



# The influence of optical and recombination losses on the efficiency of thin-film solar cells with a copper oxide absorber layer

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## ABSTRACT

We presented the results of the calculations of optical and recombination losses in photo-conductor layers on the basis of heterojunctions with copper oxide absorbing layers (CuO, Cu<sub>2</sub>O) and zinc magnesium oxide (ZMO) window layer. Aluminum-doped zinc oxide (AZO) and indium tin oxide (ITO) were used as the solar cell frontal contacts. The spectral dependences of the transmission coefficient of these devices were determined. The reflection of light from the boundary of two contacting materials and light absorption in the auxiliary layers of photo-conductors were taken into account. The influence of optical and recombination losses on the internal and external quantum yield, short circuit current density, and maximum efficiency of solar cells are investigated. It has been established that the highest efficiency ( $\eta = 19.12\%$ ) is shown by the device with the structure of AZO/ZMO/CuO.

## 1. Introduction

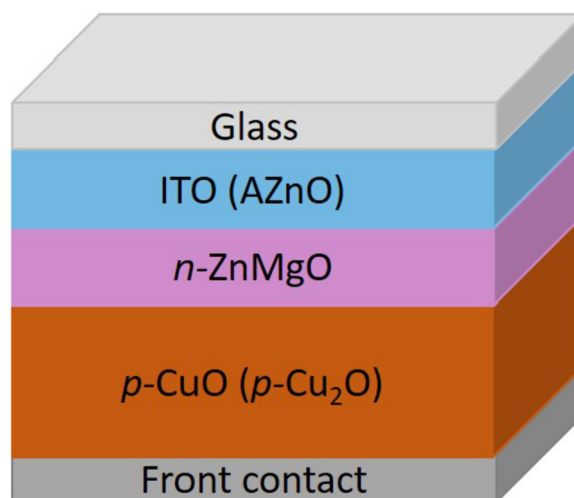
Solar energy is one of the most promising renewable energy sources. Semiconductor metal oxides (TiO<sub>2</sub>, ZnO, CuO, Cu<sub>2</sub>O, WO<sub>3</sub>, etc. [1–8]) are widely used in photovoltaics, since most of them are non-toxic, chemically stable in the atmosphere, and their components are widespread in the Earth's crust with exception of In. Solar cells (SCs), which researchers' consist entirely of metal oxide layers, the so-called oxide photovoltaic cells, have recently attracted considerable attention due to the prospects for a significant reduction of the price of energy produced by the use of cheap materials and methods for its deposition [1]. On the basis of these materials, it is possible to create a flexible thin-film SCs for various uses [9].

Copper oxide (Cu<sub>x</sub>O) is a perspective material for photovoltaics. Generally, two phases of this compound, tenorite CuO and cuprite Cu<sub>2</sub>O are used to create the SCs. CuO is a semiconductor material with a band gap width that varies from 1.30 to 1.44 eV [4–6], depending on the conditions of the preparation, while Cu<sub>2</sub>O is a material with a band gap of 2.0–2.6 eV [10]. The band gap of the first material corresponds to the Shockley-Queisser optimum, while on the basis of the second one, it is possible to create transparent solar cells in the visible spectral region [11]. In this case, ITO or aluminum-doped zinc oxide (AZO) is most often used as a material of window layer and conductive front contact [12–15].

The efficiency of the conversion of the energy of the solar cells based on the heterojunction of *n*-ZnO/*p*-Cu<sub>2</sub>O in our time does not exceed 1.53% [2], while for solar cells with the structure *n*-ZnO/*p*-CuO, obtained efficiency values of only 3.83% [3]. This is due to the large inconsistency of lattice constants of contacting materials and the formation of interphase states with the high concentration

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**Fig. 1.** The schematic structure of solar cell based on  $n\text{-Zn}_{1-x}\text{Mg}_x\text{O}/p\text{-CuO}$  and  $n\text{-Zn}_{1-x}\text{Mg}_x\text{O}/p\text{-Cu}_2\text{O}$  heterojunctions.

on the heterojunction. However, the work [16] proved the prospect of using ZnO/CuO transitions in the electronics and solar energy. According to the peculiarities of the crystalline lattice of copper oxide (monoclinic,  $a = 0.4684$  nm,  $b = 0.3425$  nm,  $c = 0.5129$  nm) and zinc oxide (hexagonal,  $a = 0.3249$  nm,  $c = 0.5206$  nm), it is possible to create a virtually defect-free heterojunction on their basis. In this case, the oriented growth of CuO layers on the surface of ZnO crystals must be made by combining the crystal plane (100) of CuO with the surface (101) of ZnO [16]. Unfortunately, in the case of the  $n\text{-ZnO}/p\text{-Cu}_2\text{O}$  heterojunction, the grain boundaries are likely to remain highly defective.

The alloying of zinc oxide with isovalent impurities of magnesium (Mg) allows to control the physical properties of a solid solution. Thus, changing the concentration of Mg in the material, it is possible to vary its lattice constants, band gap, and work function, while optimizing the interphase boundary of the heterojunction and the values of the energy barriers in the conduction  $\Delta E_c$  and valence  $\Delta E_v$  band zones [17,18].

The main purpose of this work is to study the impact of optical and recombination losses on the efficiency of thin film solar cells based on heterojunctions  $n\text{-Zn}_{1-x}\text{Mg}_x\text{O}/p\text{-CuO}$  and  $n\text{-Zn}_{1-x}\text{Mg}_x\text{O}/p\text{-Cu}_2\text{O}$ , and the optimization of the structure of these devices.

## 2. The losses of light reflection from layers in the solar cells

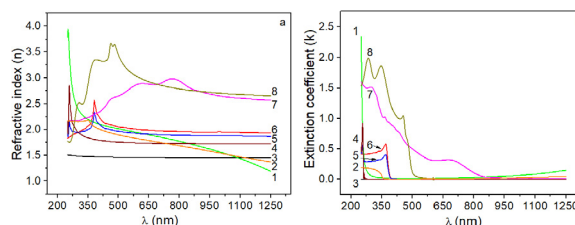
The thin-film solar cells usually consist of a window and absorbing layers, front and back contacts. Fig. 1 schematically shows the investigated structure of the solar cell.

For the simulation of reflection of light from the layers of the solar cell, the typical values of the thickness of the window layer  $\text{Zn}_{1-x}\text{Mg}_x\text{O}$  (ZMO) were chosen that varied from  $d = 25$  nm–200 nm. The thickness of the AZO (ITO) layer was taken as  $d = 100$  nm and 200 nm. The same values of thickness have real SCs [19].

The sunlight flow passes through all layers of the solar cell before reaching the CuO ( $\text{Cu}_2\text{O}$ ) layer and being absorbed by it. On that way, there is the reflection of light from the interfaces of different materials (air-glass, glass-ITO(AZO), ITO(AZO)-ZMO and ZMO-CuO( $\text{Cu}_2\text{O}$ )), as well as the absorption of light by them. These effects result in energy loss in the absorbing layer, where the generation of electron-hole pairs occurs under the solar radiation.

To calculate the reflection of light from the boundaries of two contact materials, we used the expression given in our previous works [20,21].

Fig. 2 shows the spectral dependencies of the refractive index and extinction coefficient for each layer of the multilayer structure used to calculate the optical loss of light in the solar cells. Since SCs uses a special glass with a very small absorption coefficient, the value of the extinction coefficient for glass was assumed to be zero  $k = 0$ . To determine the glass refractive index, the Sellmeier's



**Fig. 2.** Spectral dependencies of refractive index (a) and extinction coefficient (b) ITO (1), AZO (2), glass (3), MgO (4), ZMO (5), ZnO (6), CuO (7) and  $\text{Cu}_2\text{O}$  (8).

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