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Original

Design of thin film solar cells based on a unified simple analytical model

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Abstract

Polycrystalline thin film solar cells made with absorber materials such as CdTe, CIGS, CZTS and metalorganic halides (perovskites) are currently important alternatives for the silicon solar cell technology, which still dominates the photovoltaic market. Then, it is important to have tools which can be used to design this kind of solar cells. For this purpose, we have developed a unified simple analytical model that can be applied to thin film solar cells. The model is based on the basic physics of hetero-junction devices, but it takes into consideration that the space charge region can extend along the major part of the cell length, particularly for very thin cells, causing important effects that typically are not observed in conventional junction devices. Photo-generated carriers are collected by electric field-drift instead of diffusion, and simultaneously strong recombination at this region may dominate the electrical *I–V* characteristic of the cell. Since the space-charge region width varies with the applied voltage, the illumination current density and the saturation dark current density are no longer independent of the voltage as is assumed for conventional solar cells. When the model is applied to CIS and CdTe solar cells as examples, it is found that it is possible to design very thin film solar cells (absorber less than 1 μm thick) with high efficiencies, whenever the recombination velocity at the back surface becomes small (10^2 cm/s), instead of the high recombination velocities present at ohmic contacts (10^7 cm/s). This fact implies the cost reduction of thin film solar cells by reducing absorber material thickness, and therefore it poses a challenge to develop deposition methods for very thin CdTe and CIGS absorber materials without pinholes, so that improved efficiencies are obtained when the surface recombination velocity is made small at the back by having a p+ or an electron blocking region before the ohmic contact. This result also explains the high efficiencies achieved by very thin perovskite solar cells.

Keywords: Solar cells; Thin film; CdTe; CIS; Analytical model

1. Introduction

There is the expectation that thin film solar cells will be the alternative to silicon solar cells which is the dominant technology at the photovoltaic market today. Improved efficiencies and lower costs of thin film solar cells are required for this goal to become a reality. Among the most developed thin film solar cells we have CdS/CdTe and CdS/CIGS which recently have attained efficiencies above 20% (Green, Emery, Hishikawa, Warta, & Dunlop, 2015). Each one of these technologies needs solving some problems related to the quality of the deposited materials (by different techniques), but as it will be shown here, reducing the film thickness and achieving higher open circuit voltages are required for both kind of solar cells. However, in general, CdTe and CIS solar cells are studied independently of each other without having a more integral vision.

It must be observed that from the structural point of view, CdTe and CIS solar cells are similar and therefore their physical behavior is also identical. The change is in the absorbing material (with their own properties) and the technological steps followed to make the solar cells. For example, CdTe is typically obtained by closed space vapor transport (CSVT) or Rf-sputtering (Morales-Acevedo, 2006), while CIS solar cells are obtained by co-evaporation or Rf-sputtering among other different techniques (Singh & Patra, 2010). CdTe typically

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cannot be p-type doped above 10^{15} cm^{-3}, and cells with small CdTe thickness cannot be easily done because pinholes cause the device degradation. Then, present CdTe minimum thickness is around 4–6 μm. In the case of CIS solar cells, the CIS (or CIGS) thickness is around 3–4 μm.

It will be shown that good cells can be designed with absorber thickness around 1 μm or below. Hence, the technological challenge is achieving CdTe and CIS materials with good properties, but without pinholes using the present or new deposition techniques. In such a case, the amount of material would be reduced by about 60–75% with a corresponding decrease in the total cost of the cells.

In this paper, we shall describe a simple analytical model that can be used for the above mentioned solar cells (CdTe and CIS), so that they can be designed easily. This model is complete in the sense that it includes carrier transport limited by diffusion and by generation–recombination at the space charge region. It also takes into account that the space charge region width is dependent upon the operating voltage and therefore the superposition principle is no longer valid. In other words, the current density due to illumination is not a constant with respect to the applied voltage, but it has some dependence upon this variable. Similarly, the total dark saturation current density will not be independent of the operating voltage, as it is usually assumed.

Having a simple model that considers the above effects for thin film solar cells is very important because, in general, they are not taken into account because for conventional cells, such as those made with silicon, these effects are negligible. Conventional junction silicon solar cells are typically made with absorber thickness of more than 200 μm, so that the space charge region effects on good solar cells are small because the depletion region thickness is of the order of 1 μm.

For thin film solar cells, the space region effects become important because the total volumes of the space charge region and the quasi-neutral regions are of the same order, particularly for very thin film solar cells. Furthermore, under some situations (which depends upon the equilibrium majority carrier concentration and the thickness of the absorbing material) the depletion region may extend along the whole length of the absorbing material. In this case, the recombination in the depletion region will limit the total dark current, but at the same time the photo-generated carriers will be collected efficiently because of the presence of the high electric field in this region. And this electric field will be larger for thinner solar cells. Hence, there is a complex relation between majority carrier concentration (Na), absorbing thickness, lifetime and mobility of minority carriers for the whole operating voltage range of the solar cell. The main objective for this work will be to have a simple model that takes into consideration all the above effects.

It will be shown that the model predicts that if the recombination at the back surface is reduced, for example by having a p+ region before the back contact, so that surface recombination velocities are small (10^2 cm/s or less) compared to the high recombination velocities obtained at ohmic contacts (above 10^7 cm/s), then very thin cells can achieve improved efficiencies than those with thick absorbers because of the reduction of bulk recombination, although there might be some loss of photo-current density.

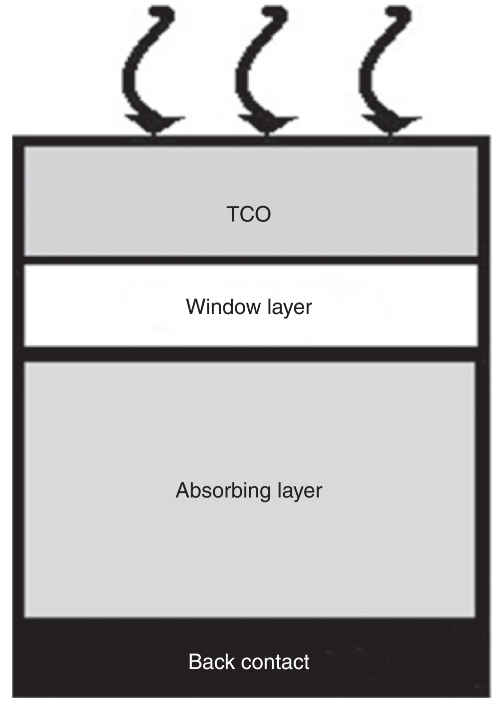

Fig. 1. Typical structure of a thin film solar cell.

Finally, in order to have a complete model for designing thin film solar cells, the optical design was also considered by using the optical matrix method applied to all the films that are part of the cells. The electrical and optical calculations were applied to CdTe and CIS solar cells, as an example of the application of the models described here.

2. *I–V* modeling

The reference structure of a thin film solar cell is shown in Figure 1. It is formed by three main regions: The transparent conducting oxide (TCO) which allows the light passing to the hetero-junction, the window semiconductor layer (typically CdS), and the absorbing semiconductor material. Ohmic contacts are both made at the back of the absorbing layer and at the front TCO layer in order to connect the cell to the external circuit. We shall assume that the back is covered by a metallic contact which reflects totally those photons that pass the absorbing layer without being absorbed causing a second pass of such photons through this layer.

As explained above, an important parameter that determines the electric and photoelectric properties in a solar cell is the thickness of the space charge region (depletion region) in both the p-type and n-type sides of the heterojunction by means of the following expressions:

$$x_p(V) = \left(\frac{2\varepsilon_p \varepsilon_n N_d (V_{bi} - V)}{q N_a (\varepsilon_n N_d + \varepsilon_p N_a)} \right)^{1/2} \quad (1)$$

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