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Determination of space charge region width and diffusion length in $Cu(In,Ga)(S,Se)_2$ absorber from solar cell spectral characteristics

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1. Introduction

The direct band gap semiconductor solid solutions $Cu(In,Ga)(S,Se)_2$ (CIGSS) are an excellent basic material for high-efficiency and low-cost thin film solar cells (SCs) of the second generation. Fig. 1 shows schematically SC on the base of CIGSS, where the CIGSS base layer is covered with a thin (30 – 50 nm) layer of wide-gap semiconductor (usually CdS).

For improvement the efficiency of the CIGSS-SCs, there is required to optimize their parameters taking into account the spectral characteristics of solar radiation. This necessitates the creation of a nondestructive control system for the parameters of SCs at various stages of their manufacture. Despite active investigations of CIGSS-SCs and the available basic principles for modeling of the SCs spectral characteristics, nondestructive control methods (specifically those based on spectral measurements) for these parameters at various stages of the production process of CIGSS-SCs are inadequate.

In this work, a method have proposed to evaluation the space charge region (SCR) width and the diffusion length of minority carriers in a CIGSS-layer from analysis of its spectral characteristics at various stages of SCs production after *p-n*-junction formation.

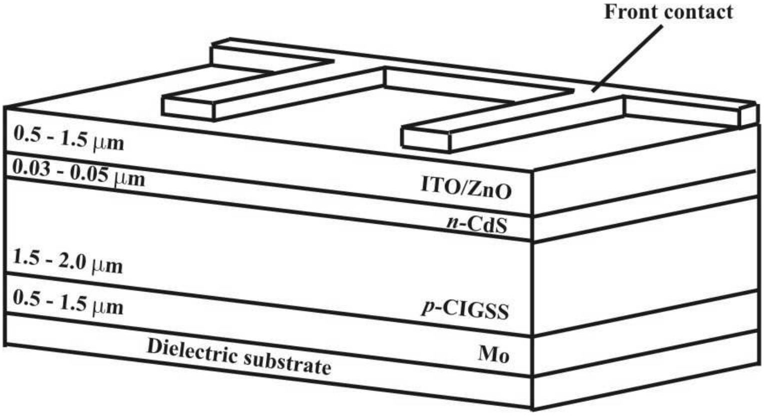

Fig. 1. The CIGSS-SC sketch

2. Photocurrent and photovoltage spectra of solar cell

To correctly, it must be understood the spectral quantum efficiency under the spectral response of SC. Namely, following ratio J_{ph}/eF, where $J_{ph} = J_{ph}(\lambda)$ is the spectral photocurrent density (photocurrent spectra), e − the elementary charge, $F = F(\lambda)$ − the photon flux spectral density. Sometimes, however, it is used an open-circuit voltage U_{OC} spectral dependence (photovoltage spectra) for estimation of J_{ph} values because there is a relationship between these two characteristics. This correlation between the photocurrent density J_{ph} and open-circuit voltage U_{OC} can be expressed by the following function [1]:

$$J_{ph} = J_0\left[exp\left(\frac{U_{OC}}{mV_T}\right)-1\right]+\frac{U_{OC}}{R_p}, \qquad (1)$$

where $V_T = \frac{kT}{e}$, k – Boltzman constant, T – thermodynamic temperature, J_0 – inverse current density, m – diode coefficient including the recombination processes in SCR (m > 1), R_p – parallel resistance in the equivalent circuit of SC. In case of a low excitation level ($U_{OC} < V_T$), with due consideration for the first two expansion components we can rewrite (1) as

$$U_{OC} = \frac{mV_T R_p}{J_0 R_p + mV_T} J_{ph} = const \cdot J_{ph} \quad (2)$$

As follows from (2), J_{ph} measuring is equivalent to the recording of U_{OC}.

Due to the requirement the condition of low excitation level, it is necessary to realize the condition

$$W^L / W \approx 1, \quad (3)$$

where W is the value of SCR in the dark, W^L is the same but at illumination. The condition (3) required for realization the condition $J_0 = const$ is always satisfied at spectral measurements for $U_{OC} < V_T$, as will be shown below.

3. The space-charge region width in Cu(In,Ga)(S,Se)$_2$-layer

The SCR width is one of the major parameters of SC which determines its spectral sensitivity and efficiency.

The SCR width in *n*- and *p*-regions, designated respectively as x_n and x_p, can be set by relations

$$x_n = V_0 \frac{2\varepsilon_n \varepsilon_0}{eN_D W}, \qquad x_p = V_0 \frac{2\varepsilon_p \varepsilon_0}{eN_A W}, \quad (4)$$

within the framework of a one-dimensional model for an abrupt junction. Here N_D and N_A are the concentrations of non-compensated donors and acceptors, respectively; ε_0 – the electric constant, ε_n and ε_p – the material permittivity, V_0 – built-in potential, $W = x_n + x_p$. According to (4), we obtain

$$W = \sqrt{\frac{2\varepsilon_0}{e} \frac{\varepsilon_p N_D + \varepsilon_n N_A}{N_A N_D} V_0}. \quad (5)$$

$$x_p = \sqrt{\frac{2\varepsilon_p \varepsilon_0}{eN_A} V_0 \cdot \frac{N_D}{N_D + \frac{\varepsilon_n}{\varepsilon_p} N_A}}. \quad (6)$$

Equation (5) makes it possible to estimate the correctness of condition (3) for $U_{OC} < V_T$. In case of the illuminated SC

$$\frac{W^L}{W} = \sqrt{\frac{V_0 - U_{OC}}{V_0}} \quad (7)$$

In the case of CIGSS–SC, V_0 is approximately equal to 700 mV [2]. In such a manner, the realization of $U_{OC} < V_T$ means fulfillment of the condition given by (3).

Note that SCR is located mainly in a CIGSS-layer (see Fig. 1). Indeed, ε_n (CdS) = 10 [3], ε_p (CIGSS) ≈ 13.6 [3], N_D (CdS) ~ 10^{18} cm^{-3} [2], N_A (CIGSS) ~ 10^{16} cm^{-3} [2]. From the condition of electro-neutrality $N_D x_n = N_A x_p$ it follows that x_p / x_n ~10^2.

4. Spectral characteristic of Cu(In,Ga)(S,Se)$_2$ based solar cell

Let us use the one-dimensional model of SC presented in [4–6]. One of the features of CIGSS-SC is a relatively large band gap of the front layer (3.3 eV for ZnO) leading to its transparency for the most part of a solar spectrum. The band gap of a buffer layer is also large enough (2.4 eV for CdS). Inasmuch as the thickness of the buffer layer is several tens of nanometers only (Fig. 1) [7], extinction of the visible and infrared radiation therein can be ignored.

Thus, a one-dimensional model of CIGSS-SC (just for a major part of the spectral sensitivity) can be schematically shown like in Fig. 2, that is similar to the appropriate scheme in [8].

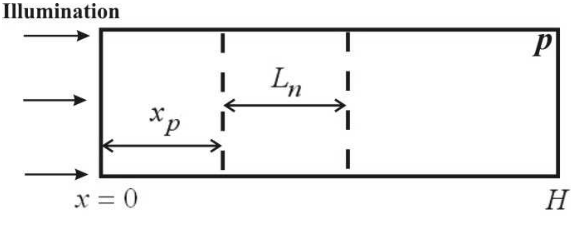

Fig. 2. One-dimensional model for SC CIGSS-layer: x_p – SCR value, L_n – region with a thickness equal to the diffusion length, H – thickness of CIGSS-layer

Within the framework of this model, the photocurrent density consists of two components

$$J_{ph} = J_n + J_{SCR}, \tag{8}$$

where J_n is the current density of the electrons generated in a quasi-neutral region of the CIGSS-layer and arriving to SCR, J_{SCR} – current density of the carriers generated in SCR of the CIGSS-layer.

$$J_{SCR} = eF\left(1-r\right)\left[1-exp\left(-\alpha x_p\right)\right], \tag{9}$$

where $r = r\left(\lambda\right)$ is the reflectance, $\alpha = \alpha\left(\lambda\right)$ – absorption index.

According to [4], at a low excitation level and in the absence of a «drawing» field in the quasi-neutral region of the CIGSS-layer an equation for J_n is given by

$$J_n = e\frac{F\left(1-r\right)\alpha L_n}{\alpha^2 L_n^2 - 1} exp\left(-\alpha x_p\right)\times$$
$$\times\left[\alpha L_n - \frac{\left(\frac{S_n}{D_n}L_n\right)\left(ch\frac{H}{L_n} - exp\left(-\alpha H\right)\right) + sh\frac{H}{L_n} + \alpha L_n\, exp\left(-\alpha H\right)}{\left(\frac{S_n}{D_n}L_n\right)sh\frac{H}{L_n} + ch\frac{H}{L_n}}\right], \tag{10}$$

where S_n is the surface recombination velocity of electrons on the backside contact, D_n – the diffusion coefficient of electrons.

For CIGSS-SC, we have $L_n \sim 1$ µm [9] and $H \sim 2 - 3$ µm. As a result,

$$exp\left(H/L_n\right) >> exp\left(-H/L_n\right). \tag{11}$$

Apart (11), we will suppose that there is no reflection of the minority carriers from the backside contact and hence $S_n \to \infty$, as it was considered in [8]. In this case, expression (10) can be rewritten as

$$J_n = e\frac{F\left(1-r\right)\alpha L_n}{\alpha^2 L_n^2 - 1} exp\left(-\alpha x_p\right)\left[\alpha L_n - 1 - \frac{1}{2}exp\left[-\left(\alpha H + \frac{H}{L_n}\right)\right]\right]. \tag{12}$$

Using (8), (9) and (12), we get

$$\frac{J_{ph}}{eF\left(1-r\right)}=\frac{\alpha L_n}{\alpha^2 L_n^2-1}exp\left(-\alpha x_p\right)\times$$
$$\times\left[\alpha L_n-1-\frac{1}{2}exp\left[-\left(\alpha H+\frac{H}{L_n}\right)\right]\right]+\left[1-exp\left(-\alpha x_p\right)\right]. \tag{13}$$

As previously mentioned, we have $L_n \sim 1$ μm [9] and $H \sim 2-3$ μm for CIGSS-SC. The absorption index α of CIGSS for a major part of the spectral sensitivity is no less than 10^4 cm^{-1} [10]. In this case, equation (13) can be simplified under the assumption that

$$\frac{1}{2}exp\left[-\left(\alpha H+\frac{H}{L_n}\right)\right]<<1 \tag{15}$$

By this means, the following relation is true:

$$\frac{J_{ph}}{eF\left(1-r\right)}=\frac{\alpha L_n}{\alpha L_n+1}exp\left(-\alpha x_p\right)+\left[1-exp\left(-\alpha x_p\right)\right] \tag{16}$$

It follows that

$$x_p=\frac{1}{\alpha}ln\frac{1}{\left(1-\frac{J_{ph}}{eF\left(1-r\right)}\right)\left(\alpha L_n+1\right)} \tag{17}$$

To determine L_n, we perform an analysis of the spectral characteristics over the range, where

$$\frac{1}{\alpha}>>x_p \tag{18}$$

In so doing, it is necessary not to violate the condition of (15). According to (18), we can use the procedure described in [11] to determine L_n.

Knowing L_n, we can determine x_p by expression (17). If we make measurements of photovoltage spectra instead of photocurrent spectra, we need to use correlation (2).

As a result, we can determine the values of x_p and L_n from the analysis of the spectral characteristics with the use of (13). The known value of x_p allows to obtain from (6) the concentration of non-compensated acceptors in the CIGSS-layer.

Resume

The method for determination of the space charge region width and diffusion length in a CIGSS-layer in SC based on the analysis of a spectral characteristic is proposed. This method can be used as a quick test procedure enabling one to estimate the evolution of the CIGSS-layer parameters at various stages of SC production after deposition of the buffer layer (*p*-*n*-junction formation).

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Abstract

In this work we present simple non-destructive method for extracting of Cu(In,Ga)(S,Se)$_2$-based solar cell parameters (space-charge region width and diffusion length of minority charge carriers in Cu(In,Ga)(S,Se)$_2$ absorber) from the analysis of solar cell spectral characteristics.

This method is based on one-dimensional model of a solar cell when the change of in-depth distribution of the photogenerated carriers and, hence, the change of its photoresponse with the variation of excitation wave-length in solar cell is taking into account. The following assumptions are accepted: the reflection of charge carriers from back contact and the «drawing» fields in the quasi-neutral area of the absorber layers are negligible; window and buffer layers are transparent in the analyzed of spectrum range; the injection level of minority charge carriers is low; the recombination losses at the metallurgical *p-n*-junction interface of the studied photosensitive structure are dependent linearly on the photocurrent density.

Streszczenie

W pracy przedstawiono prostą metodę nieniszczącego wyznaczenia parametrów (szerokość obszaru ładunku przestrzennego i długość drogi dyfuzji mniejszościowych nośników ładunku w absorberze) dla ogniw słonecznych na bazie Cu(In,Ga)(S, Se)$_2$ z analizy charakterystyk widmowych ogniw słonecznych.

Metoda opiera się na jednowymiarowym modelu ogniwa słonecznego, kiedy zmiana rozkładu generowanych optycznie nośników jest prostopadła do powierzchni i zmiana fotoodpowiedzi ze zmianą długości fali światła wzbudzającego jest brana pod uwagę.

Przyjęto poniższe założenia: odbicie nośników ładunku od tylnego kontaktu oraz zmiana pola profilu w okolicy quasi-neutralne warstw absorbera są nieistotne; warstwy czołowa i buforowa są przezroczyste w analizowanym zakresie widmowym; poziom generacji mniejszościowych nośników ładunku jest niski; straty rekombinacyjne w bazowym n-p złączu badanej struktury są uzależnione światłoczułych liniowo od gęstości fotoprądu.