



Modelling the quantum efficiency of cadmium telluride solar cells

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ABSTRACT

A simple analytical model is presented describing the quantum efficiency of cadmium telluride (CdTe) solar cells. This model is based on a consistent set of parameters that were extracted from electrical and optical measurements. These measurements also reveal the CdTe solar cells to mainly rely on carrier generation as well as carrier collection within the space-charge region. Recombination in this part of the cell is hence taken into account. As a result, quantum efficiency spectra can be closely fitted by an expression that includes the lifetime of the minority carriers and the width of the space-charge region as free variables. The comparison of the calculated quantum efficiency curves with the experimental ones gives fundamental insight into the specific operation of CdTe solar cells.

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1. Introduction

Analytical models for quantum efficiency are useful to investigate the generation and transport of carriers in solar cells and to identify the mechanisms of photocurrent losses. As an alternative, the quantum efficiency can be directly computed as the numeric solution of the continuity equation and the Poisson equation [1]. This approach requires detailed information on the electronic material properties, which are not easily accessible.

The collection of minority carriers in a thin-film solar cell can be described analytically by the Gärtner model [2,3]. This model, as well as more sophisticated ones developed e.g. for silicon solar cells [4] represent a solution of the continuity equation assuming complete carrier collection in the space-charge region (SCR). Thus, the main recombination losses are considered to occur in the neutral bulk of the absorber and possibly at interfaces, whereas recombination within the SCR is usually neglected. The need to consider recombination in the SCR has been pointed out by Hegedus and Shafarman [5]. These authors suggest that the assumption of complete collection within the SCR may no longer be justified in the case of low carrier concentration and large depletion width. Indeed, the current authors recently provided evidence for uncompensated shallow acceptor concentrations of $2 \times 10^{14} \text{ cm}^{-3}$ in typical CdTe–CdS heterojunction solar cells [6]. An apparent doping profile indicating an increase in carrier concentration with increase in sample depth was shown to be an artefact of deep levels the concentration of which may exceed the one of the shallow dopants by more than one

order of magnitude. These observations receive a growing acceptance in the CdTe community [7]. An ansatz describing the carrier collection in the SCR with losses has been presented by Kosyachenko et al. [8,9]. In an earlier work, Lavagna et al. [10] calculated the quantum efficiency of Au–CdTe Schottky-photodiodes. However, an analytical solution is only found for the case of negligible recombination in the SCR. Kosyachenko et al. [11] assume this approach to be justified for the quantum efficiency of experimental CdTe single crystal homojunction photodiodes.

In this work, we introduce a very simple analytical model for quantum efficiency whereby recombination in the space-charge region is taken into account. The key parameter in this model is the carrier lifetime.

First, the mostly applied analytical model for the quantum efficiency of thin-film solar cells is described. We then briefly review the literature on the shallow doping of CdTe in CdTe–CdS solar cells. The absorption behaviour of CdTe and CdS is crucial for the generation of the photocurrent. As the spectral absorption coefficient is reported to depend on the processing of the materials [12], optical measurements were performed in this work in order to obtain a consistent parameter set suitable for the comprehensive description of the CdTe solar cell. The electrical measurements performed in this work confirm the weak doping of the CdTe film and the associated large width of the space-charge region. The measured high absorption coefficient along with the large width of the SCR indicate that the highest fraction of the photocurrent is generated within $1 \mu\text{m}$ depth and collected by the electrical field of the p–n junction. After the determination of the optical and electrical conditions in the CdTe solar cells, a simple model is presented, which accounts for recombination within the SCR. Finally, the model is compared with experimental data.

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2. Models for quantum efficiency of thin-film solar cells

Quantum efficiency is defined as the ratio of electrical charges extracted from a solar cell to the number of incident photons. In the following, we distinguish between the external quantum efficiency (EQE) and the internal quantum efficiency (IQE). In the former, the quantum efficiency is normalized to the complete number of incident photons while in the latter only photons are considered, which actually enter the photoactive material.

In the simplest model, the contributions of the space-charge region SCR with depth W and the neutral region in the bulk material to the internal quantum efficiency IQE are [13]

$$IQE_{SCR} = 1 - \exp(-\alpha_{CdTe}W) \quad \text{and} \quad IQE_{neutral} = \frac{\alpha_{CdTe}L_{eff} \exp(-\alpha_{CdTe}W)}{\alpha_{CdTe}L_{eff} + 1}. \quad (1)$$

In this, L_{eff} is an effective diffusion length for the minority carriers in the absorber while α_{CdTe} denotes the absorption coefficient of CdTe. The combination of these equations yields the total internal quantum efficiency [14,13]

$$IQE = 1 - \frac{\exp(-\alpha_{CdTe}W)}{\alpha_{CdTe}L_{eff} + 1}. \quad (2)$$

This model assumes transport in the space-charge region without losses. Consequently, the internal quantum efficiency is unity for a sufficient width of the SCR. However, this is not necessarily true. Current losses for electron drift in a constant field have earlier been investigated by Hecht [15]. This author demonstrated that the number of photogenerated electrons exhibits an exponential decay with a characteristic drift length. This model has been applied to X-ray detectors and thin-film solar cells [9,14,16,17]. However, Nagle [18] showed by quantum efficiency simulations of CdTe solar cells that the Hecht model overestimates the collection and therefore leads to unrealistically low carrier lifetimes.

3. Electrical properties of CdTe solar cells

Describing the operation of thin-film solar cells entails the necessity to carefully specify the optical and electrical parameters. The latter are thereby most critical. Although a lot of investigations have been carried out on thin CdTe films and solar cells, the experimental evidence on the density, profile and nature of electrical defects is very incomprehensive and to some extent contradictory. Acceptor concentrations as high as 10^{15} cm^{-3} are reported [19,20]. Other authors assume that the doping is in the same order of magnitude but is compensated to an effective doping of about 10^{14} cm^{-3} [21,22]. Kosyachenko et al. [23] assume a high concentration of native impurities and defects (more than 10^{15} cm^{-3}), which should be exceeded significantly by the concentration of shallow acceptor impurities in order to minimize the electrical losses. Fritsche et al. [24] conclude from photoelectron spectroscopy measurements that the bulk material is intrinsic, which would mean that the doping concentration is 10^{13} cm^{-3} or less [25]. Some authors assume an increase in the doping profile with absorber depth [26–29]. However, as we were able to show in an earlier work [6], this apparent increase in profile is the result of a high concentration of deep defects exceeding the concentration of shallow defects by an order of magnitude while the distribution of both kinds of defects is actually homogeneous in space. These results are based on temperature dependent C–V measurements and on detailed theoretical considerations yield a typical uncompensated shallow acceptor concentration in the CdTe bulk of about $2 \times 10^{14} \text{ cm}^{-3}$.

4. Experimental details

4.1. Solar cell structure

The cell design is based on the common superstrate concept, i.e. the glass substrate faces the incident light. The film sequence on the glass is as follows: transparent front contact, n-type CdS, p-type CdTe and metal back contact. The CdS and CdTe films were deposited in high vacuum by the close-space sublimation (CSS) technique and afterwards subjected to a thermo-chemical treatment in CdCl_2 (“activation”). Further details on the solar cells and the production process can be found in an earlier work [30].

4.2. Electrical measurements

From capacitance–voltage (C–V) measurements, net dopant concentration N at the edge of the space-charge region can be extracted using [31]

$$C(V) = A \sqrt{\frac{\varepsilon \varepsilon_0 e N}{2}} \left(\sqrt{V + V_{bi}} \right)^{-1}. \quad (3)$$

Therein, ε is the relative permittivity of the material, ε_0 the vacuum permittivity, e the electron charge, V_{bi} the built-in voltage of the p–n junction and A the area of the sample in the plane of the junction. The Mott–Schottky plot $C^{-2}(V)$ yields N and V_{bi} from the slope and intersection of the linearized function, respectively [5]. The variation of width W of the space-charge region with the reverse voltage can be extracted from C–V measurements according to the relation [31]

$$W(V) = \frac{\varepsilon \varepsilon_0 A}{C(V)}. \quad (4)$$

Since the doping of the CdS layer is considered to be significantly higher than that of the CdTe layer [19,20], the space-charge region should be located on the CdTe side of the p–n junction. Hence, W denotes the width of the SCR in the absorber layer only. The combination of Eqs. (3) and (4) yields the doping profile (see discussion above). In this work, we determined the uncompensated shallow acceptor concentration of thin CdTe films by C–V measurements on CdTe solar cells. The implications of deep defects were considered by determining N at room temperature in the range of weak forward bias. These are also basically the conditions during quantum efficiency measurements without bias. In this case, the main contribution to the concentration of free carriers stems from the ionized uncompensated shallow acceptors, even if a high concentration of deep acceptors is present (see also Ref. [6]). C–V measurements were performed using an Agilent HP4285A LCZ meter.

4.3. Optical measurements

The absorption coefficient α was obtained by transmittance and reflectance measurements using the relation

$$\alpha = \frac{1}{d} \ln \left(\frac{1-R}{T} \right). \quad (5)$$

Therein, R and T are the coefficients of the reflected and transmitted light intensity, respectively, and d is the film thickness. The following stacks of layers were measured in order to determine the optical parameters—first the substrate (glass with front contact), second the substrate with CdS and third the substrate with CdS and CdTe. As a result, the absorption coefficients for CdS and CdTe were obtained from

$$\alpha_{CdS} = \frac{1}{d_{CdS}} \ln \left[\frac{(1-R_{CdS})T_{substrate}}{T_{CdS}} \right] \quad \text{and} \quad \alpha_{CdTe} = \frac{1}{d_{CdTe}} \ln \left[\frac{(1-R_{CdTe})T_{CdS}}{T_{CdTe}} \right]. \quad (6)$$

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