

# Effect nanoparticles silicon carbide on the characteristics of solar cells based on lutetium diphthalocyanine

© S.I. Rasmagin

Prokhorov Institute of General Physics, Russian Academy of Sciences,  
119991 Moscow, Russia

e-mail: rasmus123@yandex.ru

Received April 25, 2022

Revised September 29, 2022

Accepted September 30, 2022

Composites nanoparticles silicon carbide with lutetium diphthalocyanine were created. The size and shape nanoparticles silicon carbide, as well as their phase composition, were determined by electron microscopy. The absorption spectra of nanoparticles silicon carbide, a solution of lutetium diphthalocyanine, and a composite nanoparticles silicon carbide with lutetium diphthalocyanine were measured. Raman scattering spectra were obtained for nanoparticles silicon carbide. A comparative analysis of the absorption spectra of various samples was carried out. The effect of lutetium diphthalocyanine molecules on the optical properties nanoparticles silicon carbide was elucidated. The resulting composite of lutetium diphthalocyanine and nanoparticles silicon carbide was used as a sensitizer to create Grätzel cells. In the control Grätzel cell, lutetium diphthalocyanine was used as an absorber; in the working cell, lutetium diphthalocyanine was used in combination with nanoparticles silicon carbide. The open-circuit voltage and short-circuit current were measured under the same illumination of both Grätzel cells.

**Keywords:** Solar photovoltaics, sensitizers, solar cells, silicon carbide, lutetium diphthalocyanine, semiconductor nanoparticles, Grätzel cells.

DOI: 10.21883/EOS.2022.12.55251.3602-22

## Introduction

The rapid development of solar panels attracts scientific and research interest in creating new and improving the characteristics of existing solar cells. The main element of solar panels are photocells. At present, photocells are mainly created on the basis of inorganic semiconductors (crystalline and amorphous Silicon), perovskite compounds (for example, methylammonium lead halide) and molecular dyes (phthalocyanines, anthocyanins, copolymer solutions etc.).

Solar cells based on single-crystal Silicon have a high coefficient of performance (COP), a long service life (more than 10 years), are completely harmless, but expensive to manufacture.

Solar cells based on Perovskites have a high COP, they are cheaper than silicon photocells, but they have such disadvantages as a short service life (1–2 years), toxic due to the presence of lead, and relatively expensive to manufacture.

Solar cells based on natural molecular dyes are harmless and have a low manufacturing cost, but they have such disadvantages as lower COP compared to photocells based on silicon and perovskites, short service life (1–2 years) and toxic when used Ruthenium.

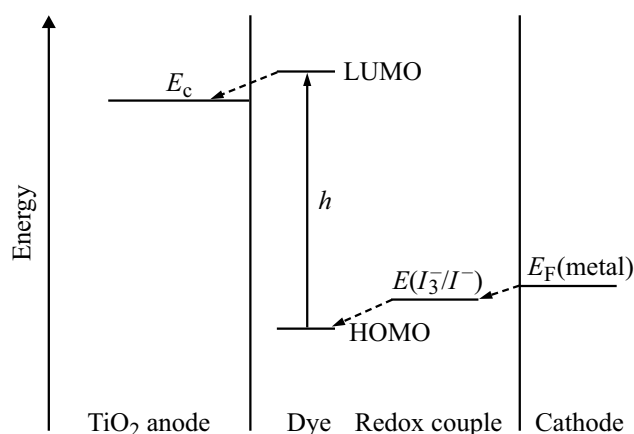
Photocells based on crystalline Silicon have an efficiency of ~ 24%, while those of amorphous silicon have a COP of ~ 8% [1,2]. Photocells based on Perovskite compounds have COP ≥ 24% [3]. Photocells based on molecular dyes have COP ~ 8% when toxic Ruthenium is used in dyes [4]. Dye-based photocells are also often referred to

in the literature as Grätzel cells. In this work, we have studied the optical properties of molecular dyes for their use in Grätzel cells. Grätzel cells use a bulk heterojunction and are mesoporous semiconductor layers coated with dye monolayers as molecular sensitizers and an electrolyte layer playing the role of a redox element Metal oxides of the Titanium dioxide type (TiO<sub>2</sub>) act as semiconductor layers. The principle of operation of Grätzel cells differs significantly from the operation of photocells on *p–n*-junctions. The principle of operation of Grätzel photocells is based on the photoelectrochemical effect caused by photoexcitation of organic dye molecules and redox reactions in the electrolyte. In a particular case, organic semiconductors of the Metal Phthalocyanine type can be used as organic dyes. Since organic semiconductors have a low dielectric constant, when excited by light, electron-hole pairs (excitons) bound by the Coulomb interaction are formed in them. In other words, when Grätzel cells are excited by light, dye molecules (an organic semiconductor, for example, lutetium Diphthalocyanine LuPc<sub>2</sub>) pass from the ground state to an excited state (i.e., a molecular exciton is formed in the organic semiconductor). The created molecular exciton diffuses to the transition boundary between TiO<sub>2</sub> and LuPc<sub>2</sub>, passing a distance of the order of 10 nm. Then the molecular exciton at the transition boundary decays into free electrons and holes. In this case, electrons diffuse into the TiO<sub>2</sub> semiconductor, and holes diffuse into the KI + I<sub>2</sub> electrolyte. The photoexcitation of dye molecules can also be described by the where HOMO is molecular orbital method, where and LUMO is lowest unoccupied molecular

orbital. The HOMO molecular orbital is the bonding  $\pi$  orbital, and the LUMO molecular orbital is the antibonding  $\pi^*$  orbital. When excited by light, an electron passes from the HOMO level to the LUMO level. Then the electrons from the lowest unoccupied molecular orbital of the dye molecule (LUMO) pass into the conduction band of the  $\text{TiO}_2$  semiconductor in a time of the order of  $10^{-15}$  s. Then, from the conduction band of  $\text{TiO}_2$ , the electrons diffuse to the conducting electrode (anode), and the holes pass from the highest occupied molecular orbital of the excited molecule (HOMO) to the electrolyte and are delivered by the electrolyte to the counterelectrode (cathode) through redox-chemical reactions [5]. As an electrolyte, a solution of  $\text{KI} + \text{I}_2$  in Ethylene Glycol is used, in which iodine ions  $\text{I}^-$  and complex ions  $\text{I}_3^-$  (triiodites) are formed. The dye molecule is oxidized with the loss of an electron. The restoration of dye molecules to a neutral state occurs due to the receipt of electrons from iodide ions ( $\text{I}^-$ ), which diffuse towards the semiconductor-dye. After donating an electron by the iodide ion, neutral atoms  $\text{I}$  form an iodine molecule  $\text{I}_2$ . In this case iodine molecules ( $\text{I}_2$ ) diffuse in the opposite direction to the electrode (cathode). Approaching the electrode, the molecule  $\text{I}_2$  receives an electron from it, forming a complex  $\text{I}_3^-$ . The  $\text{I}_3^-$  complex can both attach two electrons from the cathode and decay at some distance from the cathode. In the process of attaching two electrons, three iodide ions  $\text{I}_3^- + 2e^- = 3\text{I}^-$  are formed, which diffuse towards the semiconductor-dye. In the process of decomposition, the  $\text{I}_3^-$  complex decomposes into an iodine molecule  $\text{I}_2$  and an Iodine ion  $\text{I}^-$ , which diffuse from the cathode towards the semiconductor-dye and again participate in the dye reduction reaction. Simultaneously with the electron, the hole in the process of redox reactions occurring in the electrolyte passes into the electrolyte and moves to the cathode. In an electrolyte, a hole can recombine with an electron of the  $\text{I}_3^-$  complex, as well as with an electron of the cathode. In the Grätzel photocell, the dye (photosensitizer) plays the main role, and the titanium dioxide anode, cathode and electrolyte are additional functional components. The simplest Grätzel cell and the corresponding energy diagram are shown in Fig. 1.

At present, much attention is paid to the use of nanostructured materials in photovoltaics, in particular, metal and semiconductor nanoparticles. For metal nanoparticles, the main studies in nanovoltaics is related to the study of the use of plasmonic field amplification near nanoparticles to increase the photocurrent [6]. This mechanism has the drawback of strong absorption of light in metal nanoparticles near the plasmon resonance, which limits the efficiency of the Grätzel cells.

In the literature, the possibility of using semiconductor nanoparticles with relatively low absorption in photovoltaics is being studied. At the same time, a wide range of models based on different physical mechanisms is considered. Among them the creation of cells based on the Schottky transition in a semiconductor-metal contact [7], the use of



**Figure 1.** Grätzel cell and energy diagram organic semiconductor + inorganic semiconductor.

depleted heterojunctions [8], hybrid cells with semiconductor nanoparticles and perovskites [9] and various options related to the interactions of semiconductor nanoparticles with other nanostructures [10], as well as semiconductor nanoparticles as sensitizers in traditional Grätzel cells [11]. The purpose of this work is to study the effect of semiconductor nanoparticles on the characteristics of sensitizers of Grätzel cells, in which Lutetium Diphthalocyanine dye with silicon carbide nanoparticles is used as sensitizers. Lutetium Diphthalocyanine, unlike simple phthalocyanines, is readily soluble in organic solvents. In contrast to the approach described in [12], in which nanoparticles were introduced into the  $\text{TiO}_2$  matrix and thereby changed the characteristics of the matrix, in this work, semiconductor nanoparticles are used to modify the characteristics of the dye, primarily to optimize the characteristics absorption and transfer of electrons in the photoactive layer.

## Experimental part

The following substances were used to obtain samples: Lutetium Diphthalocyanine ( $\text{LuPc}_2$ ), Silicon Carbide nanoparticles ( $n\text{SiC}$ ), and Tetrahydrofuran (THF). The complex compound of Lutetium Diphthalocyanine has the form  $[\text{Lu}(\text{C}_{32}\text{H}_{16}\text{N}_8)_2]$ .

Sample 1 is a stock solution of Lutetium Diphthalocyanine with a volume of 2 ml ( $\text{LuPc}_2 + \text{THF} - 2 \text{ ml}$ ).

Sample 2 was obtained by mixing an initial solution of Lutetium Diphthalocyanine with a volume of 1 ml with an initial solution of silicon carbide nanoparticles with a volume of 1 ml ( $\text{LuPc}_2 + \text{THF} 1 \text{ ml} + n \text{ textSiC} + \text{THF} 1 \text{ ml}$ ).

Sample 3 is an initial solution of 2 ml Silicon Carbide nanoparticles ( $n\text{SiC} + \text{THF} - 2 \text{ ml}$ ).

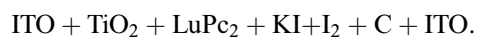
The initial solution of Lutetium Diphthalocyanine was obtained by mixing 2 mg  $\text{LuPc}_2$  powder in 25 ml THF solvent. The molar mass of  $\text{LuPc}_2$  is 1199 g/mol. The molar concentration of Lutetium Diphthalocyanine in Tetrahydrofuran was  $7 \cdot 10^{-5} \text{ mol/l}$ .

The initial solution of Silicon Carbide nanoparticles was obtained as follows. The powder with Silicon Carbide nanoparticles was obtained by laser-induced pyrolysis by mixing  $\text{SiH}_4$  Monosilane and  $\text{C}_2\text{H}_2$  Acetylene gases at a temperature of  $1500^\circ\text{C}$ . A dark-colored powder with Silicon Carbide ( $n\text{SiC}$ ) nanoparticles weighing 3 mg was dissolved in 10 ml in Tetrahydrofuran (THF), chemically pure grade. The solution was dispersed on an ultrasonic unit (US) with a power of 100 W with 5 intervals of 30 s with breaks of 30 s. The resulting suspension was subjected to the action of a centrifuge with a rotation speed of 8000 rpm for 5 min. The liquid above the precipitate was then decanted and a yellow, slightly opalescent solution was obtained. The resulting colloidal solution was diluted 2 fold with THF, centrifuged again for 45 min at 8000 rpm. The decanted solution was used to obtain samples.

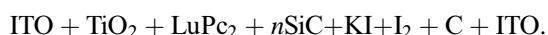
The following substances were used to prepare Grözel Cells: Lutetium Diphthalocyanine dye ( $\text{Pc}_2\text{Lu}$ ) as a photosensitizer, iodine solution with potassium iodide ( $\text{KI} + \text{I}_2$ ) as an electrolyte, titanium dioxide ( $\text{TiO}_2$ ) as a medium for electron diffusion, Indium Tin Oxide (ITO) coated glass as electrodes, Silicon Carbide ( $n\text{SiC}$ ) nanoparticles as an additive in organic dyes.

To obtain electrolyte ( $\text{KI} + \text{I}_2$ ), a sample of 1.67 g of Potassium Iodide and 0.25 g of Crystalline Iodine was dissolved in 20 ml of Ethylene Glycol [ $\text{C}_2\text{H}_4(\text{OH})_2$ ].

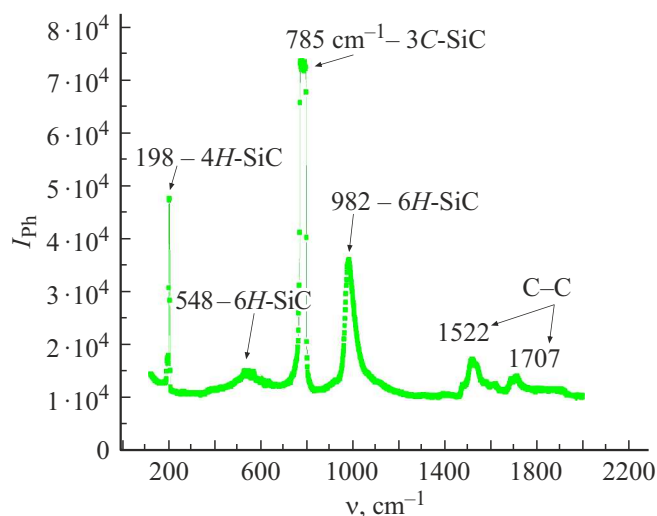
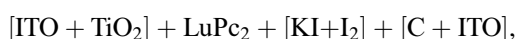
To obtain a composite of Titanium Dioxide with ITO, the following operations were carried out. The  $\text{TiO}_2$  powder was stirred into Ethylene Glycol and then into Citric Acid. The resulting mixture was applied to a ITO film on glass and heat treated at temperature of  $400^\circ\text{C}$  for 30 min. After heat treatment, the initial  $\text{TiO}_2 + \text{ITO}$  composite was cooled in air for 24 h. After cooling, the  $\text{TiO}_2 + \text{ITO}$  composites were impregnated with a  $\text{LuPc}_2 + \text{THF}$  solution. Then the  $\text{TiO}_2 + \text{ITO} + \text{LuPc}_2 + \text{THF}$  complex solution was dried for 24 h at a temperature of  $22^\circ\text{C}$ . As a result, an intermediate solution  $\text{ITO} + \text{TiO}_2 + \text{LuPc}_2$  of light blue color was obtained. After that, the  $\text{ITO} + \text{TiO}_2 + \text{LuPc}_2$  solution was impregnated with a solution of  $\text{KI} + \text{I}_2$  in ethylene glycol, and conductive layers of carbon were deposited on the impregnated sides. Next, another glass with ITO was attached to the Carbon layers. The final composite is conventionally labeled



By adding nanoparticles of Silicon carbide ( $n\text{SiC}$ ) to lutetium Diphthalocyanine, a composite was obtained



As a result of technological operations, two composites were obtained in the form of a sandwich, which actually represented Grözel cells. The first (control) Grözel cell was conventionally designated as



**Figure 2.** Raman scattering spectrum of silicon carbide nanoparticles.

and the second Grözel cell was denoted as



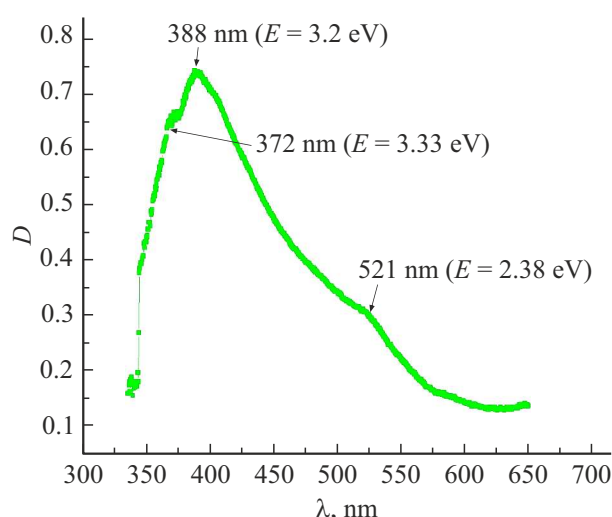
The shape, size, and phase composition of silicon carbide nanoparticles were determined by electron microscopy using a JEOL JSM-5910 LV electron microscope. The absorption spectra of dye solutions (photosensitizers) were obtained in the Option Optics 2000 spectrometer with a dynamic range of 300–1100 nm. A tungsten lamp with a power of 10 mW was used as a radiation source. The ultrasonic treatment of solutions with dyes and silicon carbide nanoparticles was performed in the UZDN-2T unit. Heat treatment of Titanium Dioxide on a glass substrate with ITO was carried out in a PM-8 muffle furnace.

## Results and discussion

For Silicon Carbide nanoparticles, a microphotograph and a diffraction pattern were taken to determine the size, shape, and phase composition, which are presented in detail in [13]. In it, the shape of Silicon Carbide nanoparticles was determined, mainly spherical, the sizes in the range 7–14 nm, and the phase composition. Analysis of the diffraction pattern [13] showed the presence of two polytypes of silicon carbide nanoparticles 3C-SiC and 2H-SiC.

The Raman scattering (RS) spectra of Silicon Carbide ( $n\text{SiC}$ ) nanoparticles at a temperature of  $23^\circ\text{C}$  are shown in Fig. 2.

RS (Fig. 2) contains maxima at  $\nu_m = 198, 548, 785, 982, 1522, \text{ and } 1707 \text{ cm}^{-1}$ . The RS maxima at 1522 and  $1707 \text{ cm}^{-1}$  correspond to carbon nanoparticles and therefore will not be considered by us. The RS maxima at  $\nu_m = 198, 548, 785, 982 \text{ cm}^{-1}$  correspond to silicon carbide nanoparticles. The RS maximum at  $\nu_m = 198 \text{ cm}^{-1}$



**Figure 3.** Absorption spectrum of Silicon Carbide nanoparticles.

is due to the 4H-SiC. RS maximum at  $\nu_m = 548 \text{ cm}^{-1}$  corresponds to the 6H-SiC polytype. The RS maximum at  $\nu_m = 785 \text{ cm}^{-1}$  is caused by the 3C-SiC polytype. And, finally, the maximum at  $\nu_m = 982 \text{ cm}^{-1}$  is due to the 6H-SiC polytype. Note that the intensity of RS peak  $\nu_m = 785 \text{ cm}^{-1}$  (the 4H-SiC polytype)  $I_{\text{Ph}} = 7 \cdot 10^4$  is the largest of all peaks. The intensity of the RS peak  $\nu_m = 198 \text{ cm}^{-1}$  (the 4H-SiC polytype) is about  $I_{\text{Ph}} = 4.5 \cdot 10^4$ , i.e., the RR intensity is 1.5 times less than for the 3C-SiC polytype. The intensities of the RS peaks  $\nu_m = 548 \text{ cm}^{-1}$  and  $\nu_m = 982 \text{ cm}^{-1}$  (6H-SiC polytype) are equal, respectively  $I_{\text{Ph}} = 1.5 \cdot 10^4$  and  $3.5 \cdot 10^4$ , i.e., the RS intensity is 4.6 and 2 times lower for the 3C-SiC polytype, respectively.

An analysis of the Raman spectrum shows the presence of three polytypes of silicon carbide nanoparticles 3C-SiC, 4H-SiC, and 6H-SiC.

In the absorption spectrum of Silicon Carbide nanoparticles in the visible range at a temperature of 23°C (Fig. 3), maxima  $\nu_m = 372$ , 388 and 521 nm were found.

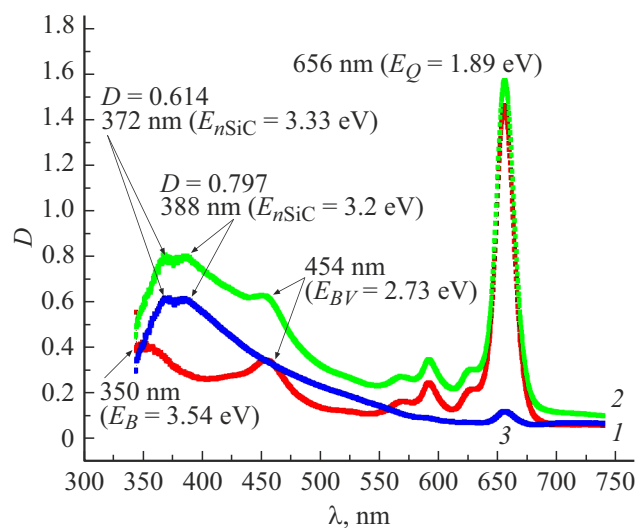
An analysis of the absorption spectrum shows the presence of three different polytypes of silicon carbide nanoparticles: 2H-SiC, 4H-SiC, and 3C-SiC. The maximum at a wavelength of 372 nm ( $E = 3.33 \text{ eV}$ ) corresponds to the 2H-SiC polytype. The absorption maximum at a wavelength of 388 nm ( $E = 3.2 \text{ eV}$ ) is due to the 4H-SiC polytype. The maximum absorption of radiation at a wavelength of 521 nm ( $E = 2.38 \text{ eV}$ ) corresponds to the 3C-SiC polytype. The results obtained are in good agreement with the data of other authors [14].

Thus, based on the analysis of electron microscopy data, Raman scattering and absorption spectra, four polytypes were found in silicon carbide nanoparticles: 3C-SiC, 2H-SiC, 4H-SiC, and 6H-SiC. In this case, the main part of silicon carbide nanoparticles is formed in the form of 3C-SiC and 4H-SiC polytypes, and only an insignificant part of them is composed of 2H-SiC and 6H-SiC polytypes.

The absorption spectra of solutions of Lutetium Diphthalocyanine in tetrahydrofuran (1, 2, 3 samples) in the presence of Silicon Carbide nanoparticles measured at a temperature of 23°C are shown in Fig. 4.

The following maxima were found in the spectra:  $\lambda_m = 656 \text{ nm}$  ( $Q$ -band of LuPc<sub>2</sub>),  $\lambda_m = 454 \text{ nm}$  ( $BV$ -band of LuPc<sub>2</sub>),  $\lambda_m = 350 \text{ nm}$  ( $B$ -band of LuPc<sub>2</sub>) and three peaks of SiC nanoparticles  $\lambda = 372$ , 388 and 521 nm.

Absorption of radiation in the range with a maximum of  $\lambda_m = 656 \text{ nm}$  occurs on conjugated double Carbon-Carbon bonds of benzene rings ( $n = 13$ ) and conjugated double nitrogen-nitrogen bonds ( $n = 6$ ), where  $n$  is number of conjugated double bonds. In total, there are  $38\pi$ -electrons in a Phthalocyanine molecule (without a complexing agent). The absorption peak ( $Q$ -band  $\lambda_m = 656 \text{ nm}$ ) of sample 1 (LuPc<sub>2</sub> + THF) corresponds to the electronic transition from HOMO  $2b_1$  to LUMO  $6e_3$  ( $\pi-\pi^*$ -transitions) with energy interval  $E_{\text{HOMO-LUMO}} = 1.89 \text{ eV}$ . This electronic transition occurs between the singlet ground state and the singlet excited state. The absorbance of the  $Q$ -band reaches values in the range  $D = 1.4-1.5$ . This is the most intense absorption band of Lutetium Diphthalocyanine dye. Absorption of radiation in the range with a maximum  $\lambda_m = 454 \text{ nm}$  occurs on conjugated double carbon-carbon bonds of benzene rings ( $n = 13$ ), i.e. radiation is absorbed on  $26\pi$ -electrons. The absorption peak ( $Q$ -band  $\lambda_m = 454 \text{ nm}$ ) of sample 2.73 (LuPc<sub>2</sub> + THF) corresponds to the electronic transition from HOMO  $5e_1$  to LUMO  $2a_2$  ( $\pi-\pi^*$ -transitions) with energy interval  $E_{\text{HOMO-LUMO}} = 2.73 \text{ eV}$ . This electronic transition occurs between the singlet ground state and the singlet excited state. The absorbance of the  $BV$ -band is equal to  $D = 0.3$ , which is 5 times less than the  $Q$ -band. Note that the absorption bands  $Q$  and  $BV$  do not contribute to the useful light absorption, which affects the COP of the Grätzel cells. The absorption peak ( $B$ -band  $\lambda_m = 354 \text{ nm}$ )



**Figure 4.** Absorption spectra of solutions Pc<sub>2</sub>Lu + THF-2 ml red (sample 1), Pc<sub>2</sub>Lu + THF-1 ml+nSiC THF-1 ml green (sample 2), nSiC + THF-2 ml blue (sample 3).

corresponds to the electronic transition of HOMO  $4a_1$  to LUMO  $6e_1$  ( $\pi-\pi^*$ -transitions) with an energy interval  $E_{\text{HOMO-LUMO}} = 3.54$  eV. The electronic transition  $4a_1 \rightarrow 6e_1$  ( $B$ -band) occurs in Lutetium Diphthalocyanine due to the absorption of radiation on conjugated double Carbon-Nitrogen bonds of pyrrole rings ( $n = 6$ ), i.e., radiation is absorbed at  $12\pi$ -electrons. The absorbancy in the  $B$ -band of sample 1 is  $D = 0.4$ . It is the  $B$  absorption band of sample 1 that is the main optical range, which affects the COP of the Grätzel cells.

A noticeable increase in absorption in the wavelength range of 350–500 nm for samples 2 and 3 (Fig. 4) indicates a strong mutual influence of silicon carbide nanoparticles and Lutetium Diphthalocyanine molecules. Silicon Carbide nanoparticles have increased adsorption activity. Due to their large specific surface and excess surface energy, silicon carbide nanoparticles easily adsorb Lutetium Diphthalocyanine molecules on their surface, which leads to energy transfer from dye molecules to semiconductor nanoparticles [13]. The adsorption process occurs due to van der Waals forces. The absorbance at the absorption maxima at 372 and 388 nm is on the order of 0.6, which is 2 times greater than the optical density in the  $B$  band of Lutetium Diphthalocyanine. The proximity of the absorption maxima of  $n\text{SiC}$  and the  $B$  band of Lutetium Diphthalocyanine facilitates the energy exchange between their energy levels, which can be seen in Fig. 4 for the  $B$  band of Lutetium Diphthalocyanine. Electrons in the LUMO molecular orbital ( $E = 3.54$  eV) of Lutetium Diphthalocyanine molecules pass into the conduction band of silicon carbide nanoparticles with energies of 3.2 and 3.33 eV. As noted earlier, these energies correspond to silicon carbide polytypes  $2H\text{-SiC}$  and  $4H\text{-SiC}$ . Since the concentrations of  $4H\text{-SiC}$  and  $2H\text{-SiC}$  differ insignificantly, energy transfer from Lutetium Diphthalocyanine molecules occurs on both polytypes. In other words, the addition of silicon carbide nanoparticles to the Lutetium Diphthalocyanine dye significantly increases the absorption of radiation and thereby improves the absorbing properties of the complex dye + semiconductor nanoparticles. This in turn should improve the performance of the Grätzel cell.

The main characteristics of the Grätzel control cell were measured

$$[\text{ITO} + \text{TiO}_2] + [\text{LuPc}_2] + [\text{KI} + \text{I}_2] + [\text{C} + \text{ITO}]$$

and Grätzel cells with silicon carbide nanoparticles in a sensitizer

$$[\text{ITO} + \text{TiO}_2] + [\text{LuPc}_2 + n\text{SiC}] + [\text{KI} + \text{I}_2] + [\text{C} + \text{ITO}].$$

For the Grätzel control cell

$$[\text{ITO} + \text{TiO}_2] + [\text{LuPc}_2] + [\text{KI} + \text{I}_2] + [\text{C} + \text{ITO}]$$

the following characteristics were obtained: open-circuit voltage  $V_{OC} = 520$  mV, short-circuit current  $I_{SC} = 150 \mu\text{A}$  and filling factor  $FF = 0.34$ .

The maximum power removed per unit area ( $1 \text{ cm}^2$ ) is calculated by the formula:

$$P_{\text{max}} = V_{OC} I_{SC} FF \quad (1)$$

and amounts to  $P_{\text{max}} = 27 \mu\text{W}$ .

high coefficient of performance can be obtained by the formula:

$$\eta = [(V_{OC} I_{SC} FF) / P_L] \cdot 100\%, \quad (2)$$

where  $P_L$  is power of the radiation source, in our case  $P_L = 2.5 \text{ mW}$ .

Substituting the values into formula (2), we obtain the high coefficient of performance  $\eta = 1\%$ . For the Grätzel cells with silicon carbide nanoparticles in a sensitizer

$$[\text{ITO} + \text{TiO}_2] + [\text{LuPc}_2 + n\text{SiC}] + [\text{KI} + \text{I}_2] + [\text{C} + \text{ITO}]$$

were obtained the following characteristics: open circuit voltage  $V_{OC} = 560$  mV, short circuit current  $I_{SC} = 350 \mu\text{A}$ , duty factor  $FF = 0.34$ .

Substituting the values into formula (1), we get the power  $P_{\text{max}} = 67 \mu\text{W}$ . Substituting the values into formula (2), we obtain the high coefficient of performance  $\eta = 2.7\%$ . Thus, the characteristics of the Grätzel cell were improved by adding silicon carbide nanoparticles to Lutetium Diphthalocyanine as a sensitizer. At the same time, the power increased by 2.5, and the high coefficient of performance of the Grätzel cell increased by 2.7 times.

In this work, we obtained a stable Grätzel cell with embedded silicon carbide nanoparticles in Lutetium Diphthalocyanine as a photosensitizer with improved power and efficiency characteristics. The data obtained by us on the COP and power of the Grätzel cells are also in good agreement with the data of other authors [15].

## Conclusion

A study was made of the influence of Lutetium Diphthalocyanine molecules ( $\pi-\pi^*$ -electronic transitions) on the optical properties of silicon carbide nanoparticles. It has been found that the absorption intensity of Lutetium Diphthalocyanine molecules increases when silicon carbide nanoparticles are added to the dye. This fact can be explained by the additional absorption of radiation on silicon carbide nanoparticles due to the proximity of the absorption maxima of  $\text{LuPc}_2$  and  $n\text{SiC}$ .

As a result of the studies of Lutetium Diphthalocyanine complexes with silicon carbide nanoparticles, the following conclusions were made.

1. Silicon Carbide nanoparticles obtained by laser-induced pyrolysis have an almost spherical shape. The diameter of nanoparticles varies from 7 to 14 nm. Spherical Silicon Carbide nanoparticles contain four types of polytypes:  $3C\text{-SiC}$ ,  $2H\text{-SiC}$ ,  $4H\text{-SiC}$ , and  $6H\text{-SiC}$ . The main part of the nanoparticles is formed in the form of the  $3C\text{-SiC}$  and  $4H\text{-SiC}$  polytypes, while the rest consists of the  $2H\text{-SiC}$  and  $6H\text{-SiC}$  polytypes.

2. The addition of Silicon Carbide nanoparticles to the Lutetium Diphthalocyanine dye significantly increases the absorption of radiation and contributes to an increase in the absorbing properties of the photosensitizer.

3. In Götzel cells, the main part of the energy upon photoexcitation of Lutetium Diphthalocyanine molecules is transferred to the 4H-SiC polytype, and the remaining part of the energy (1.15 times smaller) is transferred to the 2H-SiC polytype.

4. The addition of Silicon Carbide nanoparticles to the Lutetium Diphthalocyanine sensitizer increases the power by 2.5 times and 2.7 times the efficiency of the Götzel cell.

### Conflict of interest

The author declares that he has no conflict of interest.

### References

- [1] J.H. Zhao, A. Wang, M.A. Green. *Appl. Phys. Lett.*, **73**, 1991–1993 (1998). DOI: 10.1063/1.122345
- [2] S.A. Kalogirou S.A. McEvoy's *Handbook of Photovoltaics: Fundamentals and Applications*, 3rd edition, (Academic Press, 2017). DOI: 10.1016/C2015-0-01840-8
- [3] M.J. Jeong, K.M. Yeom, K.M. Kim, E.H. Jung, J.H. Noh. *Energy Environ. Sci.*, **14**, 2419–2426 (2021). DOI: 10.1039/d0ee03312j
- [4] B. O'Regan, M. Gratzel. *A Low-Cost. Nature*, **353** (6346), 737–740 (1991). DOI: 10.1038/353737a0
- [5] C. Longo, M.-A. De Paoli. *J. Brazilian Chem. Soc.*, **14** (6), 889–901 (2003). DOI: 10.1590/S0103-50532003000600005
- [6] T. Jägeler-Hoheiselet, F. Selzer, M. Riede, K. Leo. *J. Phys. Chem. C.*, **118** (28), 15128–15135 (2014). DOI: 10.1021/jp5025087
- [7] K.W. Johnston, A.G. Pattantyus-Abraham, J.P. Clifford, S.H. Myrskog, D.D. MacNeil, L. Levina, E.H. Sargent. *Appl. Phys. Lett.*, **92** (15), 151115 (2008). DOI: 10.1063/1.2912340
- [8] D.A.R. Barkhouse, R. Debnath, I.J. Kramer, D. Zhitomirsky, A.G. Pattantyus-Abraham, L. Levina, L. Etgar, M. Gratzel, E.H. Sargent. *Advanced Mater.*, **23** (28), 3134–3138 (2011). DOI: 10.1002/adma.201101065
- [9] Z.J. Ning, X.W. Gong, R. Comin, G. Walters, F. Fan, O. Voznyy, E. Yassitepe, A. Buin, S. Hoogland. *E. Sargent. Nature*, **523** (7560), 324–328 (2015). DOI: 10.1038/nature14563
- [10] G.-Y. Lan, Z. Yang, Y.-W. Lin, Z.-H. Lin, H.-Y. Liao, H.-T. Chang. *J. Mater. Chem.*, **19** (16), 2349–2355 (2009). DOI: 10.1039/B817000B
- [11] J.-H. Yum, S. Jang, R. Humphry-Baker, M. Gratzel. *J.-J. Cid, T. Torres, M.K. Nazeeruddin. Langmuir*, **24** (10), 5636–5640 (2008). DOI: 10.1021/la800087q
- [12] L. Jin, D. Chen. *Electrochim. Acta*, **72**, 40–45 (2012). DOI: 10.1016/j.electacta.2012.03.167
- [13] S.I. Rasmagin, V.I. Krasovskii. *Technical Phys.*, **66** (3), 476–480 (2021). DOI: 10.1134/S1063784221030208.
- [14] R.A. Andrievskii. *Russ. Chem. Rev.*, **78** (9), 821–831 (2009). DOI: 10.1070/RC2009v078n09ABEH004060.
- [15] T.M. Serikov, N.K. Ibrayev, O.Y. Isaikina, S.V. Savilov. *Russ. J. Inorg. Chem.*, **66** (1), 117–123 (2021).