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A simple model for the photocurrent density of a graded band gap CIGS thin film solar cell

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Abstract

A simple model for the photocurrent density of a linearly graded band gap $Cu(In,Ga)Se_2$ solar cell is presented. Both generation and recombination mechanisms in the space charge region and absorber region of the cell are considered. The carrier collection function and effective absorption coefficient are introduced in the calculations to obtain a more realistic model. The results show that photocurrent density of the graded band-gap solar cell is higher than that with a constant averaged band gap. There is an optimum for grading strength or band gap widening of the absorber region. Recombination current reduces the photocurrent density with a lower reduction in the absorber material than in the depletion region. For longer diffusion lengths (or greater values of carrier collection factor), a higher photocurrent density is obtained except where collection probability is already unity everywhere in the absorber.

Keywords: Thin films; CIGS solar cells; Graded band gap; Photocurrent density

1. Introduction

In the last few years, $Cu(In,Ga)Se_2$ (CIGS) thin film solar cells have shown a record efficiency of about 20.1% in laboratory scale (Jackson et al., 2011). As potentially efficient and low cost materials, many groups are working on the electrical and optical properties of these types of solar cells (Nadenau et al., 2000; Jasenek et al., 2001). To enhance the electrical properties, (e.g., transport properties of the carriers), the recombination mechanisms and electronic loss effects of the cell have been considered (Thomas and Uwe, 2007; Turcu et al., 2002). To promote the optical properties of the cell, the experiments evidenced that grading the band gap of the absorber material improves the device performance (Gloeckler and Sites, 2005). Along with the experimental works, the numerical modelling and simulation of CIGS solar cells have also been developed using programs such as SCAPS (Burgelman et al., 2000) and AMPS (Zhu et al., 1999). Analytical approaches for modelling and determination of the cell parameters help to achieve a clear understanding of the physics of these structures which is necessary for design strategy and its optimization. Grading the Conduction Band (CB) or Valence Band (VB) influences the recombination and generation mechanisms, light absorption process and the carrier collection of the cell (by an induced reverse quasi-electric field through the absorber material) (Gorji et al., 2011; Song et al., 2004; Dullweber et al., 2000). In the current work, we consider a graded band gap CIGS solar cell with a linearly increased CB toward the back contact (Fig. 1). This profile is interesting to be considered because increased grading toward the back contact leads to enhanced carrier collection with a limit in the immediate vicinity of the metallurgical back interface due to high recombination velocity. Dullweber et al. showed that

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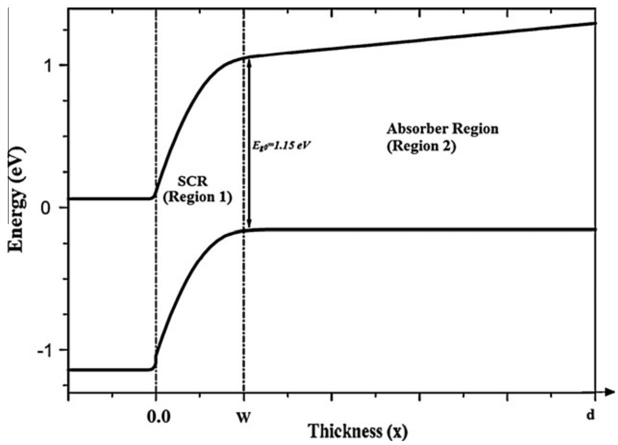

Fig. 1. Band structure of linearly graded solar cell divided to SCR (region 1) and absorber region (region 2).

this grading of the absorber material enhances the carrier collection of the cell and absorption of the long wavelength light (Zhu et al., 1999). In the literature, some of beneficial effects of this profile have been underlined (Mattheis et al., 2007; Decock et al., 2011). Mattheis et al. have considered a semi-analytical theoretical model for quantum efficiency of this profile to investigate the back contact recombination velocity as well as the optical and electronic parameters of its absorber layer (Mattheis et al., 2007). Decock et al. (2011) have derived a closed form analytical expression of the current density including a quasi-electrical field component originating from this grading. In their analysis they assumed the absorption to be constant and neglected the recombination current. In this paper, we present an analytical model to analyse the photocurrent of this profile considering absorption coefficient, generation and recombination rates and carrier collection function relating their dependency to the thickness of the cell. Our theoretical approach considers the photocurrent density of the cell similar to Acevedo's method, but in his calculations he considered the ideal photocurrent of the cell only, neglecting the recombination current, assuming 100% carrier collection efficiency and supposing that all photons reach the absorber without any generation or recombination in the Space Charge Region (SCR) (Morales-Acevedo, 2009a,b). We take into account the recombination and generation currents in the SCR and absorber region of the cell. For different values of grading strengths and diffusion lengths (or carrier collections), we calculate the photocurrent density of the cell and the influence of recombination currents on this quantity. Furthermore, we compare the photocurrent density of the graded band gap and constant averaged band gap cells.

2. Theory

In Fig. 1, we divided the cell into SCR (from 0 to $w = 0.4\ \mu m$) and absorber region (from w to $d = 2\ \mu m$). For each region, we calculate the photocurrent density which depends on the recombination and generation rates. We assume that the increase of the band gap is due to grading the CB only with a grading strength ($kT\zeta$). Then, the graded band gap is $E_g(x) = E_{g0} + kT\zeta x$, with k the Boltzmann constant, T the temperature and $E_{g0} = 1.15$ eV. For the incoming light from the left the total photocurrent density of the cell, we can write

$$J_{tot} = J_1 + J_2, \tag{1}$$

where, J_1 and J_2 are the photocurrent densities of the SCR (region 1) and absorber region (region 2), respectively. The photocurrent density of each region is assumed to be proportional to the integral of the difference between the generation and recombination rates

$$J_1(x) = -q\int_0^w (G_1(x) - U_1(x))dx, \tag{2}$$

$$J_2(x) = -q\int_w^d (G_2(x) - U_2(x))dx, \tag{3}$$

where q is the electron charge, U_1, U_2, G_1 and G_2 are the recombination and generation rates in the SCR and absorber region, respectively. In the absorber region, we use an energy and position dependent absorption coefficient $\alpha(E,x) = A(E - Eg_0 - kT\zeta x)^{1/2}$ where $A = 10^4\ \mathrm{cm^{-1}\,eV^{-1/2}}$ is a constant. To calculate the generation rate, we need the number of photons per unit of area at the surface of the cell F_0. If the sun is assumed to be a blackbody at $T_S = 5760$ K, F_0 is given by Araujo and Marti (1994)

$$F_0(E) = \frac{2\pi}{c^2h^3}\int \frac{E^2}{\exp\left(\frac{E}{kT_s}\right) - 1}dE. \tag{4}$$

For the generation rate in SCR (region 1), we assume the following expression:

$$G_1(x) = \int_0^w F_0\alpha_1 \exp(-\alpha_1 x)\eta_{c,1}dE, \tag{5}$$

where α_1 is the absorption coefficient in SCR and $\eta_{c,1}$ is the carrier collection function of the SCR region. In SCR it is assumed that the absorption coefficient is constant ($\alpha_1 = 10^5\ \mathrm{cm^{-1}}$). Choosing this constant value for absorption coefficient in SCR leads to a minimum depletion width of $0.4\ \mu m$ corresponding to an acceptor density of $2.75 \times 10^{16}\ \mathrm{cm^{-3}}$. The maximum generation rate is obtained if we integrate over the solar photon spectrum and neglect all loss mechanisms due to optical and electrical losses. The most important electrical loss is due to charge carriers which undergoes recombination. Then, we consider the recombination rate as the only loss mechanism in the cell. For U_1, we assume equal lifetimes for holes and electrons ($\tau_n = 1000$ ns, doping density of $10^{15}\ \mathrm{cm^{-3}}$) with a trap energy level equal to the intrinsic Fermi level. Under forward applied voltage, the recombination rate in the SCR is given by (Sze and Ng, 2007)

$$U_1(x) = \frac{(q\eta_{c1}(x))(np - n_i^2)}{[2\tau_n(n + p + 2n_i)]}, \tag{6}$$

where n and p are the minority and majority carrier densities in SCR, respectively, n_i is the intrinsic carrier density.