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Effect of absorbing layer thickness on efficiency solar cells based on Cu(In,Ga)(S,Se)$_2$

Abstract. *On the basis of one-dimensional model of the solar cell (SC) the influence of photoactive layer thickness on the photocurrent (a key parameter for the collection efficiency of photogenerated charge carriers) of a has been studied. It is shown that for a typical Cu(In,Ga)(S,Se)$_2$ - based SC the optimal value of the photoactive layer thickness is about 1.5 μm. Reducing the thickness of the photoactive layer leads to a sharp decrease in the photocurrent and increase the series resistance.*

Streszczenie. *Na podstawie jednowymiarowego modelu ogniwa słonecznego zbadano wpływ grubości warstwy fotoaktywnej na natężenie fotoprądu (parametru kluczowego dla ustalania sprawności fotogenerowanych nośników ładunku). Wykazano, że dla typowych ogniw słonecznych opartych o Cu(In,Ga)(S,Se)$_2$ optymalną wartością grubości warstwy fotoaktywnej jest w przybliżeniu 1,5 μm. Redukując grubość warstwy fotoaktywnej doprowadzono do gwałtownego spadku wartości fotoprądu i wzrostu rezystancji szeregowej. (**Efekt absorbcji grubości warstwy na sprawność ogniw słonecznych na bazie Cu(In,Ga)(S,Se)$_2$**).*

Keywords: Cu(In,Ga)(S,Se)$_2$, solar cell, absorbing layer.
Słowa kluczowe: Cu(In,Ga)(S,Se)$_2$, ogniwo słoneczne, warstwa absorbcyjna.

Introduction

The suitability of thin-film Cu(In,Ga)(S,Se)$_2$ (CIGSS) solar cells (SCs) usage is shown in many studies [1-4] because these chalcopyrite compounds have shown the highest efficiencies (> 19 %) for laboratory thin film SCs. The semiconductor CIGSS material have a high value of absorption index, therefore, it is possible to use a fairly thin films in absorber layer of SC [4, 5]. This, in turn, significantly reduces material costs. The band gap in CIGSS-based solar cells can be varied from 1.0 to 2.4 eV and can be reconciled with the optimal value for the Sun radiation spectrum [6-9]. Moreover, these SCs have a very long term stability and radiation resistance [5].

It was developed many methods to produce thin films of CIGSS. Depending on the production method the following photoactive layer thicknesses are possible: ~1.5 μm for vacuum deposition [4], ~2.0 μm for co-evaporation in vacuum [10], ~2.0 μm for metalic precursors handling in S/Se-vapor [11], ~10.0 μm for combination of mechano-chemical synthesis, wet bead milling, and screen-printing/sintering process [12]. The maximum efficiency of CIGSS-SCs was achieved by the using of the method of vacuum deposition [4].

Since the CIGSS solid solution allows production of thin enough SCs, there is a need to clarify the optimal value of the thickness of the absorbing layer in SCs based on CIGSS. Too small thickness of the absorbing layer leads to a lower value of the photocurrent. Too thick absorbing layer leads to a large series resistance and increase in material consumption and, consequently, the cost per unit of power produced. As shown [1-4, 11, 12] exprimentally, typical values for the thickness of the absorbing layer are in the range of 2.0-3.0 μm.

In this paper we consider the influence of the photoactive layer thickness on photocurrent for a CIGSS-based SC. The value of the photocurrent is a key SC parameter which shows the collection efficiency of photogenerated charge carriers.

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

Let us use the unidimensional model of SC presented in [13-15]. 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 [16], extinction of the visible and infrared radiation therein may be ignored. Thus, a unidimensional model of CIGSS-SC (just for a major part of the spectral sensitivity) can be schematically shown as in Fig. 1, similar to the scheme in [17].

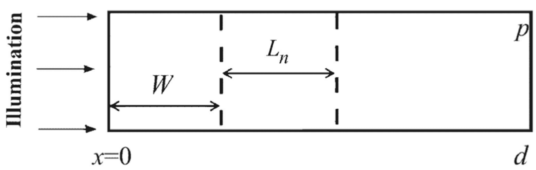

Fig.1. One-dimensional model of SC CIGSS-layer: W – the SCR value, L_n – the diffusion length, d – the thickness of CIGSS-layer

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

$$J_{ph} = J_n + J_{SCR}, \quad (1)$$

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

To calculate the density of the photocurrent we used the expression

$$J_{ph} = e\sum_i \eta(\lambda_i)\frac{F_i(\lambda_i)}{h\nu_i}\Delta\lambda_i, \quad (2)$$

where η – quantum efficiency at a wavelength λ_i, $\Delta\lambda_i$ – spacing between adjacent wavelengths used to calculate, $F_i(\lambda_i)$ – optical power of incident radiation for λ_i.

In this case, according to (1), quantum efficiency consists of two parts

$$\eta = \eta_{drift} + \eta_{dif}. \quad (3)$$

Drift component for SCR

$$\eta_{drift} = 1 - exp(-\alpha W). \quad (4)$$

where α – the absorption index. In equation (3) for quantum efficiency in the SCR, we have neglected the recombination losses on the metallurgical boundary of the *pn*-junction, because of their smallness in consequence of the strong electrostatic field.

We have simplified the diffusion component in (3) for quasi-neutral region of the CIGSS-layer in the absence of drawing field [13] by assuming that the reflection of carriers from the back contact is

$$\eta_{dif} = \frac{e^{-\alpha W} L_n \alpha \left(L_n \alpha - cth \frac{d-W}{L_n} \right) + e^{-\alpha (d-W)} csch \frac{d-W}{L_n}}{L_n^2 \alpha^2 - 1}. \quad (5)$$

The expressions (2-5) were used to calculate the density of the photocurrent.

Effect of absorbing layer thickness on SC efficiency

Qualitative characteristics of the solar cell efficiency for different photoactive layer thicknesses can be obtained by calculating the photocurrent density, taking into account the spectral distribution of solar radiation.

We calculated J_{ph} for solar radiation AM0 and AM1.5 (Fig.2) using standard of American Society for Testing and Materials (ASTM) [18,19].

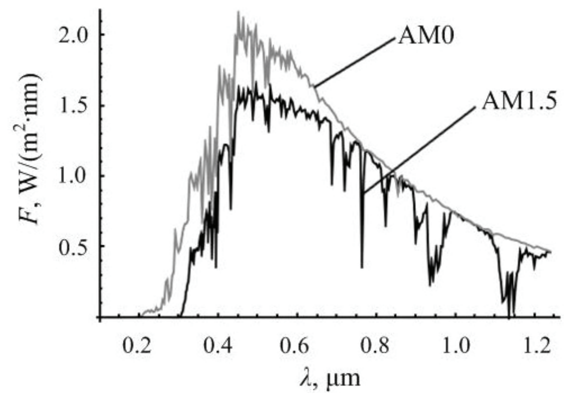

Fig.2. Spectral solar irradiance [18, 19]

To calculate the density of the photocurrent, it is also necessary to know the spectral dependence of the optical absorption in absorber layer. We used the following expression for the absorption index

$$\alpha = \frac{A}{\nu} (h\nu - E_g)^{\frac{1}{2}}, \quad (6)$$

where E_g – band gap, A – experimentally determined constant. To determine A, we used the data presented in [1].

Fig. 3 and Fig. 4 shows the calculated dependence of the photocurrent density on the width of the SCR and the diffusion length. As can be seen, the width of the SCR and the diffusion length has an effect on the photocurrent density. Therefore, required thickness of the SC absorbing layer is determined by the diffusion length and the width of the SCR.

To calculate dependence of the photocurrent density on the absorber layer thickness we used the typical values of the SCR for CIGSS-SC and the diffusion length assuming W = 0.25 μm and L_n = 1 μm according to [1,20].

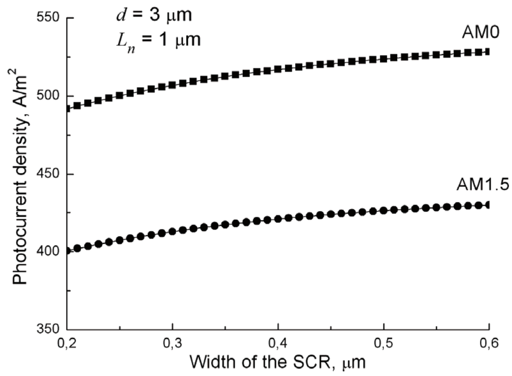

Fig.3. Dependence of the photocurrent density on the SCR width for 1.1 eV bandgap of the absorbing CIGSS-layer

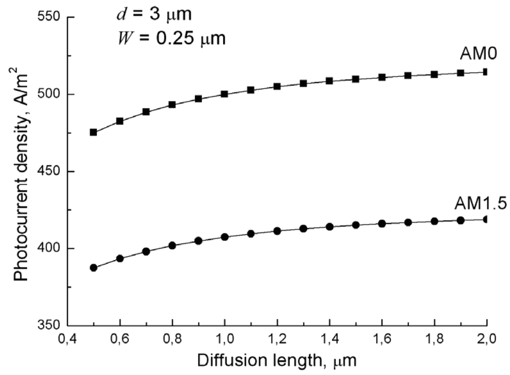

Fig.4. Dependence of the photocurrent density on the diffusion length for 1.1 eV bandgap of the absorbing CIGSS-layer

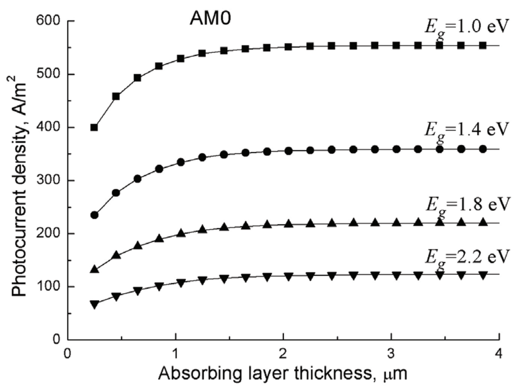

Fig.5. Dependence of the photocurrent density on the thickness of the absorbing CIGSS-layer` for different bandgaps and solar radiation conditions AM0

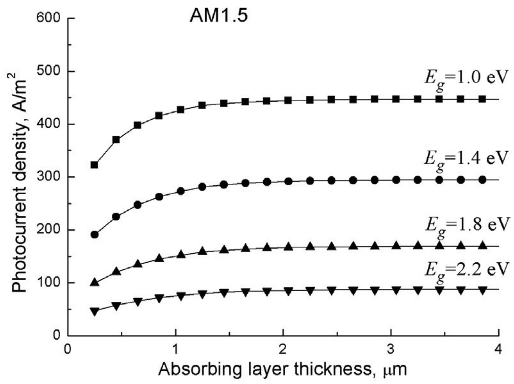

Fig.6. Dependence of the photocurrent density on the thickness of the absorbing CIGSS-layer for different bandgaps and solar radiation conditions AM1.5

Fig. 5 and Fig. 6 show the calculated dependencies of the photocurrent density on the absorber layer thickness for solar radiation conditions AM0 and AM1.5, respectively.

For sufficiently large given thickness *d* the effective diffusion length, used for the calculations by formula (5), is the diffusion length L_n of material itself.

In the case where the given thickness is

$$d < L_n + W , \quad (7)$$

the effective diffusion length defined as

$$L_n^{eff} = d - W . \quad (8)$$

As follows from the dependences obtained, the increase in the thickness of the absorbing layer over 1.5 μm does not increase the density of the photocurrent for light conditions AM0 and AM1.5. This increases the consumption of material for SC production and increases the parasitic series resistance, leading to a deterioration in the operating parameters of the SC.

Contrariwise, the decrease in the thickness of the absorbing layer less than 1.5 μm leads to a significant decrease in the efficiency of photoconversion.

Photocurrent density reached as high as 98% of the limit under AM0 for photoactive layer thickness of about 1.37 μm, and under AM1, 5 - for 1.39 μm.

Therefore, for typical CIGSS-based SCs of terrestrial and space application the sufficient thickness is about 1.5 microns. Herewith, according to findings, the value of the optimum thickness of the absorber layer is the same for different values of the band gap.

Conclusion

Our estimations of the $Cu(In,Ga)(S,Se)_2$ SC photocurrent have shown that the optimal thickness of the absorbing layer for typical CIGSS-based SCs for terrestrial and space application is about 1.5 μm. These calculations were based on one-dimensional model od SC with the assumptions that the reflection of charge carriers from back contact is absent, window and buffer layers are transparent, the recombination losses at the metallurgical *pn*-junction interface are low.

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