vs, respectively. Detailed modelling parameters are given elsewhere [5].

collection in the annealed state, while after light-soaking, the creation of the positive defect space-charge causes a rising collection, as discussed. At the n-side of the i-layer, the collection is in general increased by the electric field shift induced by the boron doping. For the cells with a p-side boron concentration of 1 ppm, the collection is completely recovered at the p-i interface, and the degraded state collection is now high and uniform within the whole i-layer, indicating the successful compensation of the positive defect space-charge by the graded boron doping. In the cell with 2 ppm p-side boron concentration, the collection towards the p-side is on the other hand not recovered after degradation. Thus, in this cell, the doping can be considered as being too strong: it can not be balanced by the positive charge of the light-induced defects (over-compensation).

Figure 4 compares the performance of the differently compensated p-i-n solar cells of Figure 3, before and after light-soaking. For the conversion of the full sun spectrum (AM 1.5, left), boron doping reduces the annealed state efficiency (low p-side collection). After light-soaking, the efficiencies of the graded boron doped cells remain more stable, due to partial collection recovery. But despite its degraded-state collection profile which is more homogeneously distributed and on the average higher, the 1 ppm doped cell (Figure 3, middle) still shows worse overall performance than the undoped cell. This is because the non-uniform AM1.5 generation profile requires high collection above all in the p-i interface region, as is already intrinsically the case in undoped p-i-n cells after light-soaking (Figure 3, top).

A different situation is encountered in the bottom cell of double-stacked tandem cell (these tandem solar cells are among the structures that yield today's highest stabilised a-Si:H solar cell efficiencies): such a bottom cell is required to convert a more homogenous generation profile, because the high initial generation peak of the AM1.5 spectrum is already absorbed in the first cell of the tandem cell. In Figure 4, right, the com-

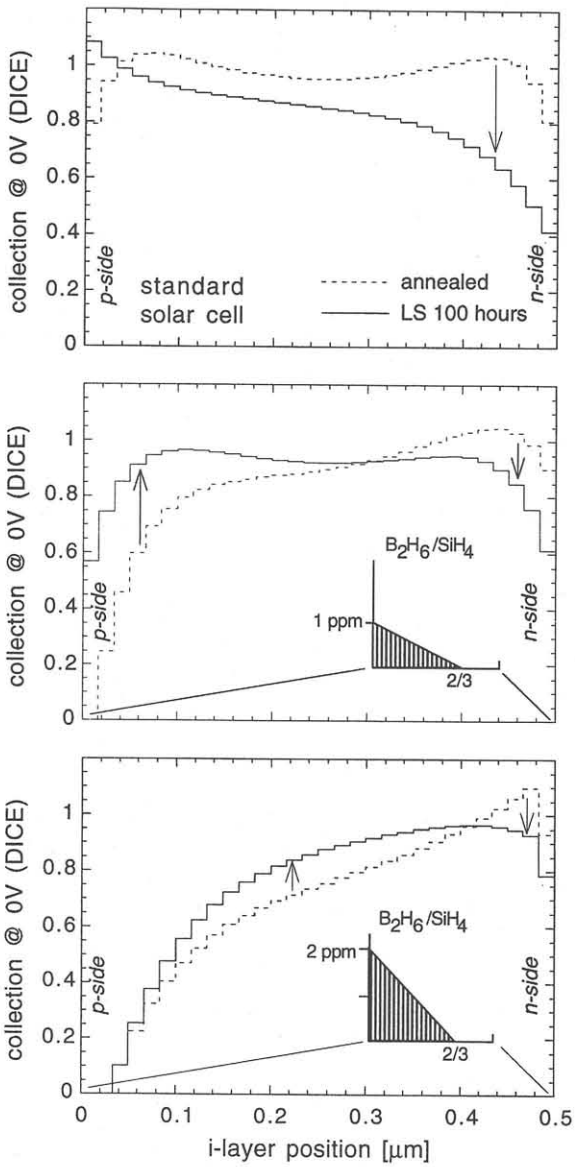

Figure 3: Bifacial DICE collection probability profiles [5] in graded boron doped p-i-n solar cells, at 0 V, in the annealed state, and after 100 hours of light-soaking. The graded doping profiles are linearly decreasing form the p-i interface over 2/3 of the i-layer, with different initial doping concentrations (undoped(top), 1 ppm (middle), 2 ppm (bottom)).

pensated cells are compared under filtered AM1.5 spectrum, i.e. red light, as would prevail in the second, bottom cell of a tandem cell. For this illumination spectrum, which attaches equal weight to the collection from all parts of the i-layer, the 1 ppm "optimally" boron doped cell now shows an increased degraded state performance over the undoped cell, and thus demonstrates for the first time the capability of the defect charge compensation method to improve the stable conversion efficiency of an amorphous silicon p-i-n solar cell device. The relative increase in efficiency, for the degraded state, is for red light conversion approx. 20 %.

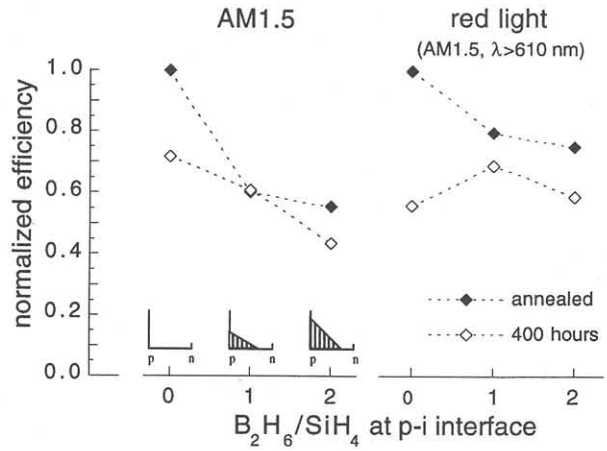

Figure 4: Solar cell efficiency of graded boron doped p-i-n solar cells (same as in Figure 3), for illumination with the full AM1.5 spectrum (left) and with the long wavelength part (>610 nm) of the AM1.5 spectrum, in the annealed state, and after 400 hours of light-soaking. The solar cell efficiencies are for each illumination normalised with respect to the annealed state efficiency of the undoped cell. The absolute annealed state AM1.5 efficiency of the undoped cell is 7.5 %.

Conclusions

After the creation of light-induced defects, the collection in a-Si:H p-i-n solar cells is found to be governed by an electric field distortion due to positively charged defects. Through linearly decreasing low-level boron doping of the i-layer, the electric field distortion of the light-induced defects was compensated, yielding p-i-n solar cells with a more uniformly distributed, and on the average increased collection in the i-layer. These cells have the potential to be beneficially employed as red light converting bottom cells of a-Si:H double-stacked tandem solar cells: An increase in the absolute efficiency of tandem solar cells of approx. 1 % could thereby be hoped for.

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