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Why is the Open-Circuit Voltage of Crystalline Si Solar Cells so Critically Dependent on Emitter- and Base-Doping?

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Why is the Open-Circuit Voltage of Crystalline Si Solar Cells so Critically Dependent on Emitter-and Base-Doping?

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ABSTRACT

This paper discusses the critical dependence of the open-circuit voltage (V_{OC}) of crystalline Si solar cells on the emitter and base doping levels. Contrary to conventional models that try to ascribe V_{OC}-limitations to (independent) bulk and surface recombination losses, we suggest, as the dominant mechanism, the formation of a compensated "buffer layer" that is formed as phosphorus is diffused into the p-type (boron-doped) base. The only purpose of the base doping is to optimize the buffer layer. Our calculations show that this model makes the achievement of high V_{OC} and good carrier collection (J_{SC}, FF) interdependent. Sanyo's 'HIT' solar cells are an example of a different method to implement this buffer layer concept for crystalline Si solar cells. The general principle for a V_{OC}-enhancing buffer layer relies on using materials with high lifetimes and low carrier mobilities that are capable of reducing surface or junction recombination by reducing the flow of carriers into this loss-pathway.

INTRODUCTION

The optimization of diffusion-processed crystalline Si solar cells faces the dilemma that the base-doping has to be limited to levels corresponding to resistivities greater a few tenths Ωcm [1]. On the other hand, for cells using a single diffusion phosphorus diffusion step, the doping level of the emitter has to be higher than required for optimum device performance in order to assure ohmic contacts to the screen-printed metal contact grids used on the cells. It is hard, but, within limits, possible, to reconcile this behavior using established solar cell models [2]. Such analyses (have to!) account for the improvements of V_{OC} with increased base doping in terms of reduced dark saturation currents (recombination) in the base. This conclusion is in conflict with the observation that excessive base-doping decreases carrier collection (J_{SC} and/or FF) [1], i.e., appears to enhance recombination in the base. This discrepancy, we suggest, can only be overcome if one is willing to us to question the validity of the prevailing recombination-loss based solar cell models.

In a previous paper [3], we have suggested that it is in principle possible to enhance V_{OC} by inserting a "resistive," low carrier mobility buffer layer near the junction. We also reviewed a number of cell preparation schemes where we believed that this concept had been experimentally realized. The use of resistive layers is often thought to be undesirable because they introduce series resistance losses into the solar cell. However, we argued that a carefully optimized limited additional series resistance can be tolerated and allows maximizing cell performance. This has essentially the effect of shifting the current-voltage [*log*I(V)] dependence "to the right" along the voltage axis, while traditional thinking always looks for improvement by shifting *log*I(V) down to lower current values. The behavior suggested by us is indeed experimentally observed [1,2, and many other examples in ref. 4]. It is of interest to note that frequently a shift of *log*I(V) to the right, i.e., to higher voltage values, is accompanied by a decrease in the steepness of the *log*I(V) dependence, also reported in Refs. 1 and 2. Traditional considerations would suggest that such flattening of the *log*I(V) dependence would also indicate lower device performance (increase in diode quality factor corresponding to increased recombination losses). However, many examples have been reviewed in Ref. 4 suggesting that a correlation between a diode quality factor and solar cell performance cannot be substantiated experimentally.

PROPOSED MECHANISM

For the investigation of the potential benefit of buffer layers seen as separating the high recombination regions of contacts from the base or absorber layer, we used an analytically solvable method for the determination of "best cases," and thus show the maximum achievable beneficial effects. The approach is based upon:

- Determination/estimation of best case V_{OC} in ideal diffusion diodes as an upper limit of V_{OC} behavior in non-ideal (real) diodes.

- Calculation of local minority carrier concentration m(x) (in $0 \leq x \leq d$) in a homogeneous (Fig. 1a) as well as in an inhomogeneous absorber (Fig. 1b) via 1-dimensional steady-state continuity equation (exclusively diffusion currents) under exp($-\alpha x$) generation with boundary conditions at x=0 and x=d resulting from surface recombination with velocities $S_o=S(x=0)$, and $S_d=S(x=d)$ as a function of layer parameters.

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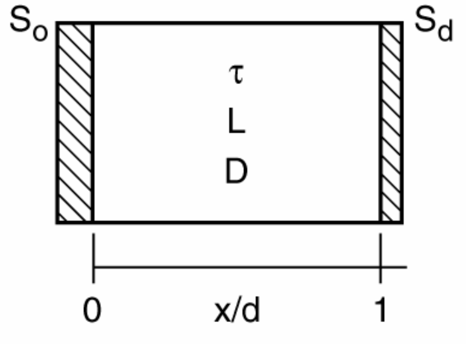

Fig 1a: Schematic of "solar cell" used for calculation.

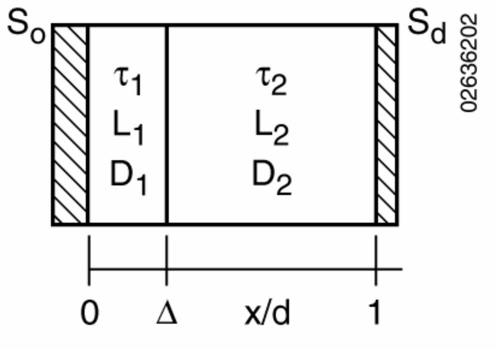

Fig 1b: Schematic of "solar cell" with a buffer layer of thickness Δ

- The resulting local minority-carrier distribution reads:

$$m_i(x) = A_i \exp[x/L_{m,i}] + B \exp[-x/L_{m,i}] + [(g_o\tau_i)/(1-(\alpha L_{m,i})^2)] \exp(-\alpha x) \qquad (1)$$

(with A_i, B_i being dependent in a complex manner on $L_{m,i}$, τ_i, α, S_o, S_d, Δ, and d;

the solution $\alpha L=1$ is excluded for reasons of numerical instability; i=1,2, with i=1 for $0\leq x\leq \Delta$ and i=2 for $\Delta<x\leq d$).

- The translation of local minority excess carrier densities $m_{phot}(x)$ into the chemical potential and thus the maximum open-circuit voltage V_{OC} is performed via Boltzmann-approximation and the assumption that photogenerated majorities M_{phot} are small compared with their thermal equilibrium concentration M_o:

  $$\mu(x) = kT \ln[(m_o+m_{phot})(M_o+M_{phot})/m_oM_o] \approx kT \ln[(m_o+m_{phot})/m_o] \qquad (2)$$

  where $\mu(x)$ is an ambiguous and monotonous function of m(x).

In Ref. 3 we showed that the introduction of an absorber layers with decreased μ and unaffected τ increases the minority-carrier concentration m(x) continuously with decreasing mobility, or increasing buffer thickness Δ, which means displacing the surface region (at x=0) with its high recombination rate (in terms of diffusion lengths) as far as possible from the junction $x(m_{max})$. Formally, this can be achieved by L_m->0 (except with $x(m_{max})$-> ∞). The introduction of buffer layers with unaffected L and decreased τ (i.e., a defect layer) results in an optimum position for maximum excess-carrier density and maximum chemical potential as well. However, such a layer has a tendency to also decrease m(x) near the junction making it a less desirable candidate in comparison with a layer having a reduced carrier mobility.

The operation of solar cells at maximum power point (mpp) conditions requires the extraction of nearly the entire I_{SC} at nearly V_{OC}, which means that the amount of "internally" created (photo-induced) chemical potential $\Delta\mu_{transp.}$ necessary for the transport of minorities to the contacts has to be minimized; because of the introduction of low-mobility buffer layers at current densities according to mpp, some of the internal chemical potential has to be consumed for transport. Our calculations − which due to the large number of parameters have been numerically run only for a limited number of different variables − show that using a buffer layer with reduced mobility the balance of the benefit in V_{OC} equals or is smaller than the losses at mpp.

From an experimental device optimization point, this type of buffer layer leads to a regime in which J_{SC} and fill factor are "traded" for V_{OC}, that is a common observation in many types of cells, and, as an interesting side observation, not necessarily sensitive to the V_{OC}-, J_{SC}-, or efficiency levels of the cell, suggesting that this mechanism is operable whether or not cells are optimized as much as possible. We suggest that the formation of a low-mobility compensated buffer layer that automatically forms in diffusion processed Si would be responsible for this mechanism. If the V_{OC}-enhancing buffer layer can be produced by other means, for example, in "HIT" solar cells manufactured by Sanyo [5], the doping requirements for the cell base become much relaxed. Indeed, Sanyo is using n-type wafers to produce the HIT cells. Sanyo has highlighted the improved temperature coefficients that give HIT cells an additional advantage over diffused Si cells, without being able to explain what would be the cause for this behavior. We suggest that the temperature dependence of buffer layer properties, not bulk Si wafer properties as is conventionally assumed, will account for this difference.

Phenomena observed in other types of Si solar cells can also be explained by our postulation that the presence of a low-mobility buffer layer is required to obtain high V_{OC}-values. A classical example are MIS solar cells. Conventional explanations suggest that the major benefit comes from a passivation effect of the Schottky barrier interface by the oxide layer. The dilemma with this explanation is that it is well known that one or two mono-layers of a suitable thermal oxide provides near perfect passivation of the silicon surface. On the other hand, in order to improve V_{OC} of an MIS cell (in comparison to V_{OC}-values obtainable in a Schottky barrier device) the oxide has to been grown so thick as to almost impede electric transport through it (sometimes referred to approaching the "tunneling limit"). Another example are the "firing through silicon nitride" cells [6]. The dilemma in understanding the benefits of this process is that while one would expect the benefits to come from surface passivation, cell analyses suggest that bulk passivation may be the most responsible mechanism. We suggest to consider the nitride layer as part of the buffer, and suggest that the physical presence of this layer, rather than a bulk passivation resulting from the application of this layer, will be required in order to enhance V_{OC}.

The latter schemes are similar to the technique of using transparent conductor (TCO) bilayers for contacting $CuInSe_2$- and CdTe-based thin-film solar cells. A TCO bilayer with the resistive surface allows thinning and even elimination of the CdS heterojunction emitter layer without a loss of V_{OC} [7,8]. It is of interest to note that for both $CuInSe_2$- and CdTe-based solar cells the best results for cells with very thin or no CdS layers are achieved when the resistivity of the resistive TCO layers is about 10^4 Ωcm [7,8]; typically these layers are a few tens of nanometers thick. It is also of interest to note that the benefit s of the buffer layer could not be broken down systematically into surface and bulk recombination losses [7]. We postulate that traditional loss analyses of Si solar cells (modeling analyses separating surface and bulk losses) would not hold up to systematic investigations (experimental changes causing changes only in either surface or bulk losses) , but are merely two-parameter fits without physical relevance to account for the overall losses.

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