ISSN 1606-867X (Print)
ISSN 2687-0711 (Online)
Condensed Matter and Interphases
Kondensirovannye Sredy i Mezhfaznye Granitsy
https://journals.vsu.ru/kcmf/

Original articles

Research article
https://doi.org/10.17308/kcmf.2025.27/12808

Effect of the re-emitting layer of organic thin film on the efficiency of silicon solar cells

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Abstract

Purpose: Photovoltaic solar energy conversion technologies represent promising pathways to clean and renewable energy production. Research on organic solar cells is actively developing, especially in the last decade it has attracted scientific and economic interest driven by the rapid increase in energy conversion efficiency. In recent years, luminescent materials capable of converting a broad spectrum of light into photons of a specific wavelength have been synthesized and used to minimize losses in the solar cell-based energy conversion process. This paper presents a study of the optical and luminescent properties of thin films of copper complexes $C_{62}H_{50}Cu_2I_2N_8P_2$.

Experimental: It is proposed to use this material as a re-emitting layer on the surface of a solar cell in order to increase the coefficient of performance (COP) of the latter by converting energy from the ultraviolet range to the visible range. A study of the volt-ampere characteristics of a pure single-crystal solar cell and a cell with an re-emitting copper complex layer has been carried out.

Conclusions: It is shown that deposition of $C_{62}H_{50}Cu_2I_2N_8P_2$ on the surface of solar cells allows increasing the efficiency of converters by 1.45 % in the ultraviolet range at low economic costs. Mechanisms for enhancing energy conversion are discussed and recent experimental results on similar studies are analyzed.

Keywords: Solar cell, Photovoltaic converters, Optical spectrum, Luminescence, Thin films, Copper complexes

Funding Source: The study was supported by the grant of the Russian Science Foundation No. 23-22-10007 and the region of Crimea.

For citation: Tyutyunik A. S., Gurchenko V. S., Mazinov A. S. Effect of the re-emitting layer of organic thin film on the efficiency of silicon solar cells. *Condensed Matter and Interphases*. 2025;27(2): 316–322. https://doi.org/10.17308/kcmf.2025.27/12808

Для цитирования: Тютюник А. С., Гурченко В. С., Мазинов А. С. Влияние переизлучающего слоя органической тонкой плёнки на КПД кремниевых солнечных батарей. *Конденсированные среды и межфазные границы*. 2025;27(2): 316–322. https://doi.org/10.17308/kcmf.2025.27/12808

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1. Introduction

The problem of finding alternative energy sources is very relevant nowadays, attempts are being made to make wider use of solar and other types of energy. Research on organic solar cells has evolved over the last 40 years, but especially in the last decade it has attracted scientific and economic interest driven by the rapid increase in energy conversion efficiency. This has been achieved through the introduction of new materials, improved manufacturing techniques and more sophisticated device designs [1]. Scientists estimate that between 2004 and 2030, annual global energy consumption will increase by more than 50 %. A commensurate increase in CO_2 emissions is expected, most of which is due to the burning of coal, the world's fastest growing energy source. Despite the projected steady increase in oil and gas prices, less than 10 % of global energy production in 2030 is projected to come from renewable energy sources such as hydroelectric, solar, wind, hydrothermal and biomass. To reduce global dependence on exhaustible natural resources and their environmentally hazardous burning, more scientific effort must be directed towards reducing the cost of renewable energy production. Current annual solar energy use is well below 1% of total energy use, while fossil fuels account for over 90 % of energy use. Before solar energy can be utilized on a large scale, more efficient photovoltaic systems need to be developed at lower costs [2–8].

The high cost of solar radiation conversion largely restrains the development of this area. A possible way to make it cheaper is to attract new low-cost materials and technical devices based on them that increase the efficiency of sunlight conversion [9]. Such systems can include photovoltaic concentrators, which are designed to increase the electrical energy obtained from the solar panel [10]. High optical concentration without excessive heating in a stationary system can be achieved using luminescent solar concentrators (LSC) [11–13]. Luminescent solar concentrators consist of a dye dispersed in a transparent waveguide. The incident light is absorbed by the dye and then re-emitted. The energy difference between absorption and emission prevents the dye from re-absorbing light. Thus, luminescent solar concentrators can achieve high optical concentrations without tracking sunlight [14]. Unfortunately, the efficiency of fluorescent solar concentrators is limited by self-absorption losses.

In recent years, luminescent materials capable of converting a wide spectrum of light into photons of a specific wavelength have been synthesized and used to minimize losses in the solar cell-based energy conversion process [15]. This technique, called third generation solar photon conversion, involves the introduction of a passive luminescent layer in photovoltaic cells [16–18]. An important aspect of using this technology is that the spectral converters are easily applicable to existing solar cells with minor modifications, since the spectral converters and solar cells can be optimized independently. To improve the efficiency of single junction solar cells, three luminescence processes including upconversion, quantum reduction, and downconversion are being investigated to develop efficient photovoltaic devices. Trivalent lanthanide ions are prime candidates for efficient spectral conversion because of their rich energy level structure (known as the Dicke diagram), which allows photons to be easily manipulated [19–21]. In order to increase the efficiency of the initial solar cells within the framework of the conducted research, binuclear complexes of copper with pyridyltriazole were used as luminescent materials, namely, copper complex $C_{62}H_{50}Cu_2I_2N_8P_2$ was considered [22].

2. Materials, methods and main idea

The basic idea of increasing the efficiency of a solar cell (SC) is to apply to the surface of the SC a thin film material having such optical properties that the material will transmit the main spectrum of the incident electromagnetic radiation. At the same time this material due to luminescent properties will convert a part of the spectrum from the region of low efficient operation of the solar cell to the region of the spectrum of more efficient operation of the SE. The realization of this task is possible thanks to the achievements in the field of organic and inorganic chemistry, which make it possible to create materials with specified optical properties. In particular, it is proposed to apply to the surface of the solar cell a material having absorption in the ultraviolet range region and re-emission in the visible range region.

The objects of research were binuclear complexes of copper with pyridyltriazole, namely, the complex of Cu $C_{62}H_{50}Cu_2I_2N_8P_2$ (b-phen). The methodology of synthesis of these materials is described in detail in [22].Copper b-phen complexes are interesting materials due to their mechanochromic properties. When this material is mechanically pulverized, a shift of luminescence spectra from green to yellow area is observed. At the same time, this effect is reversible by mild annealing [22]. The second interesting property of this compound is the variation of the luminescence spectrum depending on the excitation wavelength. This phenomenon occurs in the excitation wavelength range of 385 to 435 nm with corresponding over-emission in the range of 508 to 595 nm. Note that the quantum yield of the compound $C_{62}H_{50}Cu_2I_2N_8P_2$ is 28 % at room temperature and 55 %, at 77 K [22].

Absorption and transmission spectra were investigated using a GBC Cintra 4040 spectrophotometer. Tungsten and deuterium lamps were used as sources, which made it possible to realize the range of incident radiation from 250 to 800 nm with a slit width of 0.1–2 nm. Analyzing the absorption spectra of copper complexes, we note that the absorption maximum of these materials is in the range of 290–350 nm with a subsequent decline in the visible range (Fig. 1a). In turn, analyzing the transmission spectra, we emphasize the fact of almost complete transmittance of electromagnetic radiation in the visible range and near-IR (Fig. 1a). Luminescence spectra were studied using a FluoroMax-4 instrument. In order to identify the optimal maximum of excitation radiation, a standard technique of pulse excitation, in which multiple irradiations of film structures are performed, was employed. Fig. 1b shows the luminescence spectrum of the copper b-phen complex at an excitation wavelength of 400 nm. Note that the luminescence maximum is observed at a wavelength of 530 nm (Fig. 1b).

The presented copper complexes fully meet the objective of increasing the efficiency of solar cells, but the thickness and homogeneity of the corresponding film is also an important factor. Therefore, the formation of b-phen thin films on the surface SE was carried out by centrifugation (Fig. 2b). Chloroform ($CHCl_3$) was used to create a solution from the original solid-state, powdered copper complexes. The concentration of the starting substance in the solution was 1 mg/ml. The mass of powder materials was controlled by weighing on high-precision analytical scales HR-250AZ. In the process of material application, the rotational speed of PE-6900 centrifuge was brought to 1500–3000 rpm in steps of 500 rpm [23]. The volume applied per application cycle was 1 ml.

In this research, single-crystalline silicon solar cells created by diffusion technology with an efficiency of ~ 22 % were used (inset of Fig. 2a) [24]. Fig. 2a shows the quantum efficiency of the silicon solar cell. It is worth noting the decline

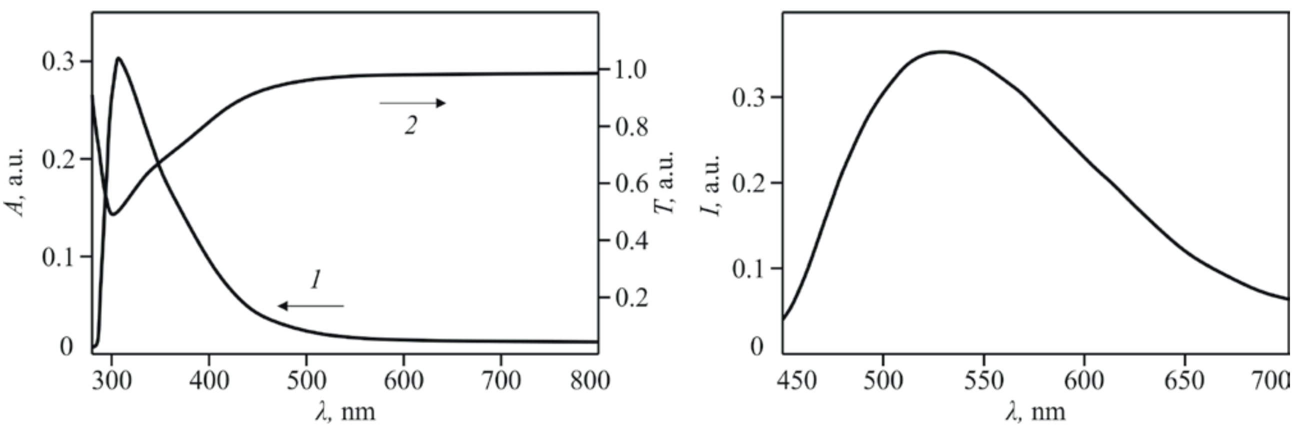

Fig. 1. Optical (a) absorption (*1*) and transmission (*2*) spectra and luminescence (b) of copper b-phen complexes

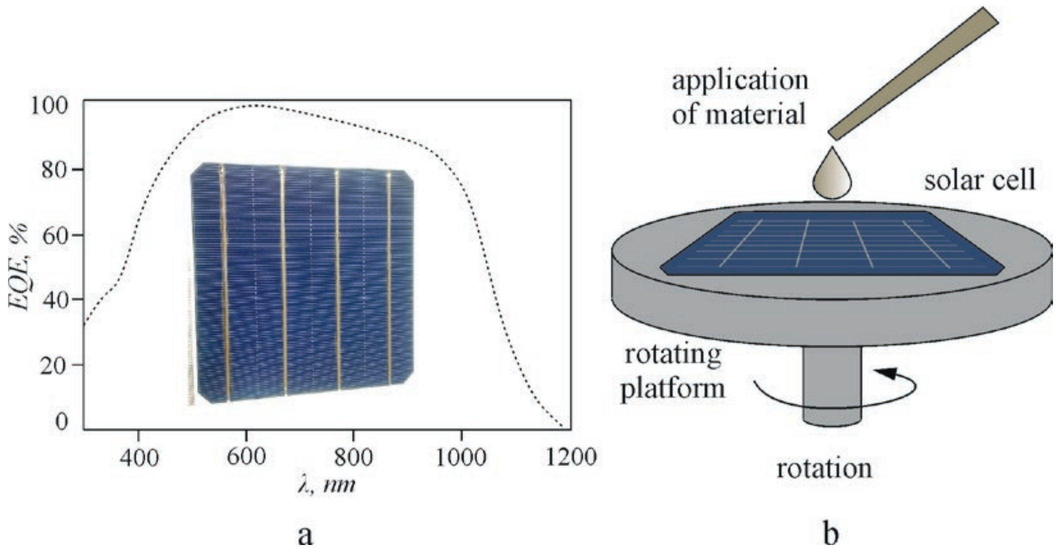

Fig. 2. Quantum efficiency of single crystal solar cell (a) scheme of deposition of copper b-phen complexes on solar cell by centrifugation (b)

in the conversion efficiency of the element in the UV range, which is due to such factors as the dissipation of part of the energy on phonons - transition to thermal energy, as well as recombination on the surface states of charge carriers [24].

An important factor in conducting measurements of the parameters of a pure solar cell and a luminescent-coated cell was strict adherence to the identity of the experimental conditions. The study of electrical parameters of solar cells was carried out using a Keysight B1500A semiconductor analyzer. Through volt-ampere characteristic analysis (VAC) and subsequent calculations, the main characteristics including efficiency and Fill factor (FF) were obtained. The measurements were carried out at a temperature of 20 °C. An LED matrix was used as an illumination source, the emission spectrum of which is in the range of 400–950 nm The total incoming power was ~ 22 W/m^2.

3. Results and discussion

The VAC was measured under two variations of the incident radiation, namely in the range from 400 to 950 nm and a power of 22 W/m^2, as well as under incident radiation with a maximum wavelength of 400 nm and a power of 6 W/m^2.

The choice of a separate narrow range of incident radiation in the UV region is due to the excitation wavelength of the copper complexes.

In Fig. 3 shows the VACs of both pure SE and with a surface layer of copper complex. In the course of the experiment, the thin film copper complex was applied layer by layer to the surface of the solar cell with the measurements of the VAC at each stage.

Analyzing the obtained results, we note that in the range of radiation 400-950 nm, the efficiency of pure single-crystalline solar cell was 21.74 %, whereas with the surface layer of copper complex, an increase in the efficiency of SE is observed (Fig. 3A). The maximum increase in the efficiency is seen when the volume of the deposited material V = 2 ml, on the surface of the SE, the efficiency was 22.17 %.

For incident radiation with a maximum of 400 nm, the increase in efficiency of a solar cell with a surface over-emitting layer is more pronounced (Fig. 3b). The efficiency of the pure element in such a case was 19.76 %. In turn, when the volume of applied material V = 3 ml, the efficiency was 21.21 %.

Photovoltaic conversion efficiency is defined as the ratio of the maximum electrical output power to the total incident power, and the solar cell fill factor is taken into account:

$$FF = \frac{P_{\max}}{U_{OC} I_{SC}}, \quad (1)$$

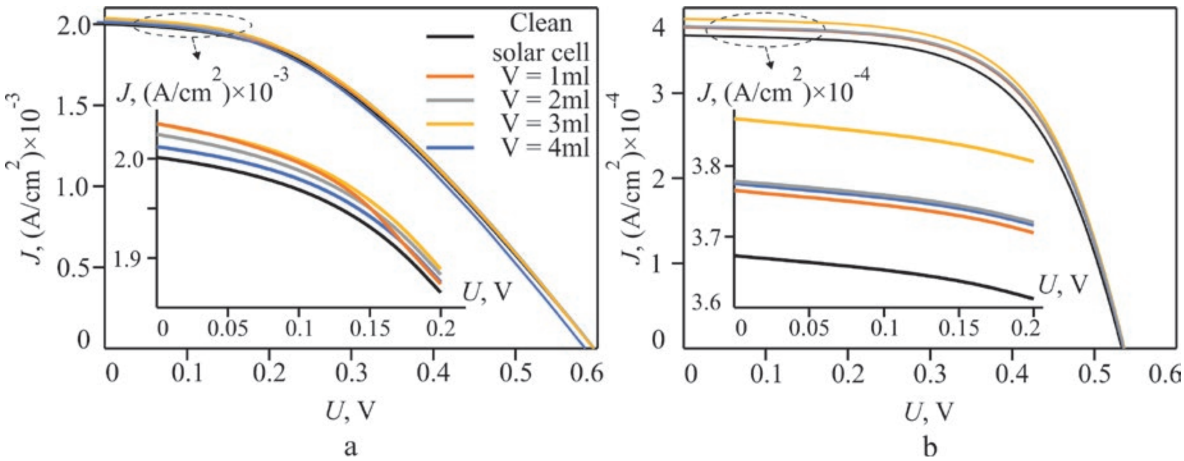

Fig. 3. Volt-ampere characteristics in the 400–950 nm range (a) and at λ = 400 nm (b)

where *FF* – solar cell fill factor; P_{max} – solar cell power; U_{OC} - solar cell no-load voltage; I_{SC} – solar cell short-circuit current.

The efficiency of a solar cell is in turn defined as:

$$\eta = \frac{P_{max}}{ES}, \quad (2)$$

where *E* is the intensity of radiation falling on the solar cell; *S* is the surface area of the solar cell.

The measurement results as well as the calculated values of the solar cell parameters with and without the applied over-emitting coating are presented in Table1 and 2 for the 400–950 nm range and the narrow range with a maximum at 400 nm, respectively.

4. Conclusion

Thus the deposition of a thin film of copper complex $C_{62}H_{50}Cu_2I_2N_8P_2$ on the surface of a monocrystalline solar cell allowed to increase the efficiency of the solar cell by converting the energy from the ultraviolet range region to the visible range region. In particular, there is an increase in the short-circuit current of the SE and, as a consequence, an increase in efficiency.

The layer-by-layer application of the investigated material on the surface of the SE allowed determining the optimal ratio of the amount of applied material, while maximizing the efficiency. As a result, with incident radiation of 400–950 nm and volume of applied material in solution – 2 ml, we observe an efficiency gain of 0.43 %, an increase from 21.74 to 22.17 %. In turn, at incident radiation in the UV region with a maximum of 400 nm and the volume of applied material in solution – 3 ml, the efficiency gain is 1.45 %, an increase from 19.76 to 21.21 %. It is worth noting that further increase in the thickness of the surface layer of the copper complex leads to

Table 1. Solar cell parameters at incident wavelength of 400-950 nm

Parameter	Monocrystalline solar cell	1 layer of material	2 layer of material	3 layer of material	4 layer of material
P_{max}, mW	114.79	115.92	117.06	116.97	116.52
U_{max}, mV	325	325	325	325	325
I_{max}, mA	353.22	356.69	360.18	359.92	358.53
U_{OC}, mV	595.25	595.22	595.80	595.37	595.14
I_{SC}, mA	480.33	488.50	485.94	488.55	482.95
FF	0.401	0.398	0.404	0.402	0.405
η, %	21.74	21.95	22.17	22.15	22.06
E, mW/cm^2	2.2	2.2	2.2	2.2	2.2
S, cm^2	240	240	240	240	240

Table 2. Solar cell parameters at an incident wavelength of 400 nm

Parameter	Monocrystalline solar cell	1 layer of material	2 layer of material	3 layer of material	4 layer of material
$P_{max,}$ mW	28.47	29.66	29.90	30.56	29.80
U_{max}, mV	400	400	400	400	400
I_{max}, mA	71.17	74.17	74.77	76.41	74.51
U_{OC}, mV	534.42	537.03	537.35	537.81	536.67
I_{SC}, mA	88.15	90.36	90.69	92.80	90.60
FF	0.604	0.611	0.613	0.612	0.612
η, %	19.77	20.6	20.76	21.22	20.69
E, mW/cm^2	0.6	0.6	0.6	0.6	0.6
S, cm^2	240	240	240	240	240

Where: η – efficiency of solar panel; P_{max} – power of solar panel

parasitic absorption of this material in the visible range, which appreciably reduces the efficiency.

Traditional inorganic solar cell models based on Shockley's work have been widely used to understand the bulk heterojunction response of organic solar cells. While these models can be useful, there are key points that differ from traditional solar cell behavior. The competition of the two physical processes described above leads to the need for strict control of the application of the luminescent material on the surface of the SE while respecting the maximum efficiency of the latter. The presence of the luminescence peak of copper complexes at wavelengths of 530-550 nm opens obvious prospects for the application of the investigated material for GaAs photovoltaic cells, in which the conversion maximum occurs in this region. Among other things, the results in this paper are of significant interest in the space industry, where the share of the high-energy spectrum is much higher.

Contribution of the authors

The authors contributed equally to this article.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Received 10.07.2024; approved after reviewing 04.09.2024; accepted for publication 16.09.2024; published online 25.06.2025.