Michael TIVANOV[1], Alexander MOSKALEV[1], Aleksy PATRYN[2]

Faculty of Physics, Belarusian State University (1), Wydział Elektroniki i Informatyki, Politechnika Koszalińska (2)

doi:10.15199/48.2015.09.49

Determination of Cu(In,Ga)(S,Se)$_2$–solar cell parameters from quantum efficiency spectra

Abstract. *A method for calculation of the Cu(In,Ga)(S,Se)2-layer parameters (space-charge region width, diffusion length, built-in potential and concentration of non-compensated acceptors) in solar cell is proposed. The method is based on analysis of the quantum efficiency spectra within the framework of a solar-cell unidimensional model.*

Streszczenie. *Zaproponowano metodę wyznaczania parametrów Cu(In,Ga)(S,Se)$_2$ ogniw słonecznych (szerokość obszaru ładunku przestrzennego, długość drogi dyfuzji nośników, wbudowane pole elektryczne, koncentracja nieskompensowanych domieszek akceptorowych). Metoda bazuje się na analizie widma wydajności kwantowej ogniwa w ramkach modelu jednowymiarowego.* ***Wyznaczanie parametrów Cu(In,Ga)(S,Se)$_2$ ogniw słonecznych z widma wydajności kwantowej***

Keywords: CIGSS, space-charge region width, diffusion length, solar cell spectra, applied bias voltage.
Słowy kluczowe:CIGSS półprzewodniki, szerokość obszaru ładunku przestrzennego, długość drogi dyfuzji nośników

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. CIGSS is base absorbing layer which covered with layer of wide-gap semiconductor for creating p-n-junction.

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. 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 SCs quantum efficiency spectral dependence after p-n-junction formation.

One-dimensional model of Cu(In,Ga)(S,Se)$_2$-solar cell

We use the one-dimensional model of SC presented in [1, 2]. 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 [3], 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. 1, that is similar to the appropriate scheme in [4].

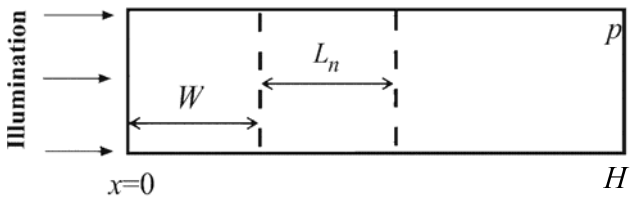

Fig. 1. One-dimensional model for SC CIGSS-layer: W – SCR value, – region with a thickness equal to the diffusion length, H – thickness of CIGSS-layer

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

$$J_{ph} = J_n + J_{SCR}, \tag{1}$$

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.

$$J_{SCR} = eF\left(1-r\right)\left[1-exp\left(-\alpha W\right)\right], \tag{2}$$

where e is the electron charge, $F = F\left(\lambda\right)$ – the photon flux spectral density, $r = r\left(\lambda\right)$ is the reflectance, $\alpha = \alpha\left(\lambda\right)$ – absorption index.

The width of SCR can be expressed as

$$W = z\left(U_0 + U\right)^{1/2}, \tag{3}$$

where U_0 is the built-in potential of p-n-junction, U – the applied voltage.

$$W = x_n + x_p, \tag{4}$$

where x_n and x_p are the SCR width in n- and p-regions, respectively.

$$z = \sqrt{\frac{2\varepsilon_0}{e}\frac{\varepsilon_p N_D + \varepsilon_n N_A}{N_A N_D}}. \tag{5}$$

Here N_D and N_A are the concentrations of non-compensated donors and acceptors in p- and n- regions, respectively; ε_0 – the electric constant, ε_n and ε_p – the material permittivity, V_0 – built-in potential. In the case of CIGSS–SC, V_0 is approximately equal to 0,7 V [5].

Let us assume that z is a constant that is independent of the SCR width. In reality, this is true for the depletion region with constant dopant concentration.

Note that SCR is located mainly in a CIGSS-layer (see Fig. 1). Indeed, ε_n(CdS) = 10 [6], ε_p (CIGSS) ≈ 13.6 [6], N_D(CdS) ~ 10^{18} cm^{-3} [5], N_A(CIGSS) ~ 10^{16} cm^{-3} [5]. From the condition of electro-neutrality $N_D x_n = N_A x_p$ it follows that $x_p/x_n \sim 10^2$. Thus, in our case

$$J_n = e\frac{F\left(1-r\right)\alpha L_n}{\alpha^2 L_n^2 - 1}exp\left(-\alpha W\right)\times$$

$$\times\left[\alpha L_n - \frac{\frac{S_n L_n}{D_n}\left(ch\frac{H-W}{L_n} - exp\left(-\alpha\left(H-W\right)\right)\right) + sh\frac{H-W}{L_n} + \alpha L_n\, exp\left(-\alpha\left(H-W\right)\right)}{\frac{S_n L_n}{D_n}sh\frac{H-W}{L_n} + ch\frac{H-W}{L_n}}\right], \quad (7)$$

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 ~ 1 μm [9] and H ~ 2 – 3 μm [10-12]. As a result, we will suppose that

$$W \approx x_p, \quad z \approx \sqrt{\frac{2\varepsilon_0\varepsilon_p}{eN_A}} \quad (6)$$

The typical for CIGSS-SC value of the SCR is W ≈ 0.25 μm [7, 8].

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

$$exp\left(H-W/L_n\right) >> exp\left(-(H-W)/L_n\right). \quad (8)$$

Apart (8), we will suppose that there is no reflection of the minority carriers from the backside contact and hence $S_nL_n/D_n>>1$, as it was considered in [4]. In this case, expression (7) can be rewritten as

$$J_n = e\frac{F\left(1-r\right)\alpha L_n}{\alpha^2 L_n^2 - 1}exp\left(-\alpha W\right)\left[\alpha L_n - 1 + 2\,exp\left(-\alpha\left(H-W\right) - \frac{H-W}{L_n}\right)\right]. \quad (9)$$

In summary, we get the spectral quantum efficiency

$$Q = \frac{J_{ph}}{eF\left(1-r\right)} = \left[1 - exp\left(-\alpha W\right)\right] + \frac{\alpha L_n\, exp\left(-\alpha W\right)}{\alpha^2 L_n^2 - 1}\left[\alpha L_n - 1 + 2\,exp\left(-\alpha\left(H-W\right) - \frac{H-W}{L_n}\right)\right]. \quad (10)$$

Calculation of solar cell parameters from spectral characteristics

In spectral range where

$$2\,exp\left(-\alpha\left(H-W\right) - \frac{H-W}{L_n}\right) << 1, \quad (11)$$

the following relation for quantum efficiency is true:

$$Q = 1 - \frac{exp\left(-\alpha W\right)}{\alpha L_n + 1}. \quad (12)$$

The condition (11) is fulfilled for most of the spectral range, becouse the absorption index α of CIGSS for a major part of the spectral sensitivity is no less than 10^4 cm^{-1} [13]. So, $\frac{H-W}{L_n} \geq 1$ and $\frac{H-W}{1/\alpha} > 1$.

It follows from (12) that

$$W = \frac{1}{\alpha} ln\frac{1}{\left(1-Q\right)\left(\alpha L_n + 1\right)}. \quad (13)$$

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

$$\alpha^{-1} >> W \quad (14)$$

is true. According to (14), we can use the procedure described in [14] to determine L_n.

If the condition (14) cannot be executed, we can take advantage of the spectral range where $\alpha^{-1} > W$. In this case, it is possible to write ratio $exp\left(-\alpha W\right) \approx 1 - \alpha W$. Then the expression (12) can be transformed to the form

$$\frac{Q}{\alpha} = L_n\left(1-Q\right) + W. \quad (15)$$

In this way, it is possible to determine the L_n and the W from linear approximation of the spectral characteristic of solar cell in coordinates Q/α and $(1-Q)$.

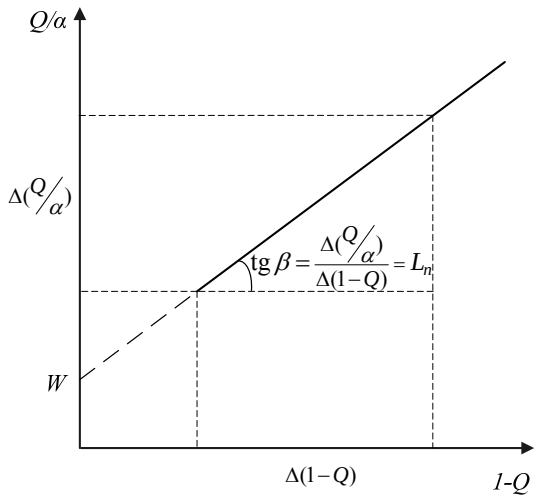

Fig. 2. Linear approximation of the spectral characteristic of solar cell in coordinates Q/α and $(1-Q)$

Measuring experimentally the spectral characteristic at different applied bias voltages U and calculating corresponding W, we obtain dependence $W(U)$. This dependence can be use for determine the built-in potential U_0 and the concentration of non-compensated acceptors N_A by equations (3) and (6).

Resume

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, diffusion length, built-in potential and concentration of non-compensated acceptors) 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» field 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.

REFERENCES

[1] Sze S.M., Physics of semiconductor devices, A Wiley-Interscience Publication, New York, 1981

[2] Mackel H., Cuevas A., The spectral response of the open-circuit voltage: a new characterization tool for solar cells, *Solar Energy Materials & Solar Cells* 81, 225-237, 2004

[3] Contreras M.A., Romero M.J., To B., Hasoon F., Noufi R., Ward S., Ramanathan K., Optimization of CBD CdS process in high-efficiency Cu(In,Ga)Se$_2$-based solar cells, *Thin Solid Films* 403-404, 204-211, 2002

[4] Klenk R., Schock H.-W., Bloss W.H., Photocurrent collection in thin film solar cells - caluculation and characterization for CuGaSe$_2$/(Zn,Cd)S, *Proceedings of 12th European Photovoltaic Solar Energy Conference*, 1588-1591, 1994

[5] Klenk R., Characterisation and modelling of chalcopyrite solar cells, *Thin Solid Films* 387, 135-140. 2001

[6] Gloeckler M., Fahrenbruch A.L., and Sites J.R., Numerical Modeling of CIGS and CdTe Solar Cells: Setting the Baseline, *Proc. World Conf. on Photovoltaic Energy Conversion* 3, 491-494, Osaka, Japan, May 2003

[7] Gloeckler M., Device physics of Cu(In,Ga)Se$_2$ thin-film solar cells, Fort Collins, Colorado, 2005

[8] Brown G., Faifer V., Pudov A., Anikeev S., Bykov E., Contreras M., Wu J., Determination of the minority carrier diffusion length in compositionally graded Cu(In,Ga)Se$_2$ solar cells using electron beam induced current, *Applied Physics Letters* 96, 022104. 2010

[9] Lux-Steiner M.Ch., Ennaoui A., Fischer Ch.-H., Jager-Waldau A., Klaer J., Klenk R., Konenkamp R., Matthes Th., Scheer R., Siebentritt S., Weidinger A., Processes for chalcopyrite-based solar cells, *Thin Solid Films* 361-362, 533-539. 2000

[10] Tivanov M., Astashenok L., Fedotov A., Effect of absorbing layer thickness on efficiency of solar cells based on Cu(In,Ga)(S,Se)$_2$, *Przegląd Elektrotechniczny* (Electrical Review) R. 88, 99-101. 2012

[11] Movla H., Optimization of the CIGS based thin film solar cells: Numerical simulation and analysis, *Optik* 125, 67-70. 2014

[12] Jarzembowski E., Maiberg M., Obereigner F., Kaufmann K., Krause S., Scheer R., Optical and electrical characterization of Cu(In,Ga)Se$_2$ thin film solar cells with varied absorber layer thickness, *Thin Solid Films* 576, 75-80. 2015

[13] Durante Rincon C.A., Hernandez E., Alonso M.I., Garriga M., Wasim S.M., Rincon C., Leon M., Optical transitions near the band edge in bulk $CuIn_xGa_{1-x}Se_2$ from ellipsometric measurements, *Materials Chemistry and Physics* 70, 300-304, 2001

[14] Lile D.L., Davis N.M., Semiconductor profiling using an optical probe, *Solid-State Electronics* 18, 699-704. 1975

***Authors**: dr Michael Tivanov, Belarusian State University, Faculty of Physics, Bobrujskaja 5, 220030 Minsk; mgr Alexander Moskalev, Belarusian State University, Faculty of Physics, Bobrujskaja 5, 220030 Minsk, prof. dr hab. Aleksy Patryn, Politechnika Koszalińska, Wydział Elektroniki i Informatyki, ul. JJ Śniadeckich 2, 75-453 Koszalin, E-mail: aleksy.patryn@gmail.com.*