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MATERIAL REQUIREMENTS FOR BUFFER LAYERS USED TO OBTAIN SOLAR CELLS WITH HIGH OPEN CIRCUIT VOLTAGES

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ABSTRACT

This paper discusses material requirements for junction layers needed to obtain solar cells with highest possible open-circuit voltages (V_{OC}). In a typical a-Si:H-based "p/i/n" solar cell, this includes the transparent conductive oxide (TCO) contact layer, the p-layer, a "buffer layer" inserted at the p/i interface, and the surface portion of the intrinsic layer. In HIT-cells, the i-layer between (n-type) c-Si and (p-type) a-Si:H may be regarded as the buffer. Our suggestion to obtain high values of V_{OC} 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. We provide a general calculation that supports these approaches and can explain why these schemes are beneficial for all solar cells.

INTRODUCTION

The open-circuit voltages of amorphous silicon solar cells are limited to values of about 1.0V. There is an ongoing discussion in the literature whether this limitation arises from bulk properties of the intrinsic layer (Urbach edges), junction recombination, or from the properties of the p- and n-layers used (built-in potential) [1]. Researchers have found that the optimization of junction layers in solar cells is extremely critical and interactive; i.e., in order to reach highest cell performance, layers have to be constantly reoptimized to achieve the best performance, or in production, yield. A unique combination of optimum materials for maximum device performance does not exist. Rather, the interactive nature of the optimization process suggests that, in many instances, materials with less than ideal properties have to be used to achieve maximum device performance.

In this paper, we argue that profiles of quasi-Fermi levels in each device have to be adjusted for optimum performance. In devices that have very high gradients of the quasi Fermilevel, which to some extent emerges in the profile of the electric field, V_{OC} is reduced in comparison with devices that have an optimized field or quasi-Fermi-level profile. The profiling of these gradients is best accomplished by using layers with low recombination (= high lifetimes) by adjusting the transport properties or carrier mobilities of these layers. Similar arguments apply to the Fermi-level or electrical-field gradients near the i/n interface.

The layers suggested to be used for V_{OC} enhancement can be rather resistive because of reduced carrier mobilities. The use of resistive layers is often thought to be undesirable because they introduce series resistance losses into the solar cell. However, we argue that a carefully optimized limited additional series resistance can be tolerated and allows maximizing cell performance. We will review some of the experimental procedures used to optimize V_{OC}, and argue that these observations support our claim and calculate in a generic (nonmaterial specific) way the benefits of using these layers.

REVIEW OF EXPERIMENTAL RESULTS

Doping of the Emitter Layer

We briefly review three experimental observations how of these buffer layers are used in practice. The first observation relates to doping of the emitter a-Si:H p/i/n cell. Dawson et al. [2] reported that cells made with the least doped (lower conductivity activation energy) a-Si:H p-layers exhibit highest voltages. It is noteworthy that the introduction of carbon alloying for the p layer, which usually makes it easier to obtain high V_{OC}, has the tendency to reduce the electron mobility and introduces a barrier for electron back diffusion. Carbon-alloyed p-layers are typically one to four orders of magnitude more resistive and are known to possess lower electron mobilities compared to boron-doped a-Si:H. A similar observation is true for crystalline Si. Here, V_{OC} values could be obtained when a lower phosphorous-doped emitter has been used. The practical requirements are to "overdope" the emitter to allow ohmic contacts between the emitter and the screen-printed collector grids on the cells. Conventional wisdom suggests that overdoping causes Auger recombination losses. We suggest that our concept may be able provide an alternative explanation for voltage loss in all solar cells whenever the emitter is doped "too much."

Use of TCO Bilayer with High Surface Resistivity

In a-Si:H and other thin-film solar cells, buffer layers are empirically used to enhance V_{OC}. It is often possible to enhance V_{OC} by using bilayer TCO films for the contact. This often allows the traditional emitter layer to be thinned without loss of V_{OC}. An example of this being achieved for a-Si solar cells was reported by Yoshida et al. [3]. For $CuInSe_2$- and CdTe-based solar cells, buffer layers have been used in production of PV modules [4]. Here, the TCO bilayer with the resistive surface allows thinning and even elimination of the CdS heterojunction emitter layer without a loss of V_{OC} [5,6]. We note that the concept of using a TCO bilayer can often be beneficial for solar cells made from materials with completely different chemistries. We therefore postulate a general mechanism (in addition to the mechanisms suggested traditionally such as "cleaning up" the interface, avoiding unwanted reactions near the interface, and suppressing diffusion of chemical species) that makes the use of these bilayer TCOs advantageous. 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 [4,5]; typically these layers are a few tens of nanometers thick.

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Use of "Resistive" Buffer Layers between the Emitter and Absorber Layer

There are many examples in which actual cell structures contain such a "buffer" layer. For a-Si cells, thin undoped a-SiC:H buffer layers, sometimes graded in carbon content, are inserted between the p- and the i-layer of p/i/n solar cells [7]. Another example is the HIT solar cell manufactured by Sanyo [8]. This cell is a crystalline-Si solar cell where the emitter and collector layers are deposited using a-Si techniques. To optimize V_{OC} in this type of cell, thin (<10-nm thick) intrinsic amorphous silicon layers are inserted between the wafer and the p-type emitter or n-type collector. Sanyo proposed that these layers are beneficial because they passivate or improve the quality of the junction. We interpret this approach in terms of using the buffer layers to control the recombination of minority carriers in the doped a-Si:H or μc-Si:H emitter. It is also noteworthy that a buffer layer is unknowingly used in c-Si solar cells prepared by phosphorus diffusion. It is well known that V_{OC} of such cells is sensitive to the doping level of the emitter and the base. Best results are typically obtained with wafers that are boron-doped in the range of 0.1 to 2 Ωcm [9]. We state that most conventional cell analyses may have misdiagnosed this doping requirement of the wafer (base). We suggest that the requirement is dictated by the need to create an appropriate buffer layer between emitter and base layer that limits the recombination of minority carriers in the emitter by providing a barrier for their movement. In c-Si solar cells, this buffer layer is provided by a compensated Si layer that is automatically formed during the phosphorus-diffusion step.

CALCULATION

Because a "resistive," gradual buffer layer appears to enhance V_{OC} in many different types of solar cells with different chemistry, interface, and interface diffusive properties, we offer below some generic (not material specific) calculations that may explain the need for the presence of such layers. Numerically, we have considered several types of buffer layers suitable to prevent photoexcited carriers to move to contacts (low-lifetime regions) and recombine there.

Buffer Layer Scenarios:

Type (1) - Buffer layer with band alignment ($\Delta E_C=0$, $\Delta E_V=0$) to the absorber and lower minority and ambipolar carrier diffusion length $L_m=(D_m\tau_m)^{1/2}$ than in the absorber; the reduction of L_m is due exclusively to lower diffusion constant D_m, as suggested by one of the authors previously [10]; this means lower mobility μ_m too, and we assume that the lifetime τ_m is unaffected.

Type (2) - Buffer layer like in (1), however the reduction in L_m results exclusively from a drop in life time τ_m, while D_m and μ_m are unaffected (i.e., a defective layer).

Type (3) - Buffer layer without band alignment for minorities and with aligning band for the majorities of which the main function consists in blocking minority motion to the contact by a barrier (i.e., back diffusion of electrons in a-Si:H p/i/ns prevented by the carbonized window) and allowing for reasonable majority flow to the contact (most probable case in real approaches).

Method

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 try 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.

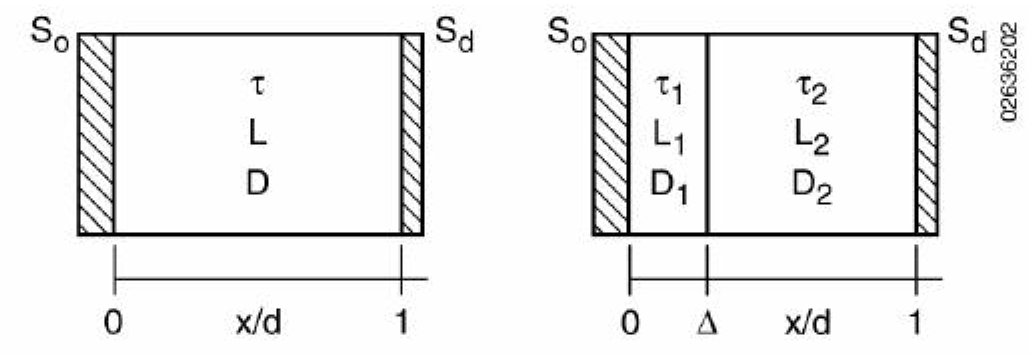

Fig 1a: Schematic of "solar cell" used for calculation.

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).

- The pn-junction, in which like in the ideal-diode approach, we neglect recombination due to geometrical relations ($w_{jct} << d$).

Results of the Calculation

The introduction of type (1)-buffer layers (decreased μ, 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 $x(m_{max})$-> ∞). Fig. 2a shows the results from introducing effects of a type (1) buffer layer (decreased L, unaffected τ) into a homogenous absorber. The introduction of buffer layers of type (2) (unaffected L, decreased τ), shown in Fig. 2b., results in an optimum position for maximum excess-carrier density and maximum chemical potential as well. Each of these magnitudes strongly depend on the parameters in the individual layers such as diffusion lengths and coefficients, life times, and on thicknesses Δ, d, surface recombination velocities S_o, S_d, and on absorption coefficient α as well. By appropriate adjustment of $L_{m,1}/L_{m,2}$, Δ, and of the position of the junction, an increase in V_{OC} is achieved. Qualitatively, for the composed structures

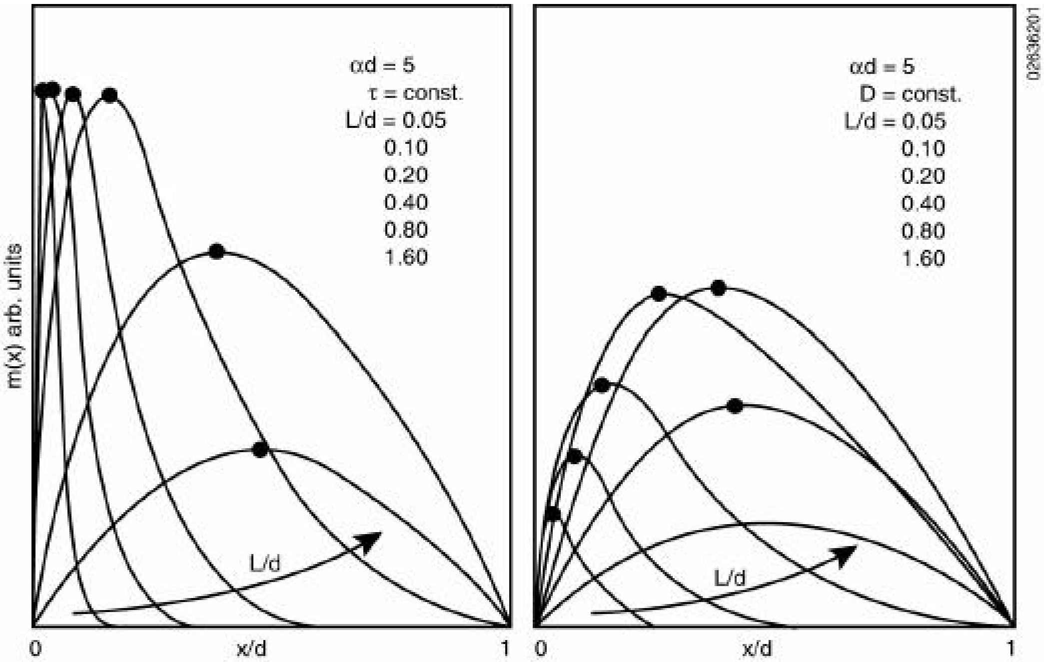

Fig. 2a: Minority-carrier concentration in homogenous structure for various L/d ratios (type (1), τ = const. condition).

Fig. 2b: Minority-carrier concentration in homogeneous structure for various L/d ratios (type (2), $D \sim \mu$ = const. condition).

(buffer/absorber) the profiles of minority carriers m(x) look similar to those in Figs. 2a, b; the introduction of buffer layers with lower L_m shifts m(x) analogous to a decrease of L/d.

While the effects of type (3) buffer layers could not be calculated analytically, this type of buffer, with majority-band alignment and barriers for minorities, will provide an optimum strategy for the prevention of the motion of photoexcited minorities into the "wrong direction" and their recombination at the interface, provided that type (3) buffer layers exhibit values of minority-carrier lifetimes at least as high as those of the absorber. Interestingly, this buffer layers also serve as an optical window with higher band gap, and consequently, lower refractive index for increased coupling of light into the absorber.

Consequences for the Operation of Buffer Layer Cells at Mpp

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 for buffer layers of type (1), 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 sensitive to the V_{OC}, J_{SC}, or efficiency level of the cell.

As the buffers of type (2) show even less V_{OC} increase versus the selection of optimum geometrical and electronic parameters the benefit with respect to output power generally seems even to be negative.

The analysis of type (3) buffer layer effects cannot be accomplished in the framework of this approach which we restrict to analytical solutions. Nevertheless, the general effect of an ideal barrier for minority carriers and the simultaneously assumed unaffected majority transport to be beneficial for V_{OC} is convincingly obvious.

CONCLUSIONS

We have argued that buffer layers play an important part in optimizing V_{OC} in all types of solar cells. The benefit of the buffer layers arises because they essentially remove the contact, which has high minority-carrier recombination losses from the absorber or base layer. Our approach appears to indicate that the best scheme is to employ a type (3) buffer layer (wider bandgap material without band alignment for minorities and with aligning band for the majorities). A secondary benefit of this type of layers, when used near the top of a cell, is optical enhancement because of reduced absorption and reflection losses. Type 1 buffer layers may offer some opportunity for V_{OC} optimization, but generally lead to losses in J_{SC} and FF, which experimentally have to be traded off carefully. Type (2) buffer layers offer no practical possibilities to increase cell efficiency.

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