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Polycrystalline CdTe solar cells on elastic substrates

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Abstract. The presented article is a report on progress in photovoltaic devices and material processing. A cadmium telluride solar cell as one of the most attractive option for thin-film polycrystalline cell constructions is presented. All typical manufacturing steps of this device, including recrystalisation and junction activation are explained. A new potential field of application for this kind of device – the BIPV (Building Integrated Photovoltaic) is named and discussed. All possible configuration options for this application, according to material properties and exploitation demands are considered. The experimental part of the presented paper is focused on practical implementation of the high- temperature polymer foil as the substrate of the newly designed device by the help of ICSVT (Isothermal Close Space Vapour Transport) technique. The evaluation of the polyester and polyamide foils according to the ICSVT/CSS manufacturing process parameters is described and discussed. A final conclusion on practical verification of these materials is also given.

Key words: solar cells, thin films, polycrystalline semiconductors, cadmium telluride, polymers, building integrated photovoltaics.

1. Introduction

A big potential of cadmium telluride in photovoltaic applications was proved by many researchers among last decade [1,2]. These cells, in their typical construction, based on the CdS/CdTe semiconductor heterojunction, are expected to be the future generation devices owing to their good mechanical and optical parameters, and relatively low production cost.

However, the monolithic CdS/CdTe cells are now entering the early production phase, there are still the possibilities of expanding of their capabilities by exploring of the new application fields. Basing on this idea authors proposed the implementation of the modified CdS/CdTe cell structure in a universal, attractive application called BIPV (Building Integrated Photovoltaics) [3, 4]. The CdTe cell construction gives the opportunity of achieving the goal, under the conditions of the proper technology modifications, as well as proper substrate implementation, based on the material studies, which is the main goal of the paper. Additionally, unique properties of the CdS/CdTe cell make possible the closest integration with the architectonic element, delivering the PV product of a new quality standard. Thus the idea of the fully integration of PV elements with the surrounding environment [5] may be practically realized. The realization of this concept is also within the scope of the presented research.

2. Manufacturing technology of CdS/CdTe cells

The CdTe/CdS solar cell is a polycrystalline thin-film device, based on a semiconductor heterojunction. This construction assures the photovoltaic conversion of photons with different energies, since the energy bandgaps of CdS and CdTe are 2,5eV and 1,45eV respectively. Thus, the spectrum of wavelengths 480nm-880nm is placed within the conversion range of the typical CdS/CdTe cell, however, to achieve this aim, a proper layer and a junction construction, as well as an efficient contacting is essential. Figure 1 explains the structure and operation coCdTenditions of the discussed construction, by presenting the band model of the real CdS/CdTe junction.

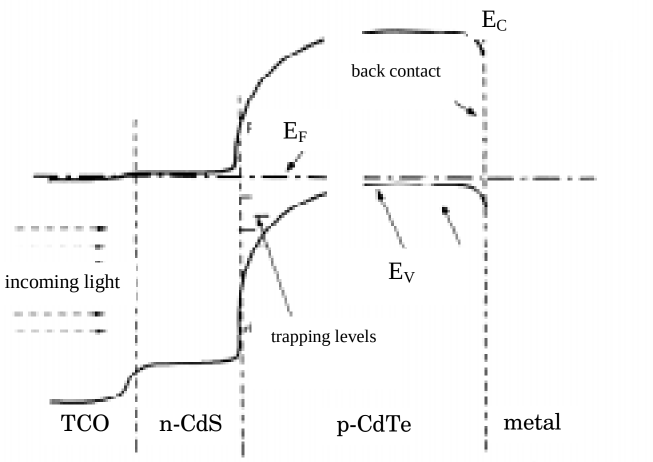

Fig. 1. CdS/CdTe semiconductor heterojunction construction

A typical manufacturing technology of cadmium telluride cell consists of few main steps [6]. First process is a deposition of the contacts and base semiconductor layer, which, depending on configuration, may be the cadmium sulfide emitter or cadmium telluride base. Then recrystalisation is commonly applied for obtaining the proper structure, orientation and dimensions of the polycrystalline material. This is typically a high – temperature process, often performed in special environment conditions. Finally deposition of the

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complementary layer and junction activation is done. This activity is used by many researchers towards obtaining better morphology of layers and increasing the lifetime of minority carriers.

In the Institute of Electronics laboratories the ICSVT technology was adopted for manufacturing of the standard glass-based CdTe cells. Owing to its high efficiency and universality one may expect that this technique can be extended for new application field. The methodology of this production process contains all described steps. At the preliminary level glass substrate is cleaned and covered by ITO (Indium Tin Oxide) as the transparent conductive contact. Further on CdS layer of 500nm-100nm is deposited by evaporation and then annealed for proper recrystallisation in the presence of catalytic admixture – $CdCl_2$. Then the most important part is taking place. During this phase in the closed chamber cadmium telluride layer is deposited and in parallel recrystallised in a single high-temperature process (Fig. 2 a, b). This task is realized by means of close-range PVD transport, conducted with the presence of cadmium dichloride, under regulated vapour pressure. Taking this way the compact layers of cadmium –telluride hexagonal grains, with the dimensions of 2-8μm were obtained (Fig. 3). The described process was originally developed in the State University of Gent and is very close to the present industrial the CSS (Close Space Sublimation) technology [7].

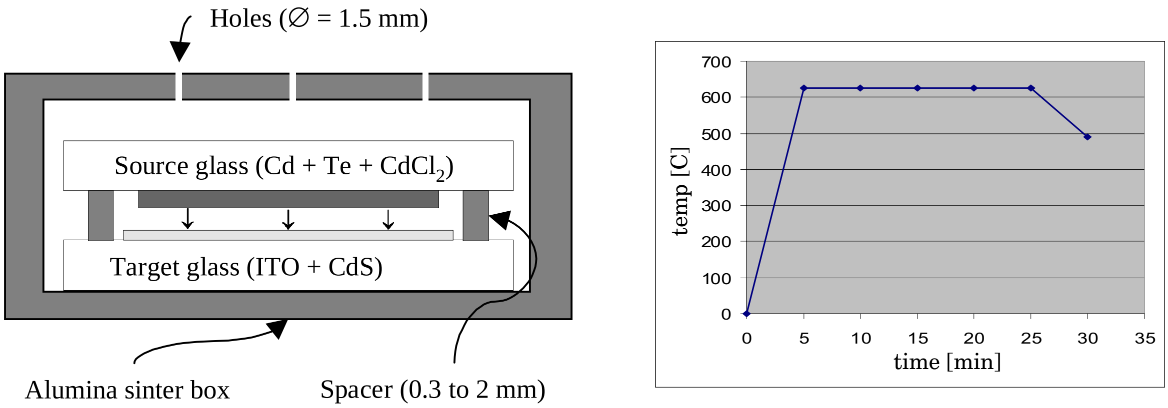


Fig. 2. The construction of ICSVT chamber a) and typical time-temperature profile of this process b) after Ref. 5

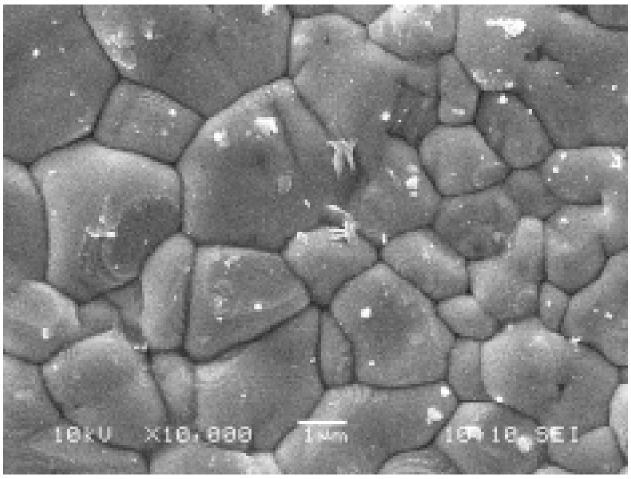


Fig. 3. SEM picture of CdTe layer, manufactured by ICSVT technology

3. Possible device configuration

Due to successful implementation of TCO (Transparent Conductive Oxide) for contacting purpose two opposite configuration of CdTe cell became possible. Historically first one is a classical substrate configuration (Fig. 4a), whereas based on glass + ITO, emitter-based configuration is called superstrate (Fig. 4b).

Both of them present some important advantages and inevitable technology shortcomings. Substrate configuration offers more mature manufacturing technology and lower substrate demands, while a superstrate configuration ensures higher efficiencies (smaller surface shadowing) and better encapsulation. Adaptation of the described technology for the new application and cell construction demanded deep consideration of all possible solutions. Formulated propositions of technology concepts are presented in Fig 5.

Every introduced concept posses some value according to different aspects of BIPV applications and each is subsequently investigated by our group [3,4]. Ceramic substrates could be recognized as the best platform for the complete integration of the photovoltaic element with the architectonic component. One may find the reports on practical investigation of this construction for other thin – film solar cells e.g. CIS devices [8], however, for CdS/CdTe construction, there is still research and technology adaptation needed. Additionally this kind of application is strictly connected with one particular architectonic element type like roof-tile or brick and it has to provide the complete modular interconnection and regulation system, since the whole installation is made of hundreds of elements, working

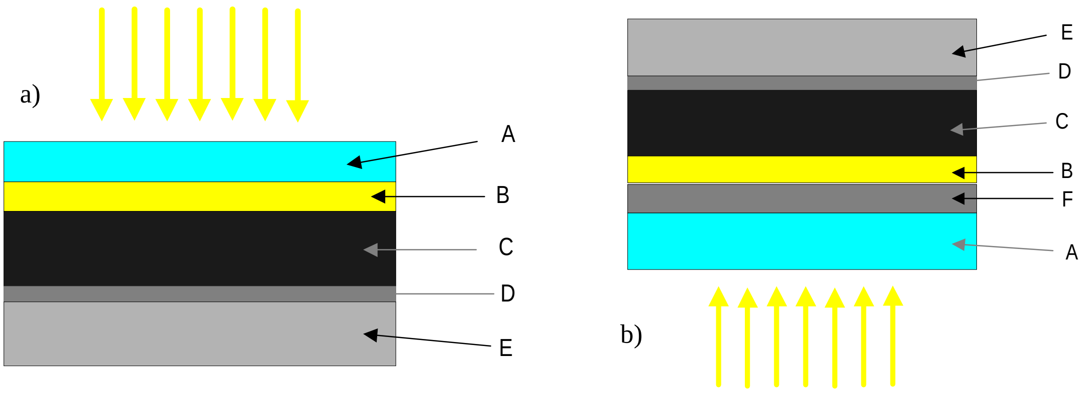


Fig. 4. Substrate a) and superstrate b) configuration of CdS/CdTe solar cell. A- glass cover, B- CdS emitter, C-CdTe base, D - base P+ sub layer, E-back contact, F-TCO layer, emitter metal contacts not visible

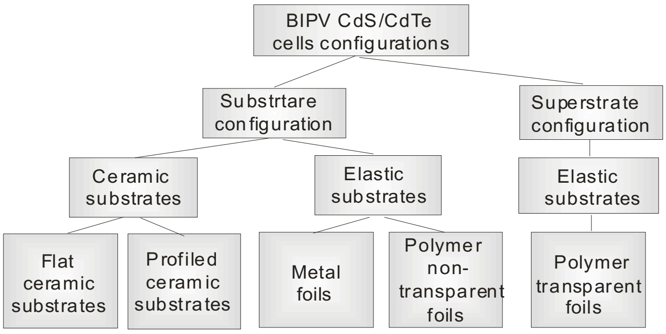


Fig. 5. Possible material and configuration solutions for CdS/CdTe BIPV solar cells

in different conditions. Furthermore, different interconnection systems (series, parallel and series-parallel) are necessary for optimum power and load polarization. Moreover, the standard ICSVT/CSS technology needs some fundamental modifications in case of implementation in profiled architectonic elements (roof tiles or ornaments) since the material transport occurs only between very closely positioned source and target.

Taking into account cadmium telluride solar cells, possessing elastic construction two base materials may be considered. One is thin metal foil, while the second is the polymer material. Implementation of metal foils, an example of Mo substrates for implementation in CdTe construction has been already investigated and reported by few groups [9,10]. In this work we focus on polymer foil implementation as the elastic solar cell substrate. Flexibility of this material combined with policrystalline thin-film structure properties gives a promise of manufacturing of elastic solar panel, ready for integration with architectonic substrate of any shape. Moreover, it gives the opportunity of constructing both substrate and superstrate configuration of CdS/CdTe cell. Finally polymer foils are lightweight, high-durable materials, what enhances the possible application field of cells. Depending on the configuration, production technology and desired application different properties of the substrate foils will be demanded. Finding the proper foil material and appropriate technology adaptation are the keys to obtaining efficient elastic cells.

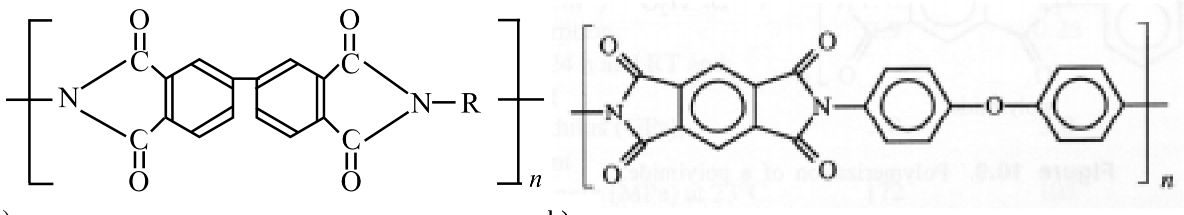
4. Elastic cells based on polymer foils

To define the properties of polymer base foils one may consider the specific of each configuration. So far, in the superstrate configuration highest conversion efficiencies were obtained [9,11], however, in this case, polymer substrates must fulfill several conditions. One can be mentioned as the most important: high optical transparency in the full conversion range of CdS/CdTe cell, ability of TCO surface electrode covering, high thermal durability, high chemical and water resistance. Apart from these specific demands, substrate foil of any configuration is expected to possess small weight, high elongation coefficient, thermal expansion similar to semiconductor polycrystalline layers (CdS and CdTe) and low price. In both cases elastic cells, manufactured on polymer foils may be easily attached to architectonic elements of different shapes. Taking this into account also substrate configuration of elastic cadmium telluride cell was investigated.

As the preliminary step of the research possible polymer material options were investigated. Polymers as the materials are constructed on a base of multi-modular chains of single, repetitive units called monomers [12]. In the manmade polymers even the number of a few thousand monomer types is being achieved. The properties of manufactured polymer material depend strongly not only on its chemical content and even monomer construction, but also on the monomers interconnecting system [13]. Due to complexity of the typical polymer construction it is impossible to evaluate the physical properties of these materials by the help of theoretical analysis. This gave the prompt to the series of experiments, aimed at comprehensive evaluation of physical parameters of polymer foils, potentially efficient as the CdS/CdTe cell substrate materials.

As the test group of polymer foils a wide set of materials, including standard commercial solutions as well as high – temperature polyester and polyamide was accepted. Among polyamide foils of high thermal durability two materials - KAPTON® and UPILEX® (Fig. 6) foils were chosen. Both of them are commercially available high-technology materials implemented in specific applications (eg: space shuttles wings and nose cover, high power loudspeakers membranes). They are characterized by high mechanical and thermal durability, high dielectric constant and UV durability. Among the polyester materials high – temperature MYLAR® material was adopted. As the reference material, popular PET foil in standard and high - temperature production version was applied. First evaluation step of material parameters is a verification of their mechanical parameters. Comparison of these results is presented in Table 1.

Obtained parameters suggest similar properties of all investigated materials, however some important differences are evident. The most important is the value of the thermal expansion coefficient (TEC). In general one may say that in the case of high –temperature materials the value of thermal expansion is lower, however in the case of UPILEX® the value of this parameter is close to standard PET foil. According to considered configuration thermal expansion coefficient of substrate foil should be adjusted to the value of the semiconductor base or emitter and contact layer. In both cases of semiconductor materials (CdS, CdTe) the value of TEC is very low (at the level of $5*10^{-4}$[%/ 1°C]), but the most typical metal contacts presents TEC value higher by the order of magnitude.



a) b)

Fig. 6. Structure of high-temperature polyamide foil UPILEX® a) and KAPTON® b), examined during the research

Table 1
Main mechanical parameters of tested polymer foils

Parameter\Foil	PET/High temp PET	UPILEX®	MYLAR®	KAPTON® HN 100
Thickness [ìm]	25	30	30	25,4
Weight [g/m^2]	30	44,1	41,7	35
Surface mass coefficient [m^2/kg]	31,2	22,7	23,98	27,9
Thermal expansion [%/ 1°C]	0,025	0,018	0,007	0,005
Standard elongation (25°C). [%]	600	54	103,5	40

The critical parameter in the standard recrystalisation process, as well as in the ICSVT, is a thermal durability of layer material. The maximum values of declared operational temperature for each investigated foil are presented in Table 2. Basing on the declared temperatures and considering the ICSVT temperature demands two, most durable foils were accepted for further investigations.

As the subsequent step the weight loss of KAPTON® and UPILEX® in higher temperatures was measured. For higher accuracy of obtained outcomes, as the additional test, the plastic properties of the materials for each temperature were estimated. Complete results of this test are presented in Table 3. Grey colour of the table cell marks a permanent deformation or loss of elastic properties.

The measurements of thermal durability were performed in the temperature range of a standard recrystaliation process (450°C - 650°C). During the experiment the percentage loss of the foil weight was measured. Additionally plastic properties were tested as the indicator of usefulness for the elastic substrate application. Basing on the obtained results one may state that in opposite to manufacturer suggestions, the biggest weight loss in temperatures above 500°C is observed in polyamide KAPTON®. Additionally the loss of its elastic parameters occurs very rapidly. Contrary, UPILEX®, which melting point is declared below 400°C proved to be fairly resistant to temperatures until 550°C. In both cases thicker foils reacted slower for the temperature rise, which was expected due to their relatively high thermal resistance. It is worth to mention that the experiment was conducted in conditions (time, equipment) similar to the manufacturing process. However identified maximal allowable temperature is relatively lower than standard demanded temperature for ICSVT process, there were reasonable presumptions suggesting the possibility decreasing of recrystallisation temperature in favour of longer process duration. Thus examined foils were conditionally positively evaluated. Taking this into account UPILEX® foil was accepted for further experiments, leading to manufacturing of the CdS/CdTe elastic layers. Considering possible configuration of designed cell the light transparency characteristic of investigated foil was measured. The light transmission in the conversion range of CdS/CdTe cell of both KAPTON® and UPILEX® foils is presented in Fig 7. Due to low transmission (below 60%) in the range 400nm-700nm, which would decrease largely the total cell efficiency, substrate cell configuration was chosen. Basing on presented results, experimental sample of CdTe base, manufactured on 25 ìm UPILEX® foil was prepared. Obtained semiconductor layer is based on Cu contact of 2μm, made by PVD in pressure 5*10^5 Torr. The total area of the sample is 30cm^2 and elastic properties of all manufactured layers are preserved (Fig 8). After the investigation the average thickness of 2μm and good uniformity of manufactured layer was observed, what makes proper base for CdS layer manufacturing and completing of the elastic CdS/CdTe construction.

Table 2.
Maximum declared operational temperatures of different polymer foils

Standard PET	130 °C
High-temp PET	185 °C
Polyester MYLAR®	254 °C
Polyamide UPILEX®	380 °C
Polyamide KAPTON®	430 °C

Table 3
Temperature durability of examined foils. Dark-grey color indicates the loss of elastic properties or permanent deformation

Weight in temperature:	**UPILEX®**		**KAPTON®**	
	12.5μm	**25μm**	**12.5μm**	**25μm**
480°C	91.82%	95.16%	96.7%	95.3%
500 °C	91.36%	94.84%	96%	94,6%
550 °C	89.55%	92.26%	74.7%	81.12%
600 °C	70%	78,38%	Burnt	Burnt

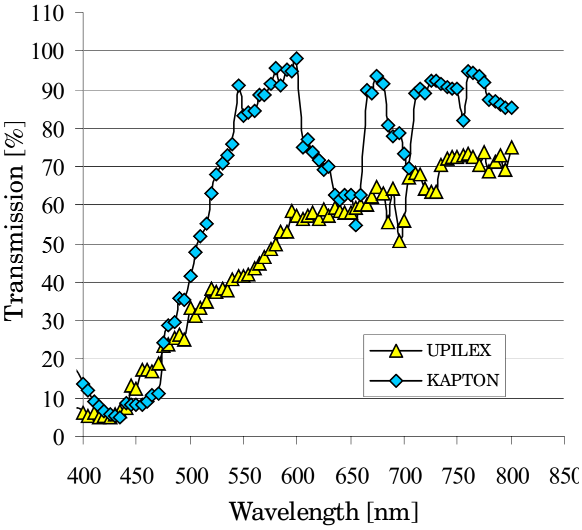


Fig. 7. Optical transparency of KAPTON® and UPILEX® foils in the wavelength range of CdS/CdTe cell effective photoconversion

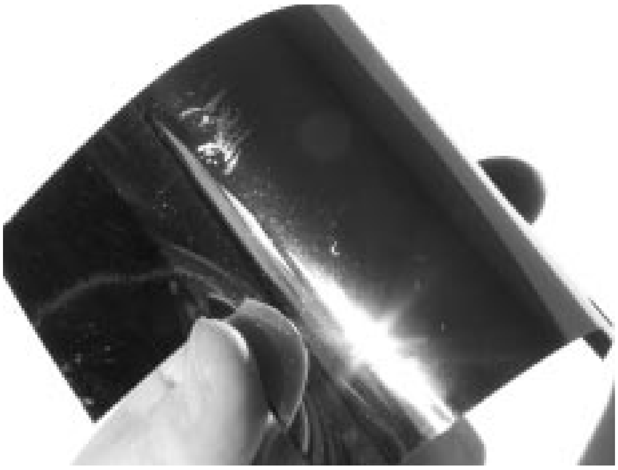


Fig. 8. Test structure of elastic CdTe layer based on UPILEX® foil and contacted by 2μm Cu layer

5. Summary and conclusions

As the first aim of the work a complete analysis of possible adaptation of CdS/CdTe cells technology and configuration for BIPV application was performed. In the experimental part of the presented work authors planed and conducted the series of experiments leading to evaluation of the possible elastic polymer substrate material for the newly designed construction. Subsequently the device configuration and necessary technology modifications were identified. Finally the first step of manufacturing of CdS/CdTe cell in substrate configuration, on commercially available polyamide foil, was made.

Obtained results confirm the assumption that flexibility of polycrystalline cadmium compound layers may be employed in alternative applications like elastic cell structure. The finding of the proper material for substrate of these devices is a key to manufacturing of an efficient cell, but it demands to consider many technological aspects. Thermal and mechanical properties of some high-temperature polymer foils give possibility of manufacturing of the complete cell under the condition of some technology modifications (particularly during the recrystalisation process). Obtaining such a device is the planned continuation of the presented work.

References

[1] P. Meyers and S. Albright, "Technical and economic opportunities for CdTe PV at the turn of the millennium", *Prog. Photovolt. Res. Appl*. 8, 161-169 (2000).

[2] C. Eberspacher, Ch. Gay, and P. Moskowitz, "Strategies for enhancing the commercial viability of CdTe-based photovoltaics", *Solar Energy Materials and Solar Cells* 41/42, 637-653 (1996).

[3] M. Sibiński, "Thin film CdTe solar cells in building integrated photovoltaics", *1st SWH Int. Con.*, 13-15 (2003).

[4] M.Sibiński and T. Widerski, "Utilization of CdTe solar cells in BIPV technology", *3rd State Conf. on Electronics,* 509-514. (2004), (in Polish).

[5] C. Sohie, "Integration of photovoltaics in architecture", 3rd *World Conf. on Photovoltaic Energy Conversion*, 2120- 2124 (2003).

[6] T. Markvart and L. Castaner, *Solar Cells: Materials, Manufacture and Operation*, Elsevier, Amsterdam, 2006.

[7] M. Sibiński and M. Burgelman, "Development of the thin-film solar cells technology", *Microtherm 2000,* 53-60 (2000).

[8] I. Lauremann, I. Luck, and K. Wojczykowski, "$CuInS_2$ based thin film solar cells on roof tile substrates", *17th EPSEC,* 1256-1259 (2001).

[9] D. Batzner, A. Romeo, D. Rudman, M. Kalin, H. Zogg, and A. Tiwari, "CdTe/CdS and CIGS thin film solar cells", *1st SWH Int. Conf.,* 56-60 (2003).

[10] M. Sibiński, A. Kalinowski, D. Sęk, and A. Iwan, "Elastic substrates for electronics", 4th *State Conf. on Electronics*, 493-498 (2005).

[11] R.Bube, "Photovoltaic materials", in *Properties of Semiconductor Materials,* vol 1, Imperial College Press, London, 1998.

[12] J.W. Nicholson, "Chemistry of polymers", WNT, Warsaw, 1994.

[13] S. Połowiński, "Physical chemistry of polymers", Publishing House of Lodz Technical University, Łódź, 2001.