Solar Energy Materials & Solar Cells 130 (2014) 291–302

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Optical and recombination losses in thin-film $Cu(In,Ga)Se_2$ solar cells

L.A. Kosyachenko [a,*], X. Mathew [b], P.D. Paulson [c], V.Ya. Lytvynenko [a], O.L. Maslyanchuk [a]

[a] ChernivtsiNationalUniversity, Kotsyubinsky Str. 2, Chernivtsi 58012, Ukraine
[b] Instituto de Energias Renovables, Universidad Nacional Autonoma de Mexico, Temixco, Morelos 62580, México
[c] Nuvosun Inc., 1565 Barber Ln, Milpitas, CA 95035, USA

ARTICLE INFO

Article history:
Received 16 May 2014
Received in revised form
26 June 2014
Accepted 11 July 2014

Keywords:
$CuIn(Ga,In)Se_2$ solar cells
Optical losses
Recombination losses

ABSTRACT

Optical and recombination losses in thin-film solar cells based on $CuIn_xGa_{1-x}Se_2$ with the bandgaps 1.14–1.16 and 1.36–1.38 eV have been evaluated. Parameters used for the analysis and calculations were verified by comparing the measured quantum efficiency spectra with the results of calculations. Optical losses due to reflections from the interfaces and absorption in the ZnO and CdS layers are found using the optical constants of materials taking into account anti-reflection coating on the ZnO surface. It is shown that for typical parameters of solar cells studied the optical losses amount to 16–18%. Losses due to the recombination of charge carriers at the front and back surfaces of the absorbing layer and in the space charge region (SCR) are calculated based on their dependences on the carrier lifetime, the concentration of uncompensated acceptors (determined the width of the SCR) and other parameters of the absorber. Total recombination losses in solar cells with the bandgaps of $CuIn(Ga,In)Se_2$ 1.14 and 1.36 eV are equal to 7.0% and 4.5%, respectively. It is also shown that for solar cell with the bandgap of absorber 1.14 eV, an incomplete charge collection is caused also due to non-optimal width of the SCR. An improvement of charge collection in this cell can be achieved by varying the concentration of uncompensated acceptors in the absorber. However, it is impossible to achieve such improvement for solar cells with the bandgap of 1.36 eV due to shorter carrier lifetime in the material.

1. Introduction

For a long time, solar cells based on $CuIn_xGa_{1-x}Se_2$ (CIGS), similar to CdTe-based devices, keep a stable position in thin-film photovoltaics as an alternative to solar modules based on mono- and poly-silicon wafers. Mass production of cost-effective CIGS-based modules has been achieved by many companies worldwide. The efficiency of such modules is in the range of 12–15%, but for small area laboratory cells, the efficiency achieved 20.3% in 2010, which was a record level among thin-film solar cells [1]. In early 2014, Solar Frontier has achieved 20.8% energy conversion efficiency for small area CIS cells and shortly Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW) improved the cell efficiency to 20.9% [2,3]. It should be noted that the CIGS devices have shown excellent long-term stability and high radiation resistance, can be made lightweight and flexible that are desirable for space, portable and building integrated applications [4]. Since the efficiency of 12–15% in modules is about half of the theoretical limit (28–30%), works to improve the CIGS module efficiency are extremely relevant both from scientific and economic points of view.

The processes of photoelectric conversion in CIGS and CdTe solar cells are largely similar. In both cases, the thin-film p-n heterostructure is the key element in determining the performance of the device. As in CdTe solar cell, a thin layer of n-CdS serves as "window", through which radiation penetrates into the CIGS absorber. The difference between these devices lies in their superstrate (CdTe) and substrate (CIGS) configuration. In superstrate configuration, the sunlight enters the absorber through the glass plate and transparent conductive layer (TCO, usually SnO_2:F) while only through the TCO layer (usually ZnO:Al) in substrate configuration. These design features are not of fundamental importance from the point of view of the physical processes taking place, but only require different device fabrication technologies. It follows that the physical models developed for the interpretation of the CdTe solar cell properties can be applied with some modifications to the CIGS devices [5,6].

In this paper we consider the optical and recombination losses in CIGS devices, which are important causes of low solar-to-electric energy conversion and quantum efficiency in solar cells. We discuss the *quantitative* determination of the losses and identify possible pathways to reduce it. Calculations of the optical losses are carried out based on the optical constants of the

* Corresponding author. Tel.: +380 372 244 22; fax: +380 372 551 809.
E-mail address: l.a.kosyachenko@gmail.com (L.A. Kosyachenko).

http://dx.doi.org/10.1016/j.solmat.2014.07.019
0927-0248/

materials used, i.e., the refractive indices and extinction coefficients. Recombination losses are determined on the basis of the continuity equation taking into account the drift and diffusion components of the photocurrent.

The analysis of the physical process discussed in this paper can be useful from a practical point of view since undoubted successes in the development of efficient $CuIn_xGa_{1-x}Se_2$ solar cells have been achieved mainly empirically [4].

2. Main parameters and optical constants of the materials used

We present analysis on CIGS solar cells with two absorber layer: one with bandgap $E_g = 1.14–1.16$ eV $(Ga/(In+Ga) \approx 0.3)$ which is the material used in the mass production of high efficiency solar modules; the second is the wider bandgap $E_g = 1.36–1.38$ eV $(Ga/(In+Ga) \approx 0.6–0.7)$ which is close to the theoretically optimal value for maximum efficiency 28–30%.

Fig. 1 shows the schematic cross-section of a typical CIGS solar cell, where the notations of the optical constants n_i and κ_i and the reflection coefficients R_{ij} at the interfaces used in the calculations are indicated. Photoelectric conversion in this solar cell occurs in the CIGS absorber with a thickness of 2 μm, while the CdS film with a thickness 30–40 nm is a window layer for the absorber. A 500-nm-thick ZnO:Al is the transparent conducting oxide (TCO) and application of an undoped high-resistivity 50-nm-thick ZnO layer between TCO and CdS is very common in substrate configuration devices. In high-efficiency devices, an antireflection ~100-nm-thick MgF_2 layer is also deposited onto the front surface of ZnO.

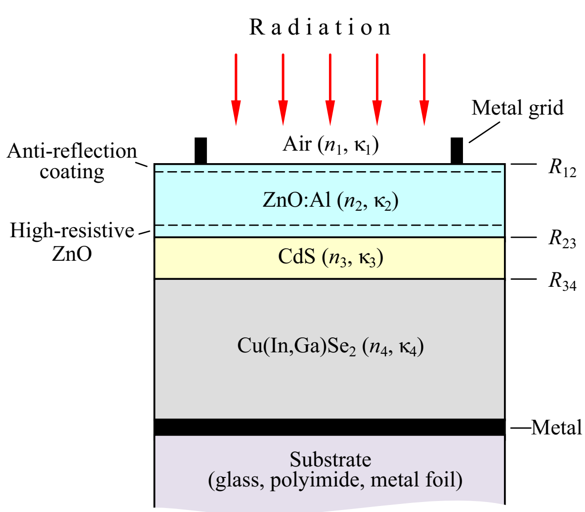

Fig. 1. Cross-section of a typical CIGS solar cell.

In the calculations of quantum efficiency of CdS/CIGS cell, one needs to know the optical transmission of the ZnO/CdS structure $T(\lambda)$, which is determined by reflections from the interfaces air/ZnO, ZnO/CdS, CdS/CIGS and absorption in the ZnO and CdS layers.

For determining the optical transmission $T(\lambda)$, it is necessary to know the refraction indices n_i and extinction coefficients κ_i of ZnO, CdS and CIGS. According to the Fresnel equations, when the light is at near-normal incidence, the reflection coefficients (reflectances) from three interfaces R_{12}, R_{23} and R_{34} can be calculated as

$$R_{ij} = \frac{\left|n_i^* - n_j^*\right|^2}{\left|n_i^* + n_j^*\right|^2} = \frac{(n_i - n_j)^2 + (\kappa_i - \kappa_j)^2}{(n_i + n_j)^2 + (\kappa_i + \kappa_j)^2}. \quad (1)$$

where n_i^* and n_j^* are the refractive indices of the materials, which account for their conductivity containing imaginary parts and are written as $n_i^* = n_i - i\kappa_i$ and $n_j^* = n_j - i\kappa_j$.

Fig. 2 shows the spectral dependences of n and κ for ZnO taken from [4,7], for CdS from [8] and CIGS from [9] (in some cases the extinction coefficient κ was determined as $\alpha\lambda/4\pi$, where α is the absorption coefficient). It is worth to note the fact that for CIGS, the extinction coefficient in the photon energy range $h\nu < E_g$ has a value of 0.04–0.05, which corresponds to the absorption coefficient $\alpha = 4\pi\kappa/\lambda = (4–5) \times 10^3$ cm^{-1} [9]. With such values of α, a fairly high quantum efficiency should be obtained for the solar cell, but, in fact, this is not observed. At $\lambda > \lambda_g = hc/E_g$, the quantum efficiency decreases quite rapidly with wavelength up to zero within a range about 150 nm above λ_g. This can be explained by the presence of so-called 'tails' of the density of states in the bandgap of the semiconductor with strong doping or/and disordered crystal structure. In this case, the electron wave functions and force fields of impurity atoms overlap, whereby the discrete impurity levels are broadened and transformed into an impurity band. At a certain critical concentration, the impurity band joins with the conduction (valence) band, i.e., these tails of the density of states appear. The absorption coefficient in this range depends

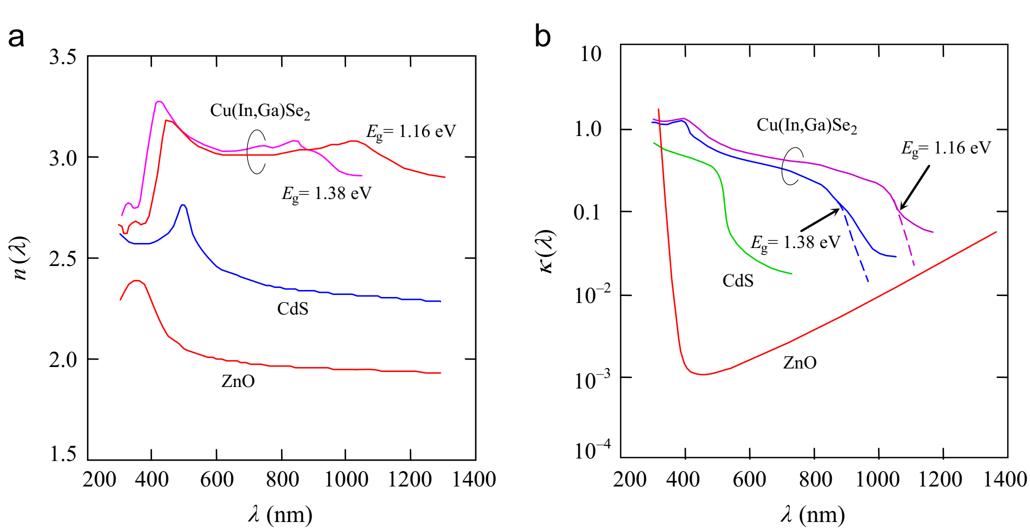

Fig. 2. Wavelength dependences of the refractive indices (a) and extinction coefficients (b) of ZnO, CdS, $CuIn_{0.69}Ga_{0.31}Se_2$ and $CuIn_{0.34}Ga_{0.66}Se_2$.