Archives of Materials Science and Engineering

Volume 74
Issue 1
July 2015
Pages 32-44

International Scientific Journal
published monthly by the
World Academy of Materials
and Manufacturing Engineering

# Influence of carbon nanotubes on properties of dye-sensitised solar cells

**L.A. Dobrzański*, A. Wierzbicka, A. Drygała, K. Lukaszkowicz**
Institute of Engineering Materials and Biomaterials, Silesian University of Technology,
ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding e-mail address: leszek.dobrzanski@polsl.pl

## ABSTRACT

**Purpose:** The purpose of the work is to examine the influence of carbon nanotubes on the properties of dye-sensitised solar cells.

**Design/methodology/approach:** The research material consisted of samples of glass plates with a conductive layer of FTO onto which layers were subsequently deposited of TiO2 titanium dioxide and titanium dioxide with an absorbed dye, a high conductivity PEDOT:PSS polymer with multi-walled carbon nanotubes, carbon black and graphite.

**Findings:** The application of carbon nanotubes as one of electrodes in a dye-sensitised solar cell is significantly improving the effectiveness of the dye-sensitised solar cell being manufactured.

**Research limitations/implications:** Carbon nanotubes are a good potential material for optoelectronics and photovoltaics.

**Practical implications:** Carbon nanotube electrodes feature high conductivity and high visible light transmission.

**Originality/value:** It is possible to change a structure of a dye-sensitised solar cell by replacing the commonly used platinum in a counter electrode with another electrode permeable for visible light made of a high conductivity PEDOT:PSS polymer with multi-walled carbon nanotubes.

**Keywords:** Photovoltaics, Dye-sensitised solar cells (DSSCs), Counter electrode, Carbon nanotubes

**Reference to this paper should be given in the following way:**

L.A. Dobrzański, A. Wierzbicka, A. Drygała, K. Lukaszkowicz, Influence of carbon nanotubes on properties of dye-sensitised solar cells, Archives of Materials Science and Engineering 74/1 (2015) 32-44.

PROPERTIES

## 1. Introduction

The growing demand for electricity and the so induced development of conventional generation entails the intensified usage of fossils. Considering the consequently rising electricity prices and the shrinking resources of natural raw materials accompanied by broadening environmental awareness, we are currently witnessing a dynamic quest for modern, alternative energy sources. Various research projects are currently in the pipeline relating to a photovoltaics development strategy. Two key directions are predominant. The first direction is focussed on efficiency enhancement of silicon solar cells and reduction of their manufacturing and operating costs [1-4]. Progress seen in the development of traditional solar technologies is feasible through the improvement of the particular solar cell components, e.g. connectors, contacts, cell geometric features, by applying state-of-the-art surface treatment methods of cells' surface layers, and - most of all - by applying engineering nanomaterials with unique properties [4-8]. The other photovoltaics development direction is seeking cutting edge technological solutions likely to replace the silicon technology used until now in photovoltaics. The third-generation cells are strongly advancing in this direction, i.e. dye-sensitised cells commonly called the Grätzel cells [2-5,9,10]. They are fabricated by means of uncomplicated, commonly available technologies allowing to lower manufacturing costs. Due to their low sensitivity to a solar radiation incidence angle they are certainly also more versatile as compared to silicon cells. They can work under the influence of secondary and deflected radiation and under partial shading. Therefore, they can be installed in a vertical position, and not as in silicon cells - under the appropriate angle. In addition, a device can be devised by using various types of dyes and oxide pastes, which satisfies both, functional and aesthetic functions [9-13]. Endeavours have also been pursued to achieve cells with efficiency higher than to date. This is one of the greatest challenges in research over solar materials, and studies concerning this aspect are inscribing themselves into the main stream and numerous research institutions are seeking methods to enhance the conversion efficiency of light energy absorbed by sensibiliser molecules [2,5,9-15]. A sensitising substance should ensure stability enabling cells to operate for many years. Figure 1 presents a catalytic cycle in which a dye is working. A dye substance may decompose when in the excited state S* or when oxidised with S+. Such processes can be prevented by injecting an electron into a semiconductor conduction band and by regeneration [2,9,12,15].

Unlike traditional silicon cells, no complicated processing equipment is required to fabricate dye-sensitised cells. This has a great effect on the final, low price of such cells. Another meaningful aspect of the dye-sensitised solar cells technology is that the majority of materials necessary to construct a DSSC can be fabricated with one's own efforts. Another essential aspect of the usage of DSSCs is that they can be integrated with building integrated photovoltaics (BIPV). This provides extensive application opportunities in modern architecture. Cell appearance can be adjusted by using different colours of natural or synthetic dyes, and this can be used mainly in construction of lampions or coloured windows panes which are lightweight and thin [12,15].

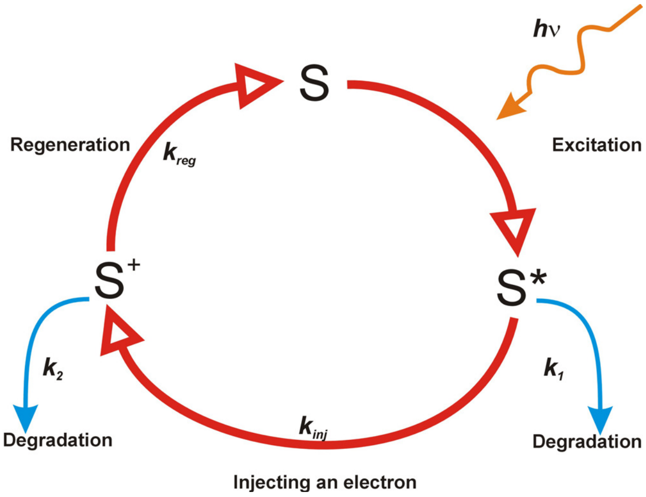


Fig. 1. Flow chart of dye working cycle in dye-sensitised solar cell [2,9,12,15]

One of the materials used most popularly as a counter electrode in dye-sensitised solar cells include platinum, carbon, conductive polymer materials and different compounds, e.g. CoS, $WO_2$, $Mo_2C$ and WC [2]. From the above-listed materials, platinum is used most often. Although platinum has a high catalyst activity, however, its shortage in the Earth's natural resources, high cost and susceptibility to corrosion under the influence of a solution of an iodide/triiodide redox couple indicate its limited use in photovoltaics of DSSCs at a large scale [2,10,16-19]. Measures are indispensable to employ alternative materials possessing electrochemical activity, chemical stability and a lower cost. For this reason, the independently fabricated multi-walled carbon nanotubes have been used, which are characterised by high corrosion resistance, high reactivity at iodide/triiodide redox couple reduction, which are dissolved in a relevant medium being an electrolyte and having a much lower cost versus platinum [20,21]. The presence of carbon nanotubes applied as a DSSC cathode improves electrical properties of the investigated cells as compared to the cells where a graphite or carbon black cathodes are used [20,22-23]. The application of carbon nanotubes as one of electrodes in a dye-sensitised solar cell is significantly improving the effectiveness of the cells being manufactured. Electrodes made of carbon nanotubes feature high conductivity and high visible light transmission of even 99% [2,22-23]. A completely colourless electrode can be achieved or such with a stained glass effect. Photovoltaic installations can thus improve aesthetic characteristics. DSCs made of carbon nanotubes can also be used for construction of intelligent windows acting as shading surfaces producing electricity at the same time

[13,23]. Thin carbon nanotube layers are flexible and durable and exhibit chemical resistance to external conditions. Such electrodes can be produced by cheap methods, e.g. by printing or spraying [8].

The authors of this publication have been pursuing intensive research work for many years in the field of organic and inorganic solar cells to heighten their efficiency [1,5-7,20,24-27]. Studies into the application of carbon nanotubes as one of DSSC electrodes, which are the essence of this publication, are elaborating and supplementing the nanotechnology and photovoltaics research carried out as avant-garde areas of the contemporary materials engineering. In the light of the growing demand for solar materials with diverse properties, this subject is important in terms of science, economy and applications.

## 2. Materials and methods

### 2.1. Materials

The materials necessary for fabrication of the studied DSCs were prepared independently under this work. Figure 2 shows the selection of materials necessary for producing a DSC in this work.

A technology has been established of manufacturing solar cells based on a cathode made of a high conductivity PEDOT:PSS polymer with multi-walled carbon nanotubes and an anode made of an independently made $TiO_2$ solution with the absorbed natural dye to replace an expensive platinum layer with other cheaper layers and to prove that the so made DSCs can operate correctly and reach the performance of over 10% identified as a minimum threshold accepted in the literature. Three configurations of the DSSCs intended for the studies [2,5,9-16], differing in the cathode material, provided in Table 1 and as a scheme in Fig. 3, were prepared based on literature analyses.

A technique has been developed for preparing a $TiO_2$ solution, an organic dye and carbon nanotubes. A $TiO_2$ solution was prepared with nitric acid, ethanol and $TiO_2$ powder (Table 2).

### 2.2. Methodology

A series of tests was undertaken in order to determine all the properties, i.e.: microscope examinations of carbon nanotubes, obtained by Chemical Vapour Deposition (CVD), examinations of nanotubes' structure with a transmission electron microscope (TEM), X-ray phase qualitative analysis of particular components of a dye-sensitised solar cell, examinations using a Raman spectrometer and examinations with an UV-Vis spectrometer.

A microstructure of the carbon nanotubes obtained by CVD on a silicone substrate and of particular layers in a DSSC (on glass substrate) was examined with a high-resolution scanning electron microscope SUPRA 35 by ZEISS at the accelerating voltage of 10-20 kV, using back scattered electrons (BSE) and secondary electrons (SE) detection (side detector (SE) and InLens detector).

Examinations into the structure of carbon nanotubes were carried out with a transmission electron microscope (TEM) S/TEM TITAN 80-300 by FEI with extensive analytical equipment allowing to examine the structure of materials and analyse their chemical composition with atomic-scale resolution and sensitivity. The accelerating voltage value during measurements was 300 kV, and observations were performed in the classical mode (TEM), i.e. by illuminating the sample with a parallel beam with a spatial resolution of below 0.10 nm.

An X-ray phase qualitative analysis of particular components of a dye-sensitised solar cell was undertaken with an X-ray diffraction pattern X'Pert Pro by Panalytical. The X-ray characteristic radiation Co Kα and an Fe filter were used. An X-ray diffraction pattern was made within the angle range of 2θ of between 30 and 105°. The step method was used with the measuring step length of 0.05°, and counting time per impulse was 10 s. An X'Celerator band detector and the razing-incidence X-ray diffraction method for the primary X-ray beam, with the use of a parallel beam collimator before a proportional detector, were used. JCPDS tables were used for the identification of phases.

The examinations performed with a Raman inVia Reflex spectrometer by Renishaw were undertaken to check the purity, type and geometry of unmodified MWCNTs. The source of excitation in the spectrometer was laser light with the wave length of 514.5 nm, and a detector was a cooled CCD camera with the resolution 2 $cm^{-1}$. In order to perform the examination, a small amount of MWCNTs in the form of powder was placed on a microscope glass, covered with a cover glass and strongly pressed to ensure maximum contact. A Raman shift spectrum between 100 and 4000 $cm^{-1}$ was recorded.

The absorption spectra of the dye-sensitised solar cell layers deposited on a glass substrate with an FTO conductive layer were measured with the UV-Vis Evolution 220 spectrometer by Thermo-Scientific fitted with a xenon lamp. The spectrometer allows to record spectra within the range starting from close ultraviolet radiation through the range of visible light to close infrared radiation for the wavelength of 190 to 1100 nm.

Table 1.
Configurations of the DSSCs intended for the studies

| Configuration number | Description |
|---|---|
| a | Glass plate with FTO layer/$TiO_2$ layer with dye absorbed at the surface/electrolyte/carbon black layer/glass plate with FTO layer |
| b | Glass plate with FTO layer/$TiO_2$ layer with dye absorbed at the surface/electrolyte/graphite layer/glass plate with FTO layer |
| c | Glass plate with FTO layer/$TiO_2$ layer with dye absorbed at the surface/electrolyte/high conductivity PEDOT:PSS polymer layer with carbon nanotubes/glass plate with FTO layer (Fig. 3). |

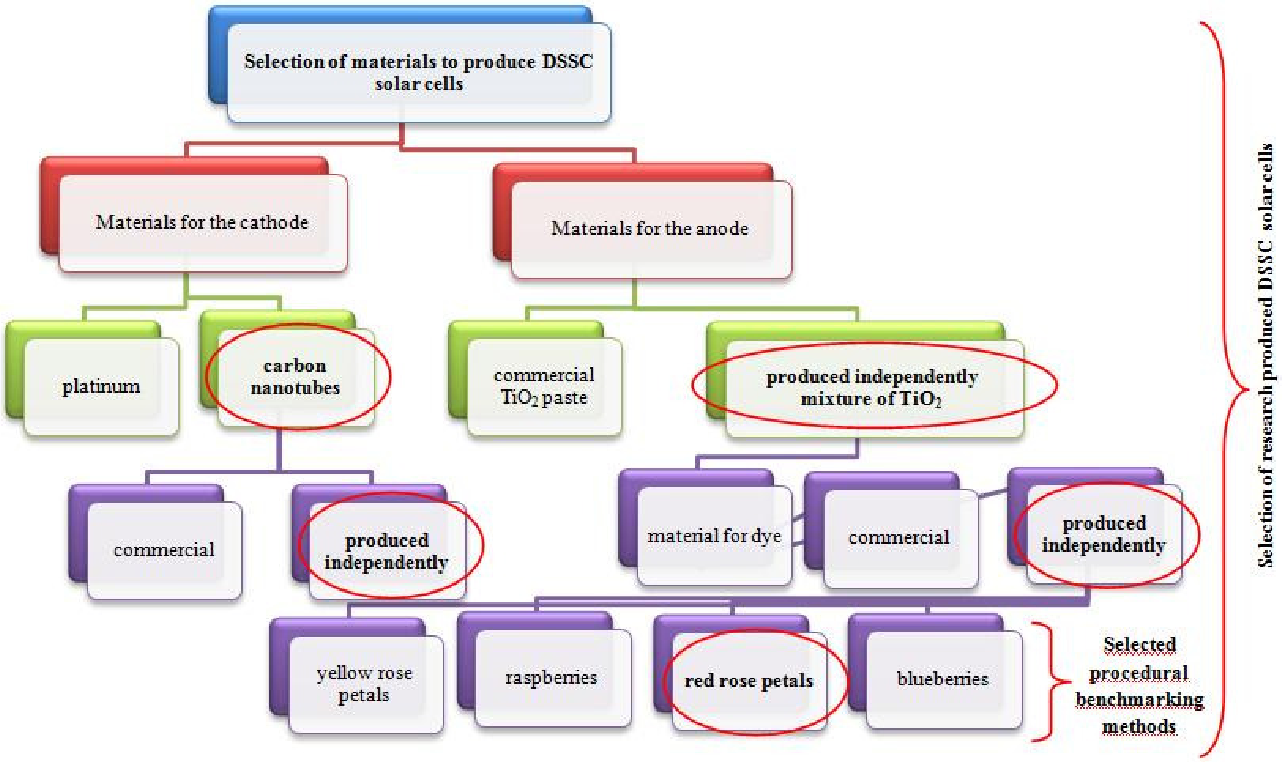


Fig. 2. Flowchart of selection of materials necessary for dye-sensitised solar cell fabrication

Table 2.
Chemical composition of $TiO_2$ suspension with preparation

| Components of paste | Preparation |
|---|---|
| • 2 ml nitric acid solution; pH 3-4<br>• 6.5 ml ethanol<br>• 1.5 g $TiO_2$ | Nitric acid mixed with ethanol, titanium oxide was added next. The solution was mixed all the time until obtaining a homogenous suspension. The so prepared suspension is ready for application onto a surface of clean glass plate with a conductive layer onto an electrode of a dye-sensitised solar cell. The layer should not smaller than 3 µm. |

The spectra obtained can be recorded and processed with dedicated software. A series of measurements of thin layers being elements of a dye-sensitised solar cell was made as part of the research. UV-Vis spectrometry allows to measure an absorption level of thin layers of a dye-sensitised solar cell based on spectra intensity distribution within the defined range of wavelength and based on their role in the studied layer.

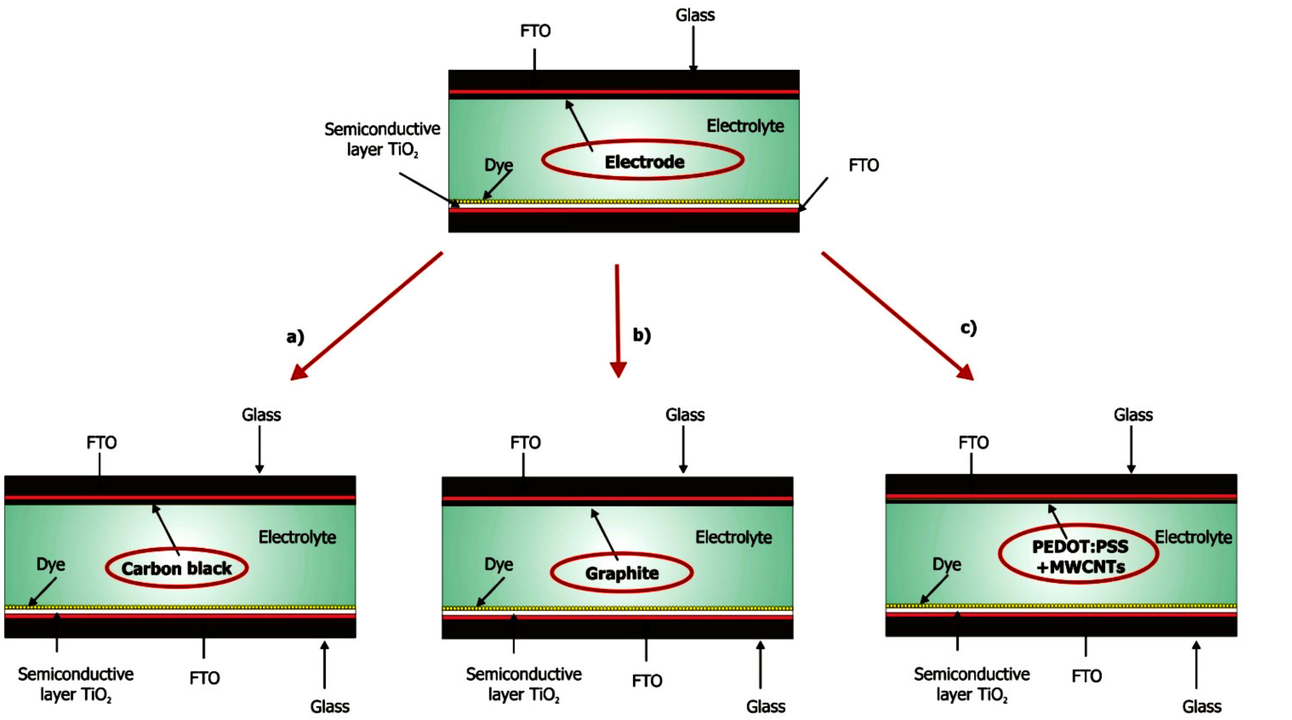


Fig. 3. Dye-sensitised solar cell with alternative electrodes made of a) carbon black, b) graphite c) high conductivity PEDOT:PSS polymer with carbon nanotubes

## 3. Results

The temperature and time were selected with the experimental method for the calcination of a $TiO_2$ layer applied onto the glass plate surface with an FTO layer, calcination was performed in such conditions. The results of X-ray examinations confirm that an active layer of $TiO_2$ is exhibiting a crystalline structure of the α-$TiO_2$ phase of titanium dioxide with a tetragonal crystallographic structure (Fig. 4). The allotrope type obtained is considered to be most desired in DSSCs [10,14,17,18]. A $TiO_2$ layer is used as a substrate for the dye carrying positive electric charges to another electrode (cathode) made of graphite, carbon black or high conductivity PEDOT:PSS polymer with carbon nanotubes.

The efficiency of DSSCs depends on the selected dye and on the technological conditions used during its application onto anode surface. A dendrological matrix of the technology value, according to the established procedural benchmarking method [28] of implementing the existing, proven procedures for another thematic area or field of knowledge, was applied for selecting a technology of fabricating natural dyes created with own efforts. Detailed assessment criteria of attractiveness and potential of the dyes from red and yellow rose petals, from raspberries and berries, were applied to select the best dye for cell fabrication (Table 3). A red rose petal dye was picked for further studies based on the analysis made.

The experimentally selected conditions for dying a $TiO_2$ layer uniformly are ensured by heating at 80°C for 24 hours followed by cooling at room temperature without the access of light. The correctly selected geometric characteristics, roughness and thickness of $TiO_2$ and $TiO_2$ layers with an absorbed dye ensure that a dye-sensitised cell operates appropriately. It can be pointed out by analysing the topography of the examined layers' surface (Fig. 5a and b) that a structure of $TiO_2$ and $TiO_2$ layers with an absorbed dye is compact in both cases.

No discontinuities were identified in the layers, and the results of measurements of layers thickness (Table 4) indicate a correctly absorbed dye by a $TiO_2$ layer. The thickness obtained varies between 15 μm for a $TiO_2$ layer and 20 μm for a $TiO_2$ layer with a dye absorbed and enable the layer to work photoactively. The layers meet technical requirements as the deposited $TiO_2$ and $TiO_2$ layers with the absorbed dye should not be thinner than 10 μm [29-30] for correct functioning of a dye-sensitised cell.

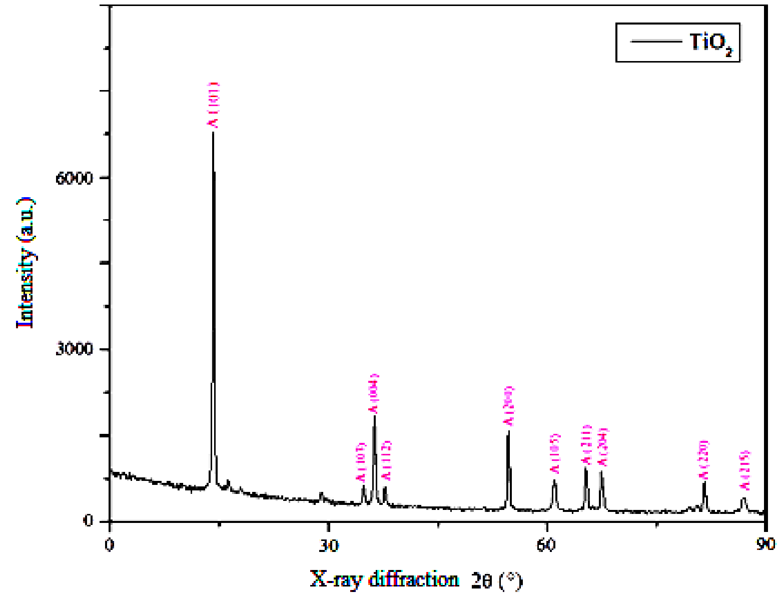


Fig. 4. X-ray diffraction pattern of $TiO_2$ layer

Table 3.
Detailed criteria for evaluation of attractiveness and types of dyes subjected to heuristic studies; the values rescaled to a universal scale of relative states are presented in the yellow fields [28]

| | Assessment criteria | Types of dye | | | | | | | | | | | | | | Weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Synthetic | | | | | | Natural | | | | | | | | |
| | | N-3 (T1) | | N-719 (T2) | | Z-907 (T3) | | Red rose petals (T4) | | Yellow rose petals (T5) | | Raspberries (T6) | | Blue-berries (T7) | | |
| | | Potential | | | | | | | | | | | | | | |
| 1. | The temperature dyeing, °C | 80 | 8 | 80 | 8 | 80 | 8 | 80 | 8 | 80 | 8 | 80 | 8 | 80 | 8 | 0.2 |
| 2. | The staining time, h | 12 | 8 | 24 | 6 | 24 | 6 | 24 | 6 | 20 | 7 | 48 | 5 | 12 | 8 | 0.1 |
| 3. | The uniformity of dyeing, % | 90 | 9 | 85 | 8 | 85 | 8 | 90 | 9 | 85 | 8 | 50 | 5 | 40 | 4 | 0.3 |
| 4. | Colour intensity, % | 80 | 9 | 80 | 9 | 75 | 8 | 90 | 10 | 70 | 7 | 70 | 7 | 60 | 6 | 0.2 |
| 5. | Availability of raw materials, % | 40 | 4 | 30 | 3 | 30 | 3 | 90 | 10 | 90 | 10 | 90 | 10 | 90 | 10 | 0.2 |
| | | Attractiveness | | | | | | | | | | | | | | |
| 1. | Preparation time, h | 24 | 7 | 24 | 7 | 24 | 7 | 24 | 7 | 22 | 6 | 1 | 8 | 1 | 8 | 0.1 |
| 2. | Quantity of raw materials used, g | 1 | 9 | 1 | 9 | 1 | 9 | 1 | 9 | 1 | 9 | 500 | 1 | 500 | 1 | 0.2 |
| 3. | Low price, PLN | 1080 | 2 | 1238 | 2 | 1564 | 1 | 2 | 9 | 2 | 9 | 5 | 8 | 7 | 7 | 0.2 |
| 4. | Toxicity, % | 50 | 1 | 40 | 2 | 50 | 1 | 0 | 10 | 0 | 10 | 0 | 10 | 0 | 10 | 0.3 |
| 5. | Ease of production, % | 20 | 2 | 20 | 2 | 20 | 2 | 90 | 10 | 90 | 10 | 80 | 9 | 80 | 9 | 0.2 |

Examinations with a confocal microscope and atomic forces microscope enable to determine the roughness factor values of a $TiO_2$ layer. The higher is the determined roughness factor value Ra, the higher catalytic activity of the $TiO_2$ layer with the absorbed dye which influences redox couple reduction in an electrolyte $I^-/I_3^-$ [35-36] thus causing the transport of electrons inside a dye-sensitised cell. Dye adhesion to the anode layer surface in an anode is also dependent on the $R_a$ factor value, which in consequence influences the electrical capacity of layers at the dye and electrolyte boundary. An average value of the $R_a$ factor characterising roughness for a $TiO_2$ layer is 0.177 µm, and for a $TiO_2$ layer with the dye absorbed it is $R_a = 0.187$ µm. The obtained results of $R_a$ factor values characterising $TiO_2$ layer roughness signify a well developed active area [29,36], while $TiO_2$ layer roughness with the absorbed dye signifies well located dye agglomerates on the surface of $TiO_2$ crystals.

A high conductivity PEDOT:PSS polymer, being a binder, and carbon nanotubes, selected according to a literature study (Table 5), were employed for manufacturing a dye-sensitised solar cell cathode.

A high conductivity PEDOT:PSS polymer, due to its high electrical conductivity of 150 S/cm, influences the enhancement of electrical values of DSCs. Carbon nanotubes were obtained independently according to an original, established chemical vapour deposition technology on a silicon substrate (Table 6).

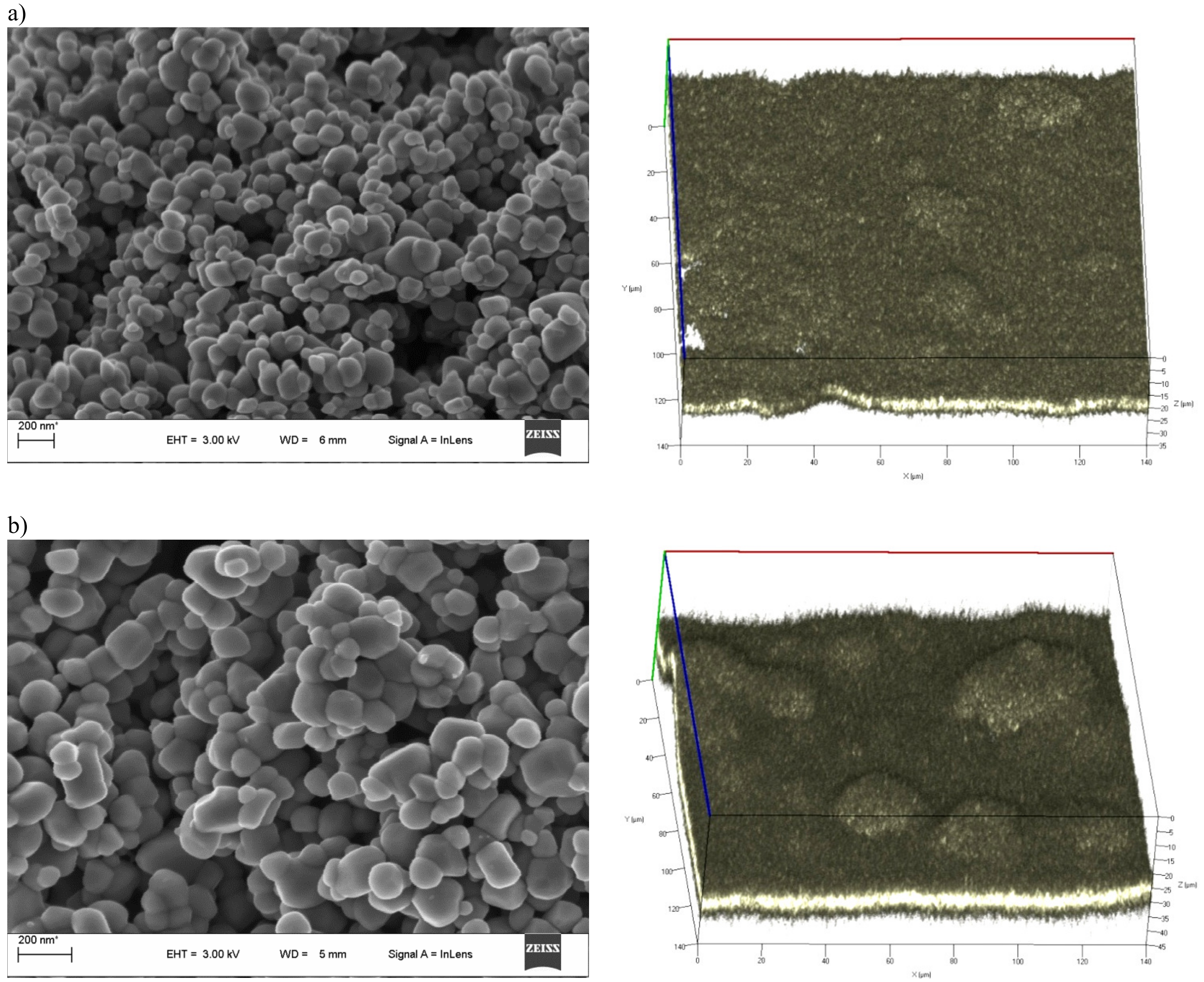


Fig. 5. Surface structure of layers of: a) $TiO_2$, b) $TiO_2$ with dye absorbed

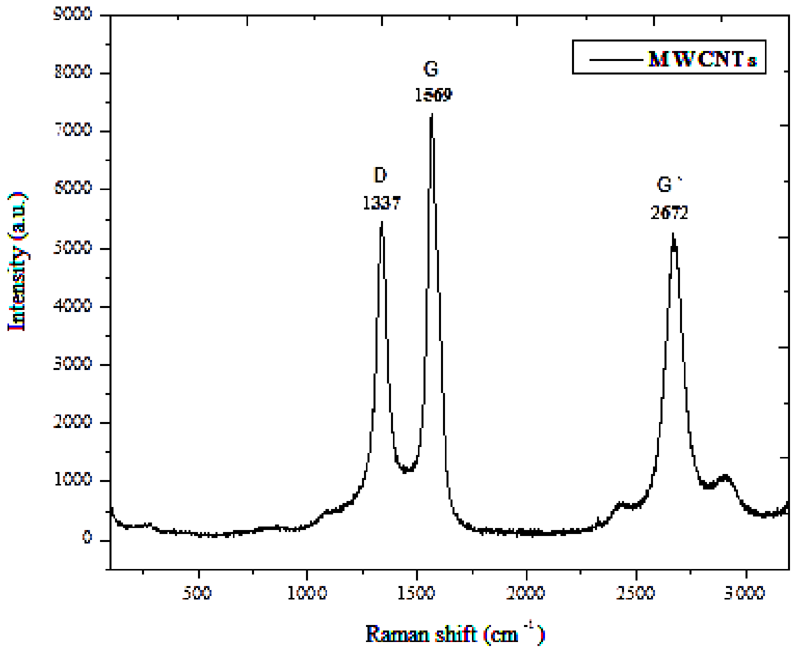


Fig. 6. MWCNTs Raman spectra

Table 4.
Average thickness of particular layers in dye-sensitised solar cell

| No. | Material | Thickness of layer |
|---|---|---|
| 1. | PEDOT:PSS + carbon nanotubes | 35-40 µm |
| 2. | PEDOT:PSS highly conductive | 5 µm |
| 3. | $TiO_2$ + dye | 20 µm |
| 4. | $TiO_2$ | 15 µm |

Table 5.
Comparison of properties of CNTs and selected materials [6,31-34]

| Material | Properties | | |
|---|---|---|---|
| | Young's modulus [GPa] | Tensile strength [GPa] | Density [g/cm$^3$] |
| Single walled carbon nanotubes SWCNTs | 1054 | 150 | 2.6 |
| Single walled carbon nanotubes MWCNTs | 1200 | 150 | 2.6 |
| Steel | 208 | 0.4 | 7.8 |
| Epoxy resin | 3.5 | 0.005 | 1.25 |
| Wood | 16 | 0.008 | 0.6 |

The results of Raman spectroscopy examinations confirm the presence of multi-walled carbon nanotubes according to the identified D band (1337 cm$^{-1}$) corresponding to the degree of nanotubes structure disorder and the G band (1569 cm$^{-1}$) corresponding to the degree of nanotubes graphitisation and their intensity and the G` band (~2672 cm$^{-1}$), corresponding to the degree of carbon nanotubes graphitisation (Fig. 6). The presence of the D` module band was not confirmed. This may signify on one hand the permitted level of nanotubes' contamination, but the intensity level of the module D signifies the presence of structural defects in the fabricated carbon nanotubes or such with the higher carbon number in the amorphous form. The intensity of the module D in relation to the module G suggests defects to the examined materials' structure. The $I_D/I_G$ relationship was calculated to be 0.85210 and the $I_D/I_{G'}$ relationship to be 0.9653. It was identified on the basis of observations in a scanning electron microscope that a forest of CNTs was created (Fig. 7a, b).

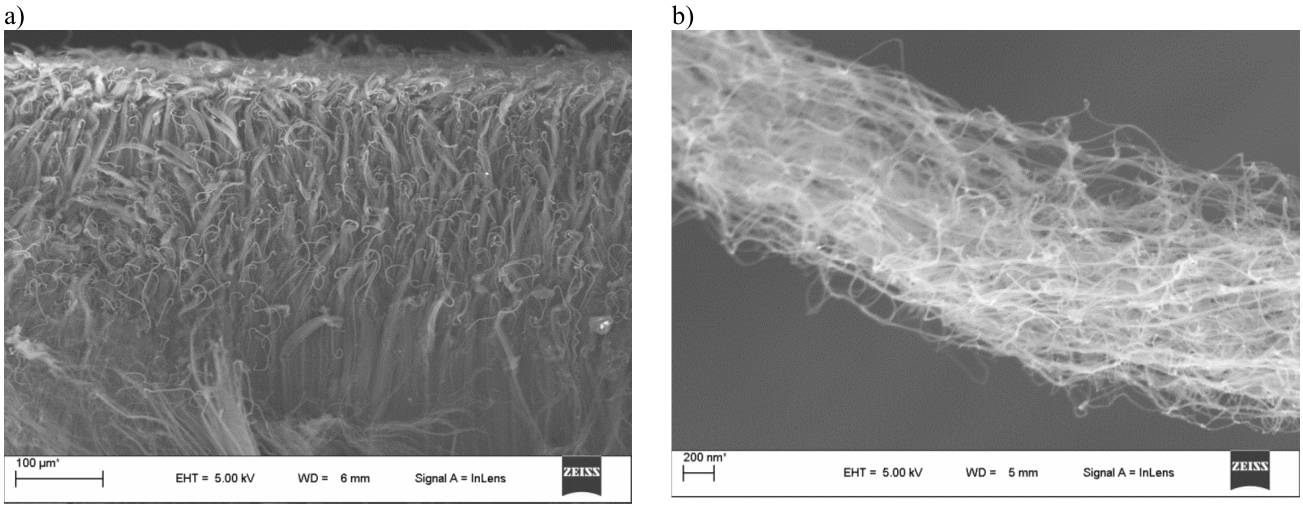


Fig. 7. Structure of carbon nanotubes a) MWCNTs forest on silicon substrate, b) MWCNTs, SEM

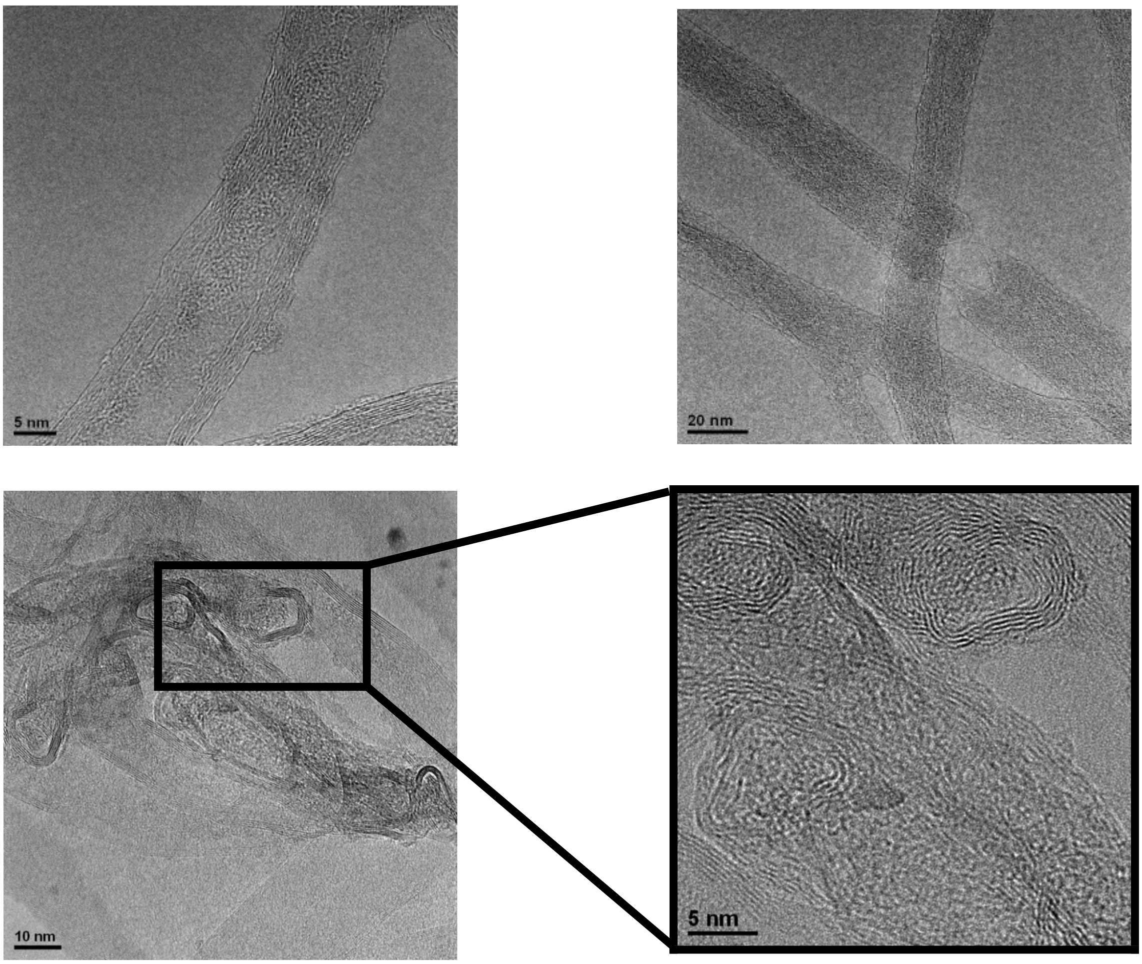


Fig. 8. High-resolution TEM image of structure of multi-walled carbon nanotubes

Table 6.
Silicon wafers with catalyst type used for MWCNTs fabrication by CVD

| No. | Material | Kind of catalyst |
|---|---|---|
| 1. | Silicon wafer | 1 nm Fe/10 nm $AlO_x$ |
| 2. | Silicon wafer | 2 nm Fe/20 nm $AlO_x$ |

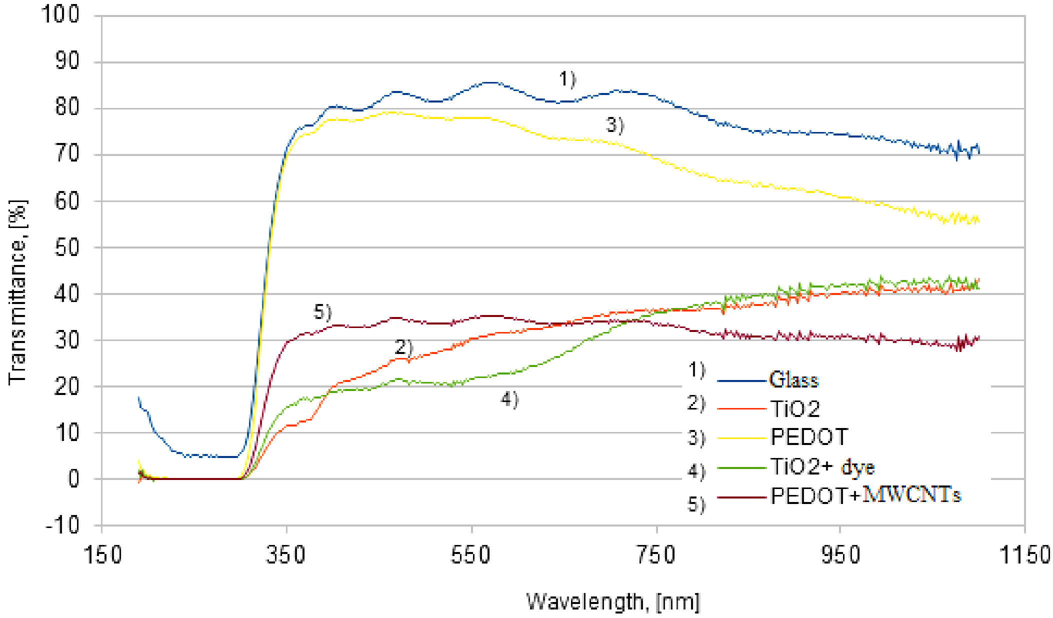


Fig. 9. Transmittance spectrum of particular dye layers of dye-sensitised solar cell

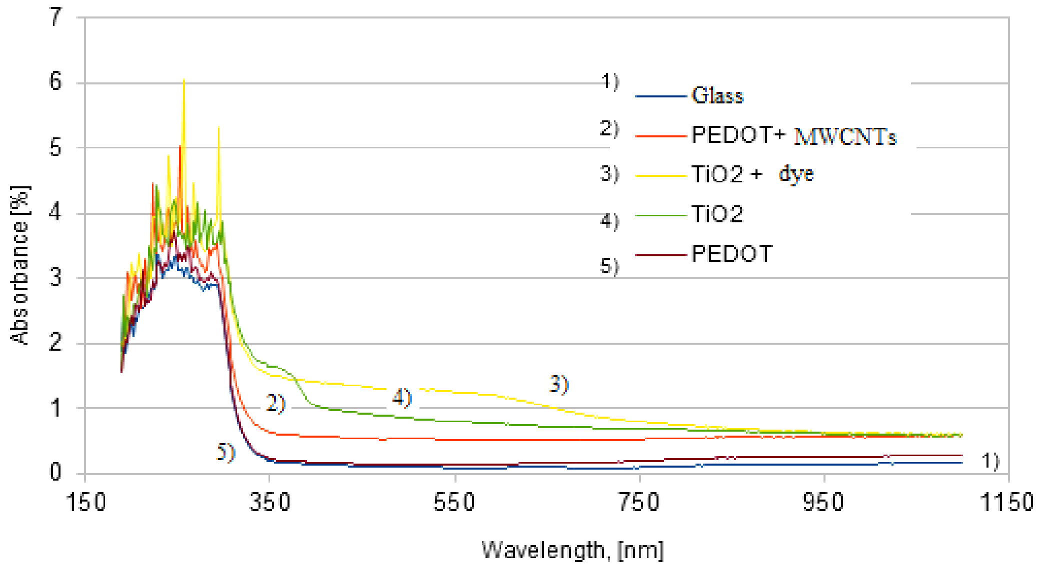


Fig. 10. Absorbance spectrum of particular dye layers of dye-sensitised solar cell

Multi-walled carbon nanotubes occur as bundles rolling and crossing in the space, and the presence of carbon nanotubes' clusters and of graphene planes was confirmed with the results of structural examinations using a transmission electron microscope (Fig. 8).

It was thus confirmed that the fabricated CNTs are suitable for application as a dye-sensitised solar cell cathode.

The thickness of a semi-conductive $TiO_2$ layer influences DSSC transparency, as confirmed with the outcomes of examinations of optical properties. As it should have been expected, the best optical properties are exhibited by pure glass with a FTO layer. Transmittance for a glass plate with a conductive layer is 86% for the wavelength of 565 nm, whilst absorbance is lower than 3.37% for wavelength ranging 228-300 nm. Optimum transmittance and absorbance values were attained for a $TiO_2$ and $TiO_2$ layer with an absorbed dye as a transmittance value for a $TiO_2$ layer is lower than 41%, for the wavelength of 918-1100 nm, and absorbance is at below 4.42% for the wavelength of 228-210 nm. A decrease in the transmittance of the studied DSC $TiO_2$ layer below 42% within the range of 918-1100 nm as compared with pure FTO glass, (Fig. 9) is caused by light absorption by a dye absorbed onto the surface of the $TiO_2$ layer. The obtained $TiO_2$ and $TiO_2$ layers with an absorbed dye are thinner (15 and 20 μm) as compared to a layer made of PEDOT:PSS with carbon nanotubes, with the average thickness of about 40 μm, with transmittance of about 45% within the spectral range of 466-568 nm (Fig. 9) and absorbance below 5% within the spectral range of 210-310 nm (Fig. 10).

## 4. Conclusions

It is possible to change a structure of a dye-sensitised solar cell by replacing the commonly used platinum in a counter electrode with another electrode permeable for visible light made of a high conductivity polymer PEDOT:PSS poly(3,4-ethylenedioxythiophene) - PEDOT doped with polystyrene sulfonate (PSS) with multi-walled carbon nanotubes. $TiO_2$ layers exhibit a transmittance value of below 41% for the wavelength of 918-1100 nm and absorbance smaller than 4.42% for the wavelength of 228-210 nm; the layers with an absorbed dye exhibit smaller transmittance below 42% for the range of 918-1100 nm, which is caused by light absorption by a dye absorbed onto a glass substrate with $TiO_2$, whereas the layers made of a high conductivity PEDOT:PSS polymer with multi-walled carbon nanotubes have the transmittance of about 45% for the spectral range of 466-568 nm and absorbance below 5% for the spectral range of 210-310 nm. The best adhesion and structural properties of the $TiO_2$ layer applied onto a glass plate surface with an FTO layer are ensured by heating at 450 ± 10°C for 45 minutes, accompanied by titanium dioxide transformation from the amorphous form into a crystalline variant of titanium dioxide with a tetragonal crystallographic structure α-$TiO_2$, considered to be most desired in DSSCs and by removing organic contaminants remaining on the surface after producing an anode. The established dye-sensitised cells fabrication technology with a cathode made of a high conductivity polymer PEDOT:PSS poly(3,4-ethylenedioxythiophene) - PEDOT doped with polystyrene sulfonate (PSS) with multi-walled carbon nanotubes, using a $TiO_2$ solution and a natural dye provides an attractive alternative for dye-sensitised cells employing the commonly used platinum in a counter electrode, ensuring comparable optical and electrical properties of the fabricated DSSCs at considerably lower manufacturing costs of about 50%.

## Acknowledgements

The project was funded by the National Science Centre on the basis of the contract No. DEC-2013/09/B/ST8/02943 and No. DEC-2012/07/B/ST8/04070.

## Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

## References

[1] L.A. Dobrzański, Non-metallic Engineering Materials, Silesian University of Technology Press, Gliwice, 2008 (in Polish).

[2] A. Zdyb, Research on improving efficiency of dye solar cells, PAN Press, Committee of Environmental Engineering, Monography, 94, Lublin, 2012 (in Polish).

[3] G. Jastrzębska, Solar cells - structure, technology and application, WKŁ Press, Warszawa 2013 (in Polish).

[4] E. Klugmann-Radziemska, Photovoltaics in theory and practice, BTC Press, Legionowo, 2010 (in Polish).

[5] L.A. Dobrzański, A. Mucha, M. Prokopiuk vel Prokopowicz, M. Szindler, A. Drygała, K. Lukaszkowicz, Characteristics of dye-sensitized solar cells with carbon nanomaterials, Materiali in Tehnologije/ Materials and Technology 5 (2016) (in Print).

[6] L.A. Dobrzański, A. Drygała, Influence of laser processing on polycrystalline silicon surface, Materials Science Forum 706-709 (2012) 829-834.

[7] A. Dobrzańska-Danikiewicz, A. Drygała, Strategic development perspectives of laser processing on polycrystalline silicon surface, Archives of Materials Science and Engineering 50/1 (2011) 5-20.

[8] M. Nanu, J. Schoonman, A. Goossens, Nano-composite Three-Dimensional Solar Cells Obtained by Chemical Spray Deposition, Nano Letters 5/9 (2005) 1716-1719.

[9] M. Grätzel, Review: Dye-sensitized solar cells, Journal of Photochemistry and Photobiology C: Photochemistry Reviews 4 (2003) 145-153.

[10] H. Desilvestro, Y. Hebting, M. Khan, D. Milliken, Understanding and successfully applying materials for dye-sensitized solar cells, Materials Matters 9/1 (2014) 14-18.

[11] S. Krawczyk, A. Zdyb, Electronic Excited States of Carotenoid Dyes Adsorbed on $TiO_2$, Journal of Physical and Chemistry C 115 (2011) 22328-22335.

[12] S. Hao, J. Wu, Y. Huang, J.Lin, Natural dyes as photosensitizers for dye-sensitized solar cell, Solar Energy 80/2 (2006) 209-214.

[13] J.J. Kim, M. Kang, O.K. Kwak, Y.J. Yoon, K.S. Min, M.J. Chu, Fabrication and Characterization of Dye-Sensitized Solar Cells for Greenhouse Application, International Journal of Photoenergy 2015 (2015) 1-7.

[14] K.M. Lee, L.C. Lin, V. Suryanarayanan, C.G. Wu, Titanium dioxide coated on titanium/stainless steel foil as photoanode for high efficiency flexible dye-sensitized solar cells, Journal of Power Sources 269 (2014) 789-794.

[15] M.K. Nazeeruddin, E. Baranoff, M. Grätzel, Dye-sensitized solar cells: A brief overview, Solar Energy 85 (2011) 1172-1178.

[16] K. Imoto, K. Takahashi, T. Yamaguchi, T. Komura, J. Nakamura and K. Murata, High-performance carbon counter electrode for dye-sensitized solar cells, Solar Energy Materials and Solar Cells 79/4 (2003) 459-469.

[17] K. Znajdek, M. Sibiński, K. Tadaszak, W. Posadowski, Verification of the possibility of applying thin layers of $TiO_2$ as a transparent conductive coatings of different types of solar cells, Electronics 5 (2013) 24-26 (in Polish).

[18] A. Kay, M. Grätzel, Low cost photovoltaic modules based on dye sensitized nanocrystalline titanium dioxide and carbon powder, Solar Energy Materials and Solar Cells 44 (1996) 99-117.

[19] X.L. He, M. Liu, G.J. Yang, S.Q. Fan, C.J. Li, Correlation between microstructure and property of electroless deposited Pt counter electrodes on plastic substrate for dye-sensitized solar cells, Applied Surface Science 258 (2011) 1377-1384.

[20] L.A. Dobrzański, A. Mucha, M. Prokopiuk vel Prokopowicz, A. Drygała, K. Lukaszkowicz, Technology of dye-sensitized solar cells with carbon materials, Archives of Materials Science and Engineering 70/2 (2014) 70-76.

[21] A.D. Dobrzańska-Danikiewicz, D. Łukowiec, Synthesis and characterization of Pt/MWCNTs nanocomposites, Physical Status Solidi B250 12 (2013) 2569-2574

[22] O. Byrne, I. Ahmad, P.K. Surolia, Y.K. Gun'ko, K.R. Thampi, The optimisation of dye sensitised solar cell working electrodes for graphene and SWCNTs containing quasi-solid state electrolytes, Solar Energy 110 (2014) 239-246.

[23] Z. Huang, X. Liu, K. Li, D. Li, Y. Luo, H. Li, W. Song, L. Chen, Q. Meng, Application of carbon materials as counter electrodes of dye-sensitized solar cells, Electrochemistry Communications 9/4 (2007) 596-598.

[24] L.A. Dobrzański, M. Szindler, A. Drygała, M.M. Szindler, Silicon solar cells with $Al_2O_3$ antireflection coating, Central European Journal of Physics 12/9 (2014) 666-670.

[25] L.A. Dobrzański, M. Musztyfaga, A. Drygała, Final Manufacturing Process of Front Side Metallisation on Silicon Solar Cells Using Conventional and Unconventional Techniques, Strojniski vestnik - Journal of Mechanical Engineering 59/3 (2013) 175-182.

[26] L.A. Dobrzański, A. Drygała, M. Giedroć, Application of crystalline silicon solar cells in photovoltaic modules, Archives of Materials Science and Engineering 44/2 (2010) 96-103.

[27] L.A. Dobrzański, A. Drygała, The effect of laser treatment on the surface topography of polycrystalline silicon, Electronic - construction, technology, application 4 (2011) 53-54 (in Polish).

[28] A.D. Dobrzańska-Danikiewicz, The methodology of computer-integrated forecasting the development of surface engineering of materials, Open Access Library 1/7, 2012 (in Polish).

[29] B. Hu, Q. Tang, B. He, L. Lin, H. Chen, Mesoporous $TiO_2$ anodes for efficient dye-sensitized solar cells: An efficiency of 9.86% under one sun illumination, Journal of Power Sources 267 (2014) 445-451.

[30] L.Y. Lin, C.P. Lee, R. Vittal, K. C. Ho, Selective conditions for the fabrication of a flexible dye-sensitized solar cell with Ti/$TiO_2$photoanode, Journal of Power Sources 195 (2010) 4344-4349.

[31] R. Kelsall, I. Hamley, M. Geoghegan, Nanotechnology, PWN Press, Warszawa, 2009 (in Polish).

[32] W. Przygocki, W. Włochowicz, Fullerens and nanotubes, properties and application, WNT Press, Warszawa 2001 (in Polish).

[33] S.J. Fonash, Solar Cell Device Physics ($2^{nd}$ Edition), Elsevier, 2010.

[34] C.S. Nair, O.A. Sreekala, J. Indiramma, K. Bala, S.P. Kumar, K.S. Sreelatha, M.S. Roy, Functionalized multi-walled carbon nanotubes for enhanced photocurrent in dyesensitized solar cells, Journal of Nanostructure in Chemistry 3/19 (2013) 1-8.

[35] S. Peng, Y. Wu, P. Zhi, V. Thavasi, S.G. Mhaisalkar, S. Ramakrishna, Facile fabrication of poly-pyrrole/funcionalized multiwalled carbon nanotubes composite as counter electrodes in low-cost dye-sensitized solar cells, Journal of Photochemistry and Photobiology A: Chemistry 223 (2011) 97-102.

[36] S. Taya, T.M. El-Agez, H.S. El-Ghamri, M.S. Abdel-Latif, Dye-sensitized solar cells using fresh and dried natural dyes, International Journal of Materials Science and Applications 2 (2013) 37-42.