10 Strategic development perspectives of laser processing on polycrystalline silicon surface

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Abstract

Purpose: *The goal of this chapter is to evaluate the strategic perspectives of polycrystalline silicon texturisation according to custom foresight methodology. The texturing type was the technology division criterion. Thus, in the chapter three technologies, as following: polycrystalline silicon texturisation by alkaline etching, laser treatment and laser treatment with chemical etching were compared.*

Design/methodology/approach: *In the framework of the foresight-materials science research, a foresight matrices set were prepared, the strategic development tracks were determined, as well as materials science experiments using a Nd:YAG laser, a scanning electron microscope, a confocal laser scanning microscope and a spectrophotometer were conducted. Finally, on the basis of the obtained results the technology roadmaps were prepared.*

Findings: *The carried out research pointed out the industrial importance of polycrystalline silicon texturisation and good perspectives for these technology groups.*

Research limitations/implications: *Research concerning polycrystalline silicon texturisation constitute a part of a larger research project aimed at identifying, researching, and characterising the priority innovative technologies in the field of materials surface engineering.*

Practical implications: *The presented results of experimental materials science research were proved the significant positive impact of texturisation on the structure and mechanical properties of polycrystalline silicon surface layers, which leads to the justification of their including into the set of priority innovative technologies recommended for application in industrial practice.*

Originality/value: *The novelty of this chapter is to evaluate the value of polycrystalline silicon texturisation in the background environment with their future development perspectives determination.*

Keywords: *Manufacturing and processing; Surface treatment; Polycrystalline silicon texturisation; Foresight; Technology Roadmapping*

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1. Introduction

In line with the European Union's development strategy formulated in the recent years called Europe 2020, it is indispensable to undertake comprehensive measures at a European, national and regional level aiming to support a more effective, competitive and low-emission economy based on knowledge and innovation ensuring high employment as well as social and territorial cohesion. It is envisaged that the level of investments for R&D and innovation until 2020 is to reach 3% of the EU's GDP from public and private funds. For the economic and social effects achieved to be satisfactory, the stream of investments has to be channelled into those fields of science and industries bringing the highest added value, with special consideration given to the role of small- and medium-sized enterprises representing 99.8% of all Polish enterprises generating 68% of the GDP. The outcomes presented have been decisive for a lively interest in the recent decade in technology foresight the purpose of which is to identify the priority innovative technologies and directions of their strategic development, also with regard to material engineering [1-5]. An analysis of the results and scope of such foresight research and development trends in the industry observed in technologically advanced countries has set a basis for conducting technology foresight for materials surface engineering [6]. Nearly 300 independent foreign and domestic experts representing scientific, business and public administration circles have taken part in the FORSURF technology foresight up till now at the different stages of works. They have completed approx. 600 multiquestion surveys and held thematic discussions during 7 Workshops. 14 thematic areas with 10 critical technologies having the best development prospects and/or being of key significance for the industry within the nearest 20 years were chosen as a result of the preliminary studies. A set of 140 critical technologies was thoroughly analysed according to three iterations of the Delphi method carried out in consistency with the idea of e-foresight [7] using information technology encompassing a virtual organisation, web platform and neural networks. Laser technologies in surface engineering including the laser texturisation of polycrystalline silicon with chemical etching were among the thematic areas analysed highly rated by the experts.

An interest in polycrystalline silicon texturisation technologies stems from economic reasons. The contemporary industry experiences growing demand for energy accompanied by the gradual depletion of the most conventional energy sources (hard coal and lignite, peat, crude oil and natural gas), constantly rising prices and supplies uncertainty for such natural fuels as well as controversies evolving concerning nuclear fuel security (uranium 235). Those factors combined with endeavours to reduce the greenhouse effect and the emissions of pollutions to the natural environment are contributing to a growing interest in the sourcing of renewable energy: solar energy, wind energy, hydro energy, geothermal energy, energy of sea currents, tidal energy and wave energy, thermal ocean energy as well as the manufacture of biofuels, biomass and biogas [8-11]. Boost in demand and the related growth in the industrial production of photovoltaic cells permitting to converts solar radiation energy directly into electric energy has been inscribing in this trend. The following is notably used for producing solar cells: gallium arsenide (GaAs), cadmium telluride (CdTe), copper-indium selenide ($CuInSe_2$), indium phosphide (InP), however a 95% market share is held by silicon (Si). The dominant role of silicon in this field is highly substantiated as it is a second, after oxygen, most widespread element on the Earth with its share in the earth crust of 27%. It occurs in nature most often in combination with oxygen in form of silica SiO_2 [12-14]. Solar cells are made from mono- and polycrystalline silicon. The cells made from monocrystalline silicon that is characterised by the ordered spatial arrangement of atoms with the same orientation of all elementary network cells in the entire volume of crystal are achieving high efficiencies, but are relatively expensive, however. A polycrystalline silicon crystallisation process with the ordered structure of grains having, however, a random crystallographic orientation, occurs at a much higher speed and consumes less energy, hence it is cheaper. A disadvantage of this solution is the presence of structural defects and, as a result, the efficiency of polycrystalline cells is lower by approx.

2-3% in respect of monocrystalline cells [8, 9]. Economic calculation justifies, therefore, scientific studies into the development of new technologies of producing solar cells from polycrystalline silicon with higher efficiencies as compared to the situation seen up till now.

The purpose of this interdisciplinary study is a comparative analysis of three alternative technologies of polycrystalline silicon texturisation using a custom foresight-materials science methodology [15]. The subject of the comparative studies are the results of investigations into the optical properties of polycrystalline silicon and electrical properties of the photovoltaic cells made of them and the results of expert studies presenting the value of the individual polycrystalline silicon texturisation technologies against the environment together with the recommended management strategies and forecast strategic development tracks. The chapter also presents the outcomes of foresight research pertaining to the position of laser technologies against other surface engineering technologies, including laser texturisation of polycrystalline silicon with chemical etching. Technology roadmaps have been established according to the results of the foresight and material sciences research being a comparative analysis tool especially helpful for small- and medium-sized enterprises not having funds for conducting own research in this domain.

2. Polycrystalline silicon texturisation usefulness and methods

High-efficiency photovoltaic cells require that optical losses are minimised extensively by decreasing the coefficient of solar radiation reflection from the illuminated surface. Electromagnetic radiation photons reaching a semiconductor surface may be either reflected from the surface, absorbed or transit through the material (Fig. 1a). In terms of photovoltaics, reflection and transmission are undesired as the unabsorbed photons cannot take part in the photovoltaic effect [8-10, 16, 17]. The $R(\lambda)$ solar radiation reflection coefficient for silicon wafers subjected to etching to remove damages made due to cutting is within 35-50% for the wavelength of about 400-1100 nm. Two methods exist for reducing the coefficient: deposition of the antireflective coating (ARC) and silicon surface texturing [17]. Through solar cell surface texturing, the photon reflected from the surface can be absorbed again (Fig. 1b).

a)

b)

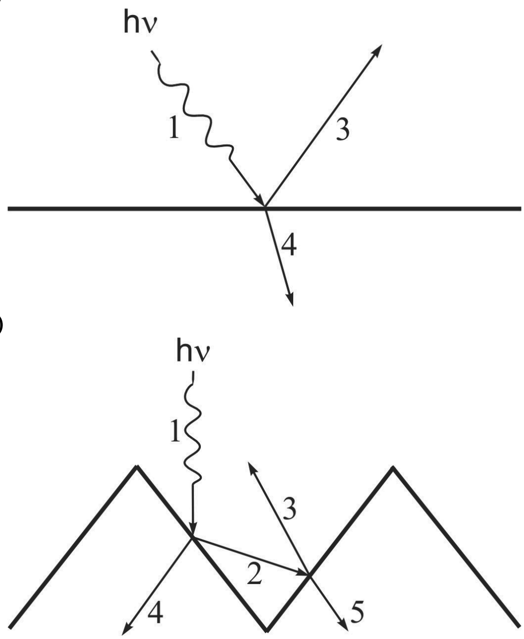

Figure 1. *The impact of surface texturing on radiation absorption: a) flat surface, b) textured surface; where: 1 – incident photon, 2, 3 – reflected photons, 4, 5 – absorbed photons*

A conventional method of surface texturisation commonly used in relation to monocrystalline silicon is anisotropic etching taking place during wet etching in alkali solutions, e.g. KOH or NaOH. A crystal is etched at various speeds according to different crystallographic directions which creates immense opportunities for its spatial shapening (e.g. pyramid structure for (100) orientation) [18, 19]. Etching anisotropy is measured with a relative relationship between (100) plane etching speed and (110) or (111) planes etching speed which for silicon create the following relationships most often [9]:

$$v_{100} > v_{110} > v_{111} \tag{1}$$

$$\frac{v_{100}}{v_{111}} \approx 100 \tag{2}$$

where:

v_{100} – (100) plane etching speed,

v_{110} – (110) plane etching speed,

v_{111} – (111) plane etching speed.

The high selectivity of such etching reagents according to different crystallographic orientations is restraining their use for polycrystalline silicon texturing. In addition, excessive grain faults between grains lead to gaps in metal contacts deposited with the screen printing method.

Other polycrystalline silicon texturisation methods described in the literature are as follows: etching in acidic solutions based on HNO_3:HF, HNO_3:HF:CH_3COOH [20-22], mechanical texturing using a diamond edge [23], reactive ion etching [24]. The surface of polycrystalline silicon can also be formed using a laser beam and this was a subject of own research described herein. The laser radiation properties permitting the precision processing of different materials with efficiency and accuracy significantly surpassing the conventional methods have a major effect on the utilisation of laser processing in various technological operations [25-35].

3. Interdisciplinary research approach

The research presented in this chapter are interdisciplinary. The foresight-materials science research method [15] employed origins directly from organisation and management (technology foresight) as well as materials science (surface engineering). The subject of the comparative analysis are both, the results of studies into the optical properties of polycrystalline silicon and electrical properties of photovoltaic cells made from them as well as a value of the individual technologies determined through expert investigations against the environment and their long-term development prospects together with the recommended management strategies and the forecast multi-variant strategic development tracks. The following selected polycrystalline silicon texturisation technologies have been analysed for the foresight and materials science efforts performed:

(A) polycrystalline silicon alkaline texturisation,

(B) polycrystalline silicon laser texturisation,

(C) polycrystalline silicon laser texturisation with chemical etching.

The materials science experiments were performed on the wafers made of polycrystalline silicon with a boron dopant with the area of 50 x 50 mm and the thickness of ~330 μm of the Bayer company. The wafer shape and dimensions are presented in Fig. 2. The properties of the tested material are given in Table 1.

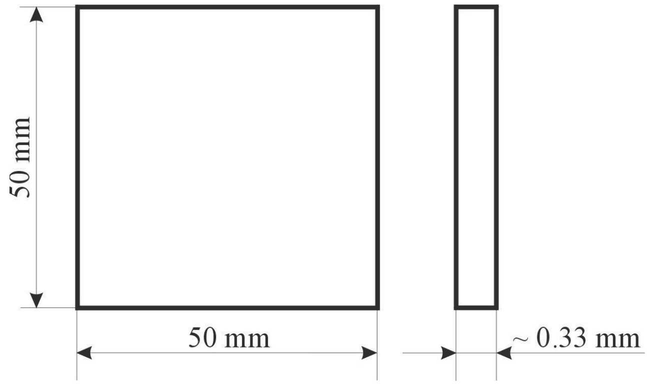

Figure 2. *Silicon wafer shape and dimensions*

Table 1. *Test material*

Basic properties of polycrystalline silicon	
Conductivity	*p*-type
Dopant type	boron
Resistivity	~1 Ωcm
Diffusion length	≥ 80 μm
Boron concentration	$5x10^{16}$ of atoms per cm^3
Oxygen concentration	$5x10^{17}$ of atoms per cm^3
Carbon concentration	$1x10^{18}$ of atoms per cm^3
Concentration of transient metals	10^{11}-10^{15} of atoms per cm^3

3.1. Materials science methodology

Laser silicon surface texturing was carried out with an Allprint DN 50A laser system by Alltec with a laser equipped with a constant active medium – an yttrium-aluminium garnet crystal doped with neodymium ions (Nd:YAG). The laser used is a small-capacity device employed for precision processing in surface engineering. An optoacoustic modulator (Q-switch) is used to produce high-capacity laser pulses in a jogging work mode in the laser system. The surface processing of polycrystalline silicon was undertaken for the following conditions: laser beam output power of 100 %, laser beam release frequency from f = 15 kHz, laser beam movement speed v = 20 mm/s. A texture was made corresponding to the lattice of grooves with the interspace of 0.09 mm.

Production scheme of polycrystalline silicon solar cells in Fig. 3 is presented. This production process were performed according to the following steps:

- saw damage removal,

- surface texturisation,
- laser induced surface damage removal,
- contamination removal,
- phosphorous diffusion,
- junction insulation and phosphorous-silicate glass removal,
- antireflection coating deposition,
- screen-printing and co-firing of metal contacts.

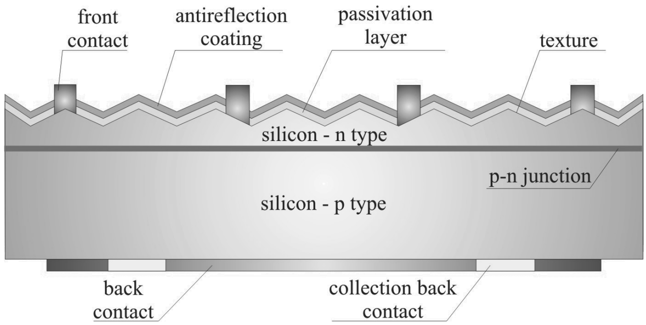

Figure 3. *Production scheme of polycrystalline silicon solar cells*

A silicon surface topography test after laser treatment was performed with a Scanning Electron Microscope (SEM) ZEISS SUPRA 25 and with a Confocal Laser Scanning Microscope (CLSM) 5 Pascal by ZEISS.

The electromagnetic radiation reflection coefficient was measured with a Perkin-Elmer Lambda spectrophotometer for the wavelength of 300 nm to 1300 nm fitted with integrating sphere. The $R(\lambda)$ reflection coefficient values obtained in the measurement were converted into the R_{eff} effective reflection coefficient value according to the following relationship [36,37]:

$$R_{eff} = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} R(\lambda) N_{ph}(\lambda) d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} N_{ph}(\lambda) d\lambda} \tag{3}$$

where:

$N_{ph}(\lambda)$ – the number of photons falling on an area unit for the specific wavelength in 1 second in AM1,5 conditions.

This coefficient informs whether the curve identifying the reflection coefficient relationship to the tested textured surface according to wavelength matches the solar radiation emission spectrum.

The tests of electrical properties of photovoltaic cells produced using laser textured wafers were made with a computerised SOLAR-LAB station for measuring voltage-current characteristics (I-V) of solar cells for a standard radiation spectrum of AM 1.5 with the radiation concentration of 1000 W/m^2 and the photovoltaic cell temperature of 25°C.

3.2. Foresight methodology

The reference data acquired as a result of implementing foresight research under the project “Foresight of surface properties formation leading technologies of engineering materials and biomaterials. FORSURF” [6] has been used in order to determine the strategic position of laser technologies against materials surface engineering and the laser texturisation of polycrystalline silicon against the surface engineering laser technologies. The research was held according to three iterations of the Delphi method carried out in consistency with the idea of e-foresight [7] using information technology encompassing a virtual organisation, web platform and neural networks. Neural networks were used in a novel and experimental manner to analyse the cross impacts emerging between the analysed trends and the events likely to occur in the future within the considered timeframe. The specific polycrystalline silicon texturisation technologies analysed in this chapter were evaluated based on experts’ opinions using a custom foresight-materials science research methodology [15]. A universal scale of relative states being a single-pole scale without zero was used in the research undertaken, where 1 is a minimum rate and 10 an extraordinarily high rate. The relevant technologies were evaluated for their potential representing a realistic objective value of the particular technology and for their attractiveness reflecting the subjective perception of a specific technology by its potential users. The results were entered into one of the quarters of the **dendrological matrix of technology value** serving to visualise the objectivised values of the specific separated groups of technologies. A wide-stretching oak is the most promising quarter guaranteeing the future success. A soaring cypress characterises highly attractive technologies with a limited potential and a rooted dwarf mountain pine symbolises technologies with a high potential and limited attractiveness likely to ensure a strong technology position if an adequate strategy is employed. The least promising technologies are placed in a quarter of the matrix called a quaking aspen with their future success being unlikely or infeasible. The results of the experts' assessment concerning the influence of the environment on the technologies analysed according to opportunities and difficulties were entered into one of the quarters of the **metrological matrix of environment influence.** Sunny spring illustrates the most favourable external situation ensuring the future success. Rainy autumn gives a chance for steady progress. Hot summer signifies a stormy environment where the success of a technology is risky but feasible. Frosty winter informs that technology development is difficult or infeasible.

The results of the expert investigations visualised with the dendrological and meteorological matrix were next entered with software based on the previously formulated mathematic relationships [15] into the **matrix of strategies for technologies** comprised of sixteen fields. The matrix presents graphically a place of each group of technologies according to its value and environment influence intensity and identifies a recommended action strategy. The strategic development prospects of a given technology expressed in numbers using a universal scale of relative states (min: 1, max: 10) correspond to the relevant areas of the matrix (Fig. 4). The anticipated development of the technologies analysed according to three variants: a positive, most probable and negative variant, was visualised by entering **strategic development tracks** into the matrix of strategies for technologies. The forecast established presents a vision of future events consisting of several variants for a 20-year time horizon for the time intervals of 2015, 2020, 2025 and 2030.

On the basis on the results of foresight-materials science research **technology roadmaps** have been predated. The set-up of the custom technology roadmap corresponds to the first quarter of the Cartesian system of coordinates. Three time intervals for the years of: 2010-11 (current situation), 2020 (goals fulfilment methods), 2030 (long-term objectives) are provided on the axis of abscissa. Seven main layers were applied onto the axis of coordinates of the technology roadmap: time, concept, product, technology, spatial, staff and quantitative ones, made up of more detailed sub-layers. The main technology roadmap layers were hierarchised starting with the top, most general layers determining all-social and economic reasons and causes of the actions taken, through the middle layers characterising a product and its manufacturing technology, to the bottom layers detailing organisational and technical matters concerning the place, contractor and costs. The relationships between the individual layers and sub-layers of the technology roadmap are presented with the different types of arrows representing, respectively, cause and effect relationships, capital ties, time correlations and two-directional data and/or resources flow.

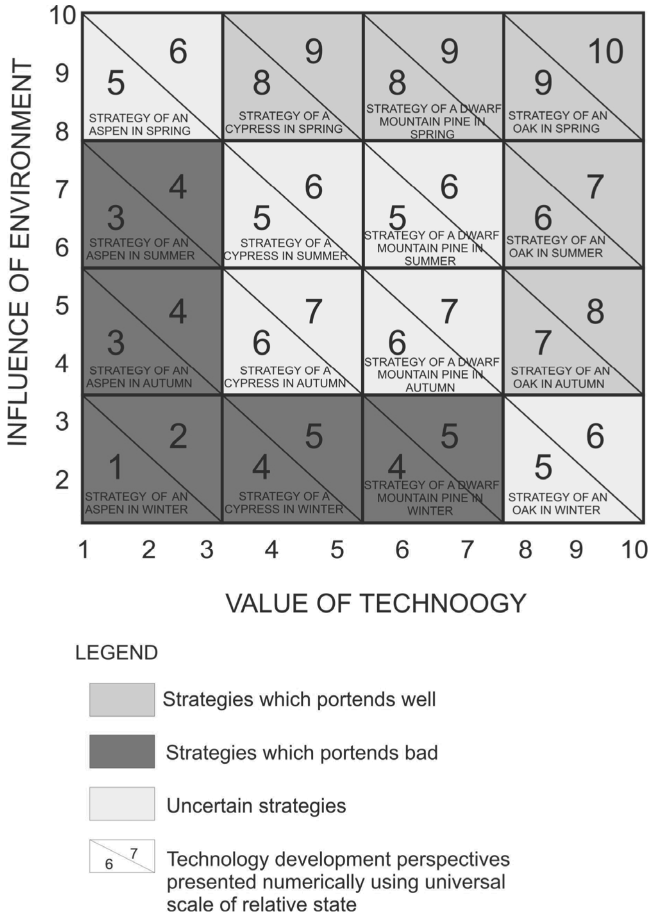

Figure 4. *The framework of the matrix of strategies for technologies with numerically expressed technology development perspectives*

4. Materials science research results

The use of the base 40% KOH : IPA : DIH_2O solution at the temperature of 80°C causes significant differences in the etching speed of polycrystalline silicon grains with a different crystallographic orientation (Fig. 5). This restricts the etching reagent's use for the texturing of polycrystalline silicon where the distribution of crystallographic grains orientation is random. If the alkaline etching time extends, the faults of the textured surface at the grain boundaries are formed [38].

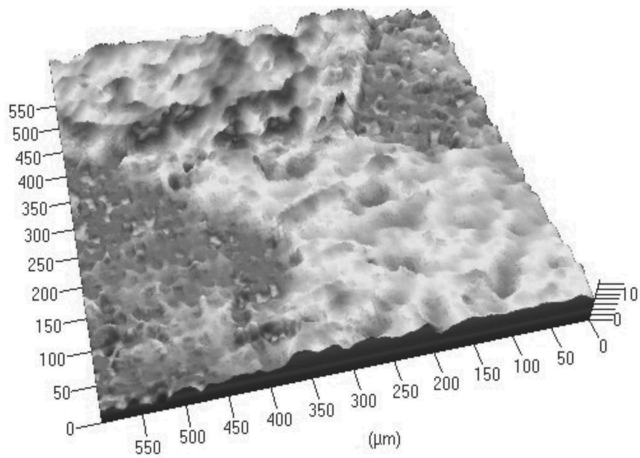

Figure 5. *CLSM three-dimensional topography of the textured wafer surface in 40% KOH:IPA:DIH_2O solution*

It was found by observing the surface topography of wafers with the texture corresponding to the lattice of grooves in a scanning electron microscope that the shape of grooves is irregular with flashes at the peripheries (Fig. 6). The hollows formed are secondary and filled with molten and incompletely evaporated material. The areas between the flashes of the neighbouring grooves are covered with clotted material ejected from the grooves and with products deposited from the gaseous phase released when the material is evaporated outside the groove. Deformed, crystallised silicon beads, so-called inflows, exist at the surface within the groove and flashes having varied dimensions. The clotted beads of the pre-melted material that is substantially ground (diameter of below 0.5 µm) are present at the material surface within the areas between the grooves. Microcracks and microgrooves are present at the surface subjected to texturing, both in the hollows and in flashes.

A laser texture was created by repeating the sequences of parallel grooves in two directions perpendicular to each other. The tracks created in the first place are largely flooded with the molten and incompletely evaporated material, thus they are not visible. The final texture appears only after etching (Fig. 7). Initially, the flashes width and height gradually decreases, then gaps appear in them and then they are completely removed. The side walls and the bottom of the hollow are also etched. Perpendicular grooves appear in the initial phase of etching. Hollows with a higher depth occur where the hollows intersect. Flashes are completely removed during etching and hollows repeating on the whole textured area appear with a regular polyhedral shaped depending on the substrate crystallographic orientation.

a)

b)

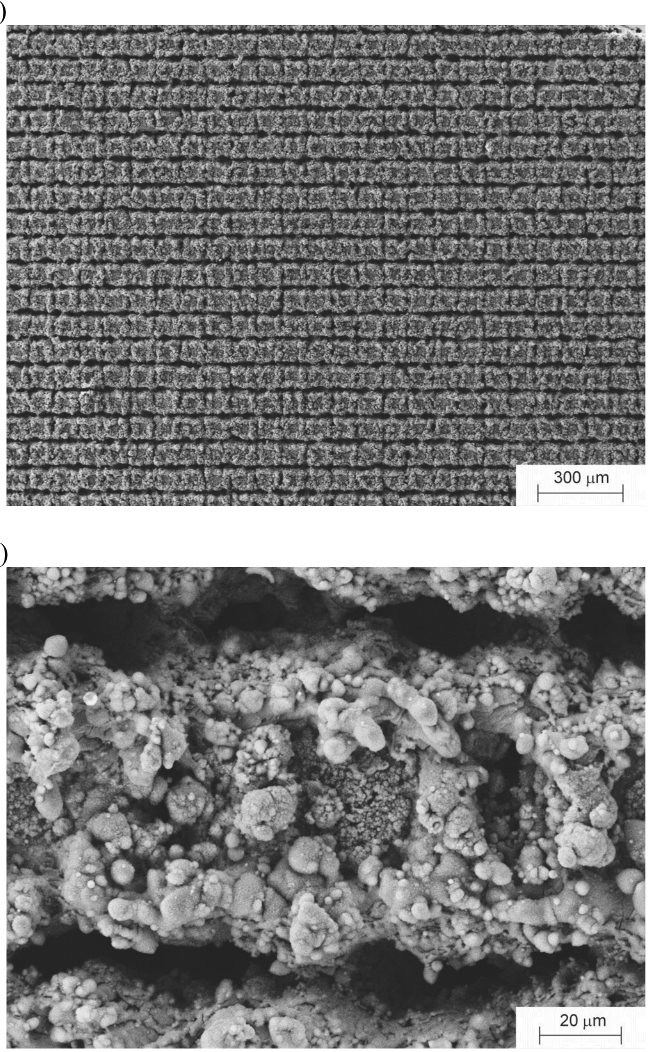

Figure 6. *SEM topography of the laser textured surface of polycrystalline silicon: a) x 150, b) x 2 000*

a)

b)

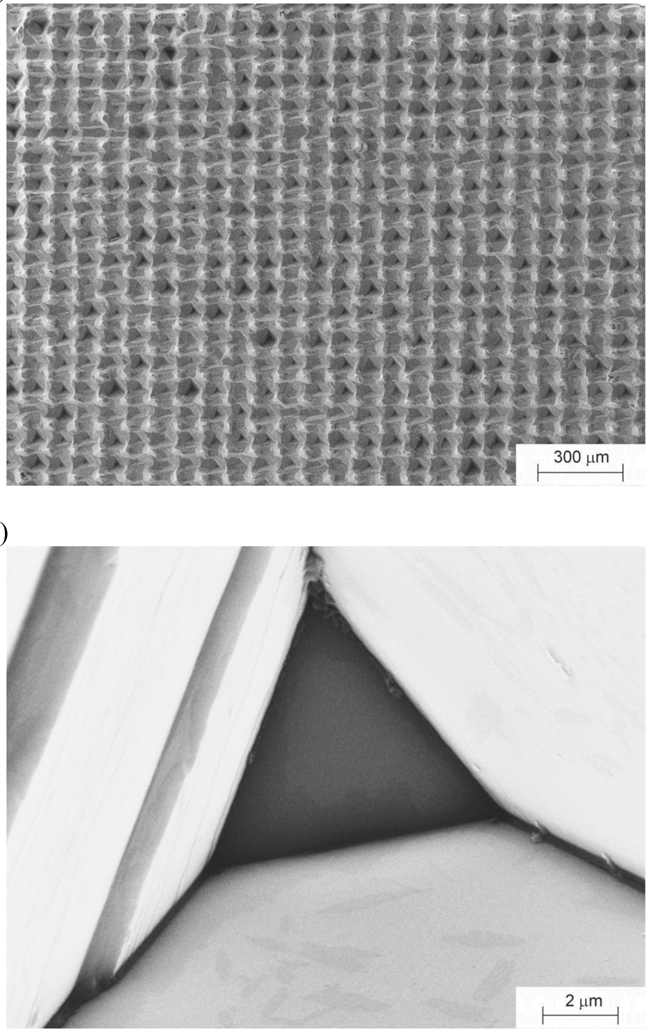

Figure 7. *SEM topography of the laser textured surface after removing 80 µm of the removed layer: a) x 150, b) x 20 000*

The light reflection coefficient was examined for untextured wafers after removing the surface layer damages formed while cutting a silicon block. The results obtained were compared to the light reflection coefficient for a wafer subjected to alkaline texturing in a 40% KOH:IPA:DIH_2O solution. Fig. 8 shows the light reflection coefficient according to the wavelength of the incident radiation for such wafers. Alkaline texturing reduces the light reflection coefficient compared to the wafers subject to no surface treatment. The optical properties of the laser-textured wafers are highly dependable upon the laser treatment conditions. If the surface of wafers is textured corresponding to the lattice of grooves, this causes a decrease in the light reflection coefficient as compared to the coefficient for untextured wafers. As the etching of laser-textured wafers is progressing gradually, the R_{eff} coefficient is clearly growing only after removing 80 μm.

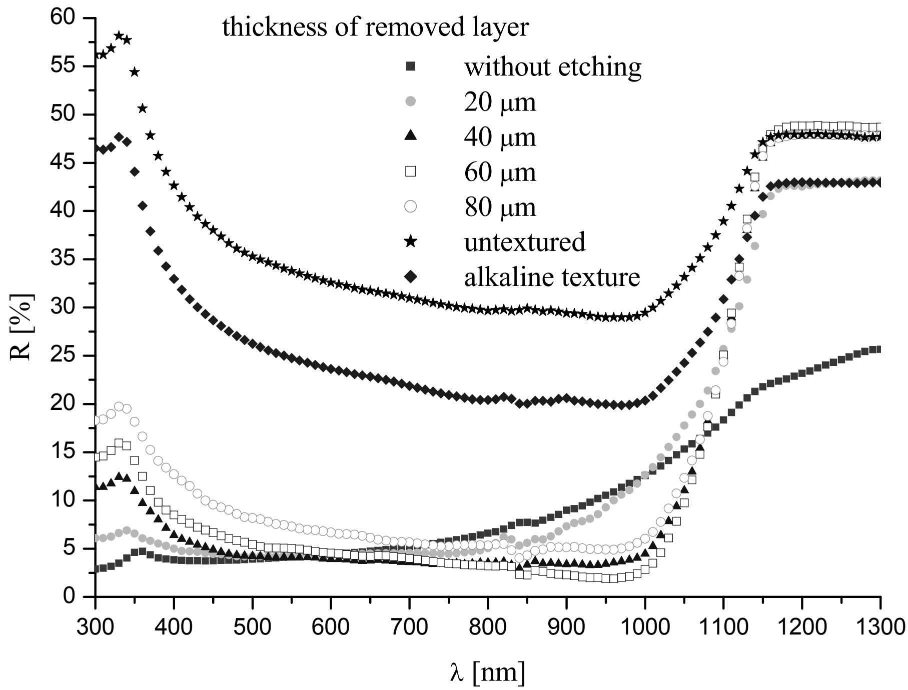

Figure 8. *The light reflection coefficient for the following polycrystalline silicon wafers: untextured, alkaline-textured, unetched laser-textured and laser-textured ones with varied thickness of layers removed during chemical etching*

It was found on the basis of the results of measuring the current-voltage characteristics that the texturing of polycrystalline silicon in an aqueous potassium hydroxide solution improves the electrical properties of the produced photovoltaic cells and enhances efficiency as compared to the cells made of wafers featuring untextured surface (Fig. 9). An increase in such cell's efficiency is negligible, as a texture is produced on the surface as a result of the alkaline etching of polycrystalline silicon in a 40% KOH : IPA : DIH_2O solution being dependent on the crystallographic orientation of the specific grains. Laser polycrystalline silicon surface texturing is deteriorating the electrical properties of photovoltaic cells made of the so prepared wafers. A layer of the damaged material is formed on the entire laser-textured area immediately after creating a lattice of grooves. The layer is produced due to the condensation of the liquid-gaseous phase occurring during laser processing. When the damaged layer of material is removed through etching, the efficiency of photovoltaic cells increases and is largest when a 80 µm thick layer has been etched.

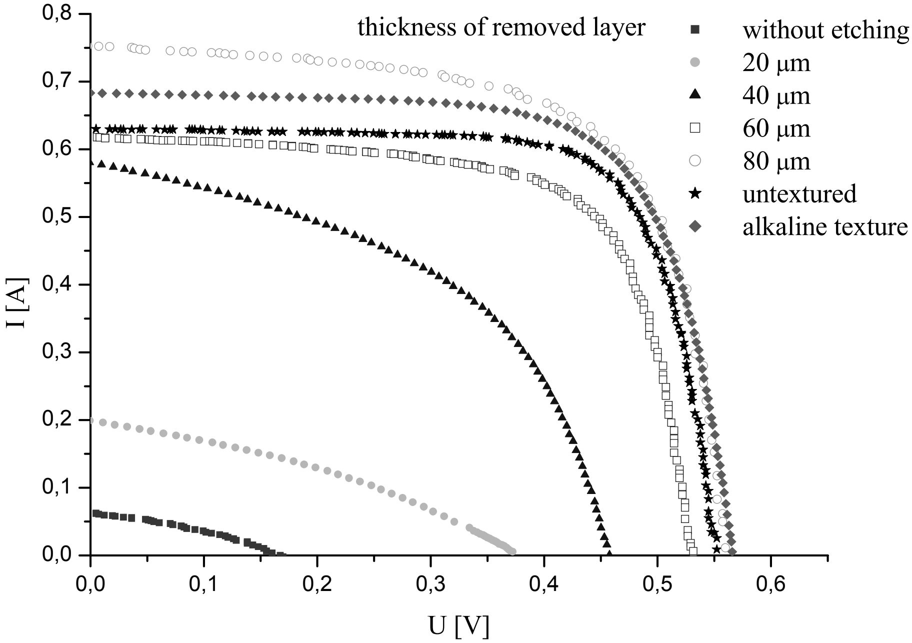

Figure 9. *The voltage-current characteristics of photovoltaic cells made of the following polycrystalline silicon wafers: untextured, alkaline textured, unetched laser-textured and laser-textured ones with varied thickness of layers removed during chemical etching*

Table 2. *The effective reflection coefficient and the efficiency of photovoltaic cells determined for the following polycrystalline silicon wafers: untextured, alkaline-textured, unetched laser-textured and laser-textured ones with varied thickness of layers removed during chemical etching*

Technology symbol	Wafer surface		The R_{eff} effective reflection coefficient, %	Photovoltaic cell efficiency, %
None	Untextured		34.08	10.21
(A)	Alkaline-textured		24.65	10.79
(B)	Unetched laser-textured		10.21	0.14
(C)	Laser-textured and chemical etched; the removed layers with the thickness of, µm	20	12.96	1.05
		40	11.71	5.09
		60	11.79	8.96
		80	13.56	11.01

The detailed values of the effective light reflection coefficient and the efficiency of photovoltaic cells determined for the following wafers: untextured, alkaline-textured, unetched laser-textured and laser-textured ones with varied thickness of layers removed during chemical etching in Table 2 is presented.

5. Polycrystalline silicon texturisation in the future

5.1. Laser treatment versus surface engineering progress

Foresight investigations with the sample size of 198 have revealed a very robust strategic position of laser technologies among other materials surface engineering technologies. The experts found that that laser technologies have the best industrial application prospects in the group of all the analysed materials surface engineering technologies in the nearest 20 years. 78% of the surveyed held such a view. Nearly a three fourth of the respondents (73%) maintain that numerous scientific and research studies will be devoted to such technologies in the analysed time horizon. 70% of the surveyed claim that the thematic area of “Laser technologies in surface engineering” is crucial and its importance should be absolutely rising so that an optimistic scenario can come true of the country's development – "Race won" – assuming that the potential available is adequately utilised to fulfil the strategic objectives of development and so that people, statistically, are better off, social attitudes are optimistic and prospects for the coming years bright. 81% of the surveyed persons argue that the significance of laser technologies in relation to other materials surface engineering technologies will be growing, whereas 18% maintain it will remain on the same level with only 3 individuals asserting that the role will diminish over the next 20 years. The very strong results of technology foresight elaborated with reference data point to the anticipated key role of laser technologies in the development of materials surface engineering in general (mezo scale) and in the development of Poland's overall economy (macro scale).

5.2. Strategic position of the texturisation technologies

The results of the foresight research described in this chapter include the assessment of the potential and attractiveness of the analysed technologies against the micro- and macro-environment performed based on the key experts' opinions and a recommended strategy of managing a relevant technology together with the predicted strategic development tracks resulting from such assessment.

The analysed polycrystalline silicon texturisation technologies were evaluated by experts using a universal scale of relative states (1: min, 10: max) for their: business, economic, humane, natural and system attractiveness as well as for their creational, applicational, qualitative, developmental and technical potential. A weighted average for the criteria considered (attractiveness and potential) was calculated using a multi-criteria analysis, and a result obtained for the individual groups of technologies was entered into the dendrological matrix of technologies value (Fig. 10). The analysis has revealed that the laser texturisation of polycrystalline silicon with chemical etching (C) is characterised by the highest attractiveness and potential. The technology was classified to the matrix quarter called a wide-stretching oak for highly attractive technologies with a large potential. The silicon wafers produced with the technology feature the lowest (most advantageous) effective reflection coefficient R_{eff}, especially after etching chemically a 40 and 60 μm thick layer (respectively, 11.71 and 11.79%). In addition, the efficiency of solar cells prepared from such wafers had the highest (most advantageous) value of 11.01% after etching an 80 μm thick layer. The (A) technology: the alkali texturisation of polycrystalline silicon was entered into the quarter called a rooted dwarf mountain pine with technologies having a high potential and a low attractiveness. This technology, used successfully for monocrystalline silicon, is ineffective for polycrystalline silicon due to the random crystalline orientation of the individual grains. In relation to the (C) technology, the silicon wafers produced with the (A) technology exhibit much more inferior optical properties (the effective reflection coefficient of R_{eff}: 24.65%), and the solar cells made from them feature worse electrical properties (efficiency of 10.79%). The laser texturisation of polycrystalline silicon (B) is highly attractive considering very promising optical properties expressed with the lowest R_{eff} value (10.21%) for the silicon wafers made with this silicon wafer technique. A relatively low potential of the technology derives from the fact that the laser texturisation of silicon surface is drastically deteriorating the properties of solar cells made of the wafers prepared this way (efficiency of 0.14%). A reason for this phenomenon is a layer of the damaged material formed in the liquid and gaseous phase condensation present during laser treatment. This technology was thus assigned to the matrix quarter called a soaring cypress grouping highly attractive technologies with a limited potential.

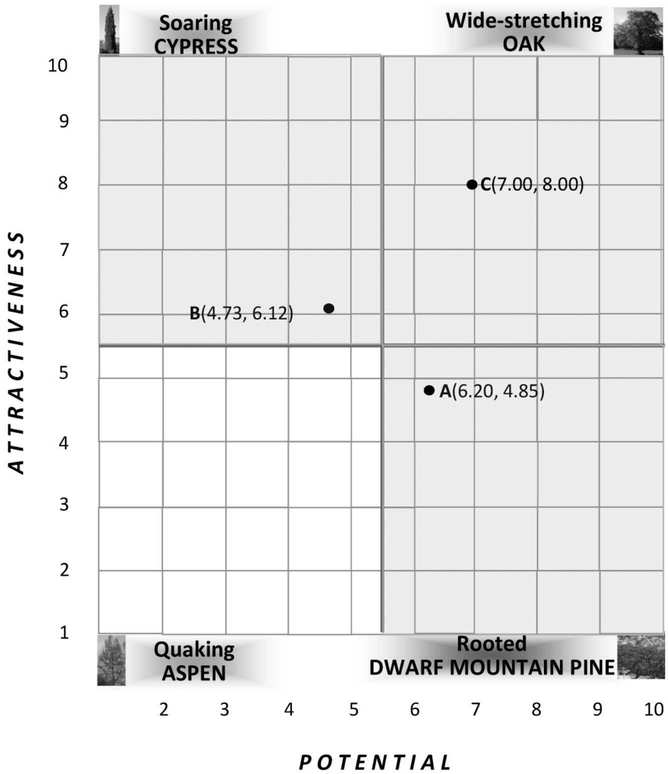

Figure 10. *The dendrological matrix of technology value for prepared for the following polycrystalline silicon texturisation: the (A) alkaline, the (B) laser, the (C) laser with chemical etching ones*

The evaluation results of positive and negative environment influence on the relevant technologies were visualised with a meteorological matrix of environment influence, as illustrated in Fig. 11. The experts surveyed have found that the environment of fresh technologies (B) and (C) is a stormy one considering a very attractive, perspective area of future industrial applications (ample opportunities) and the related fierce global competition and a far-reaching alternative search for effective solar cells manufacturing technologies (numerous difficulties). In case of a mature technology (A) being is industrial use for years, for monocrystalline silicon, an environment is predictable and stable with a neutral character. Polycrystalline silicon produced with alkaline permits to, as compared to its monocrystalline form, produce cheaper, but less effective solar cells. Considering that no specific, clearly better alternatives are at hand, this may suffice for the technology to develop further at a low rate.

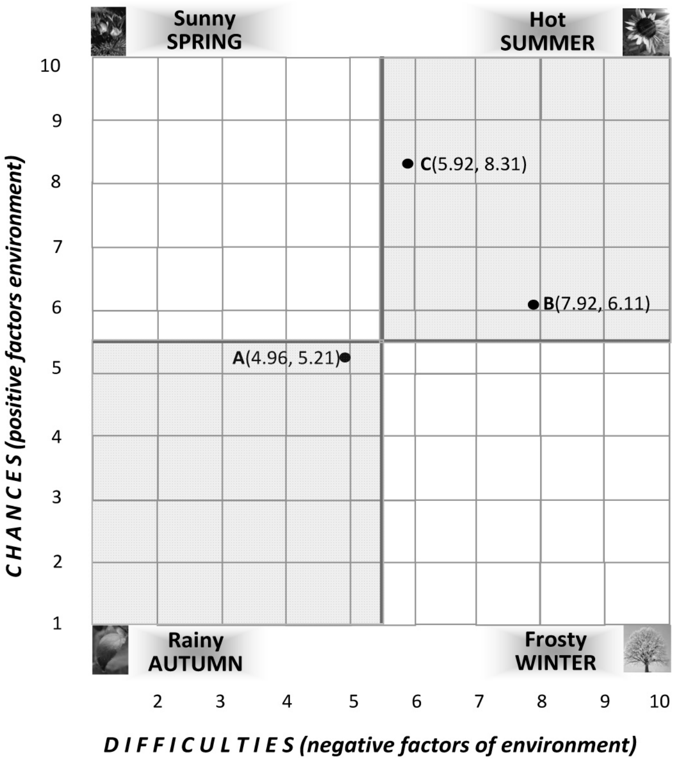

Figure 11. *Meteorological matrix of environment influence prepared for the following polycrystalline silicon texturisation: the (A) alkaline, the (B) laser, the (C) laser with chemical etching ones*

At the next stage of the research work, the results of the studies presented graphically with the dendrological matrix of technologies value and meteorological matrix of environment influence were entered into the matrix of strategies for technologies (Fig. 12). The matrix is presenting, graphically, the place of the investigated polycrystalline silicon texturisation technologies according to their value and environment influence intensity, indicating the relevant managing strategy. Using the pre-defined mathematical relationships, the specific numerical values provided in the following four-field matrices: the dendrological and meteorological matrix, were moved to the sixteen-field technology strategy matrix. The circles mark the strategic development prospects of a given group of technologies expressed in numbers. With reference to the (C) technology valued most highly, that was awarded 7 points in a ten-degree scale, it is recommended to apply an oak in summer strategy. The technology's attractiveness and potential in a risky environment should be used in line with the strategy,

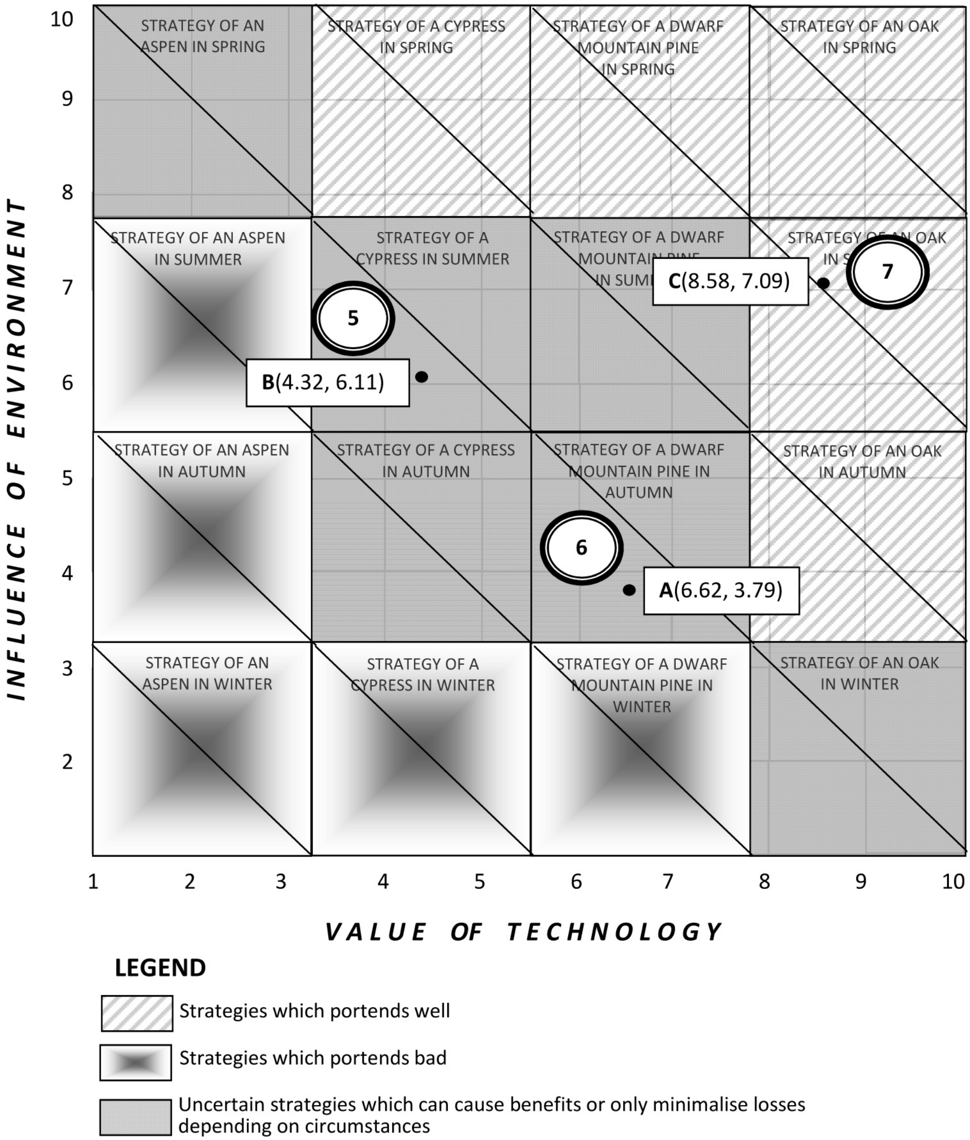

Figure 12. *The matrix of strategies for technologies prepared for prepared for the following polycrystalline silicon texturisation: the (A) alkaline, the (B) laser, the (C) laser with chemical etching ones*

opportunities should be sought for and difficulties should be avoided and the technology should be strongly promoted with publicity measures being preceded with marketing research to tailor a product to the client's demands as far as possible. A strategy of a dwarf mountain pine in autumn recommended for the (A) technology given 6 points assumes that profits are derived from running production in a stable, predictable environment using a solid technology that should be upgraded and intensively promoted to enhance attractiveness. The (B) technology of the laser texturisation of polycrystalline silicon, for which a cypress in summer strategy is recommended, has moderate development prospects (5 points). The technology consists of strengthening an attractive technology's potential in the risky environment conditions and of risk assessment. Either a customer should be fought for aggressively or the technology should be phased out from the market depending on the result of such evaluation.

Strategic development tracks for the individual technology groups were prepared based on the expert opinions in the next part of the research works according to the three variants: optimistic, most probable and pessimistic variant for the relevant time intervals of: 2015, 2020, 2025 and 2030.

The most encouraging (C) technology is the polycrystalline silicon laser texturisation with chemical etching. The excellent optical properties of silicon wafers produced as well as good properties of the photovoltaic cells made of them are ensured by this technology. The most probable track of (C) technology development assumes that its potential is to be strengthened in 2015-2020 and environment conditions bettered in the subsequent years (2025-2030) thus moving the (C) technology to the most auspicious matrix quarter: oak in spring. The greatest hopes are connected with shortening the activity of laser impulse to nano- (10^{-9}), pico- (10^{-12}) or even femto- (10^{-15}) seconds. The experiments undertaken have revealed that the shorter impulse activity time the smaller substrate material damage. It seems for the time being that although a laser acts for a very short time, the damage to the top layer of polycrystalline silicon will compromise the electrical properties of the solar cells prepared from it to such an extent that even short chemical etching will be necessary to improve such properties. An optimistic (C) technology development track envisages that the opportunities derived from the environment will rapidly exceed the related difficulties and already in 2020 this technology will be found among those having the best prospects best and fast progress will be maintained. Since an incipient the (C) technology is in a stormy environment, an adverse surprising scenario is also possible. According to such scenario, the value of the technology analysed including its potential and attractiveness will be declining gradually (2015-20) as the increasing predominance of one of the alternative technologies will be seen (etching in acidic solutions, reactive ion etching, mechanical texturisation using a diamond edge). External development prospects will be thus completely limited in 2025 (oak in winter strategy) and the technology will be ultimately forced out from the market in 2030 (aspen in winter strategy). The outcomes of the research pursued with the Delphic method confirm a good, anticipated, strategic position of the laser texturisation of polycrystalline silicon with chemical etching [6]. 73% of the experts surveyed think that the technology is critical and its importance should be absolutely rising so that an optimistic scenario of the country's development, i.e. "Race Won" can come true in the nearest 20 years.

In congruence with the most probable scenario, the potential and attractiveness of the (A) technology of polycrystalline silicon alkaline texturisation should be slowly strengthening and should be maintained for the duration of the forecast (2015-2030) in area of the dwarf mountain pine in autumn. An optimistic scenario provides for that the alternative methods of producing solar cells from polycrystalline silicon will suffer a defeat if the parameters of the cells' alkaline texturisation are fine-tuned optimally. As a result, in 2030 the technology will be transferred to the "oak in autumn" field. A pessimistic scenario of technology development (A) envisages that alternative polycrystalline silicon texturisation technologies ensuring both, better optical properties of silicon wafers and electrical properties of solar cells made from them, are developing rapidly and robustly. This will contribute to shifting the (A) technology in 2020 to the area of unfavourable influence of a dwarf mountain pine in winter and progressing degradation in 2025-2030 (aspen in winter).

The most probable scenario of the (B) technology's development: laser texturisation of polycrystalline silicon assumes that its potential will be growing slowly with the neutral environment conditions maintained (2015-20). Next, its value against other alternative technologies will diminish in 2025-30, hence it will be shifted to the "dwarf mountain pine in autumn" field. An optimistic scenario of technology development (B) assumes that its potential will be reinforced substantially while the existing attractiveness is maintained. This may, unexpectedly, improve the optical properties of silicon wafers and the electrical properties of cells prepared from them. The experiments carried out may indicate with little probability that a very short laser impulse (of pico- or femtoseconds) may cause such a little damage to the substrate material that its chemical etching will not be necessary to improve the electrical properties of cells. A pessimistic (B) technology scenario assumes that it has been surely proved that, to ensure the expected electrical properties of solar cells made from the laser-textured silicon wafers, it is necessary to etch them chemically to remove damages formed in the condensation of the liquid and gaseous phase during laser treatment. The years of 2015-2020 are witnessing a slow decline in the technology value coupled with the increasingly more difficult environment conditions with the technology being completely phased out from the market in 2025-2030 (aspen in winter). A graphical example of the (B) technology strategy matrix with the strategic development tracks entered according to three variants is presented in Fig. 13. The numerical values being a result of all the investigations performed for the three analysed technologies are shown in Table 3.

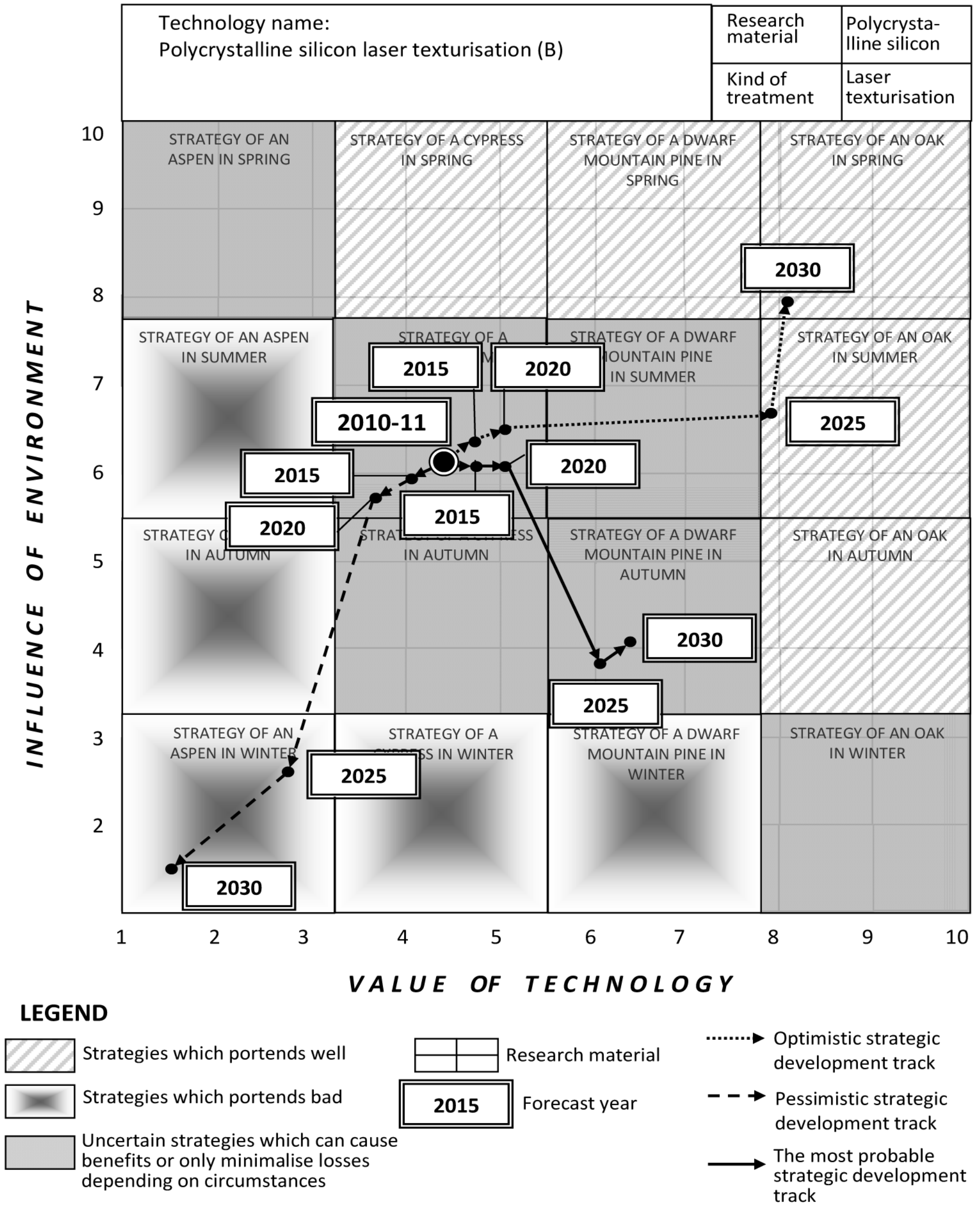

Figure 13. *The strategic development tracks created for the (B) demonstration technology: polycrystalline silicon laser texturisation*

Table 3. *The strategic development tracks of polycrystalline silicon texturisation. Types of strategic development tracks: (O) – optimistic, (P) – pessimistic, (MP) – the most probable*

Technology symbol	Technology name	Steady state 2010-11	Type of strategic development tracks	Years 2015	2020	2025	2030
(A)	Polycrystalline silicon alkaline texturisation	Strategy of a dwarf mountain pine in autumn A (6.6, 3.8)	(O)	(7.0, 4.0)	(7.4, 4.1)	(7.7, 4.3)	(8.2, 4.5)
			(P)	(6.2, 3.6)	(5.8, 3.4)	(2.6, 2.4)	(1.4, 1.8)
			(MP)	(6.8, 3.9)	(7.0, 4.0)	(7.2, 4.1)	(7.4, 4.3)
(B)	Polycrystalline silicon laser texturisation	Strategy of a cypress in summer B (4.3, 6.1)	(O)	(4.7, 6.4)	(5.1, 6.5)	(7.9, 6.7)	(8.1, 7.9)
			(P)	(4.1, 5.9)	(3.7, 5.7)	(2.8, 3.6)	(1.4, 1.4)
			(MP)	(4.7, 6.1)	(5.1, 6.1)	(6.0, 3.8)	(6.4, 4.1)
(C)	Polycrystalline silicon laser texturisation with chemical etching	Strategy of an oak in summer C (8.6, 7.1)	(O)	(8.8, 7.7)	(9.0, 8.1)	(9.2, 8.5)	(9.4, 8.9)
			(P)	(8.5, 6.7)	(8.3, 6.3)	(8.1, 2.4)	(2.7, 2.1)
			(MP)	(8.6, 7.5)	(8.7, 7.7)	(8.7, 8.0)	(8.8, 8.5)

The results of the foresight–materials science research conducted represent reference data serving to create a technology roadmap for each of the three technologies analysed. An example of a technology map was prepared for the (C) technology: polycrystalline silicon laser texturisation with chemical etching, presented in Fig. 14.

6. Summary

Economic reasons underlie an interest in polycrystalline silicon texturisation technologies. Silicon occurs in the earth crust in abundance primarily as silica and this is a reason why it is purposeful to search its wide-scale industrial applications. In the wake of the growing energy demand, depleting conventional energy sources, controversies surrounding the security of nuclear fuel utilisation and the society's growing environmental awareness, a feasible use of silicon in the processes of converting solar radiation energy into electric energy paves a way for its extensive utilisation in the future. The production of solar cells from silicon is preceded with a crystal-lisation process as a result of which two forms are produced: mono- and polycrystalline ones.

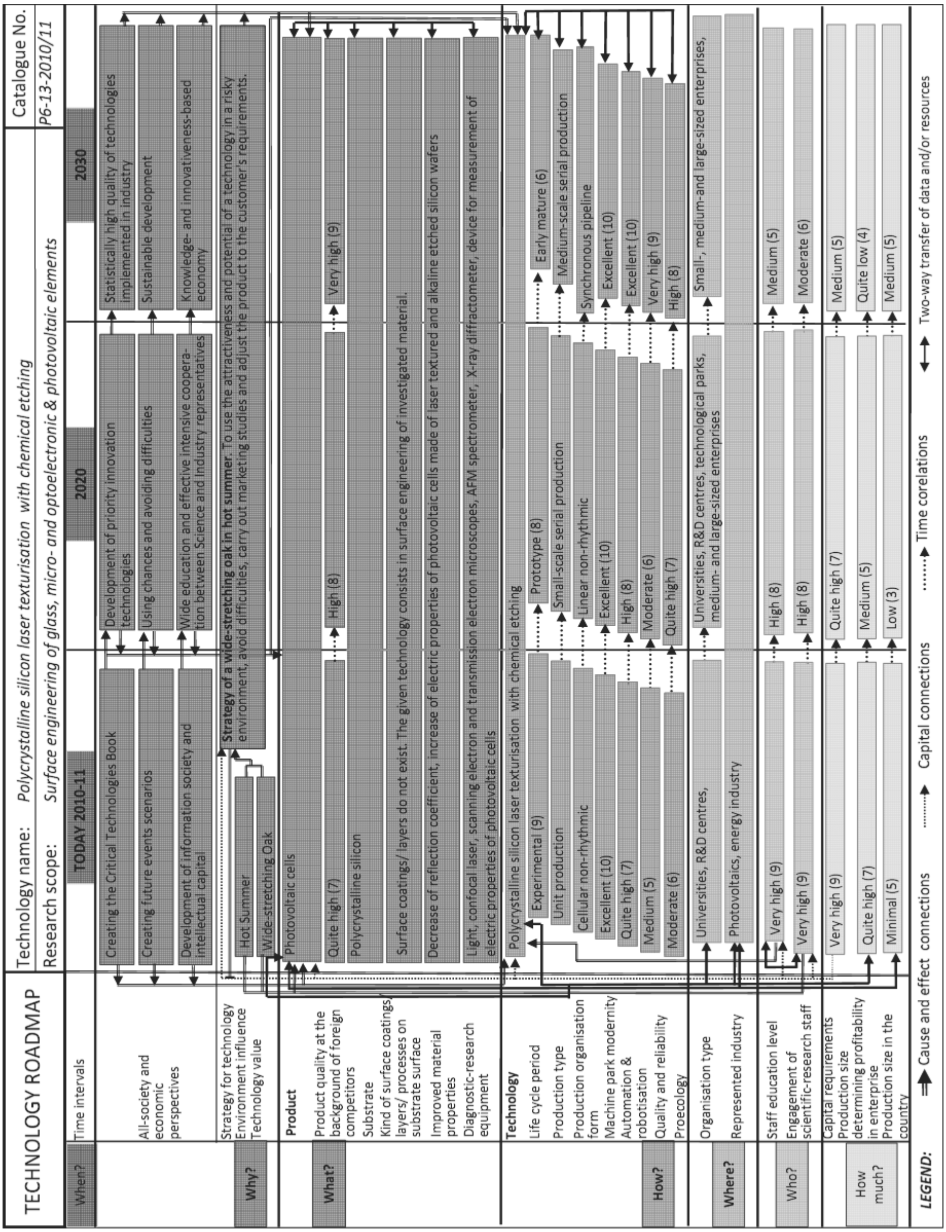

***Figure 14**. An example technology roadmap made for the (C) technology: polycrystalline silicon laser texturisation with chemical etching*

It is more expensive to produce monocrystalline silicon having grains with a uniform crystallographic orientation; however, the solar cells produced are highly efficient. The crystallisation process of polycrystalline silicon with a random crystallographic orientation of grains is faster and cheaper, however, the solar cells produced from them feature lower efficiency than the cells produced of its monocrystalline form due to structural defects present. It is justified, therefore, to seek new cells manufacturing technologies from polycrystalline silicon ensuring higher efficiency at relatively low costs. The outcome of such quests is the (C) technology of polycrystalline silicon laser texturisation with chemical etching (C) described in this study. This highly attractive technology with a large potential has been valued most highly in the group of three polycrystalline silicon texturisation technologies subjected to a comparative analysis in this chapter. Better optical properties for silicon and better electrical properties for the cells prepared from them have been attained as compared to the (A) technology: polycrystalline silicon alkaline texturisation. The (B) technology: although the polycrystalline silicon laser texturisation without chemical etching allows to obtain the lowest (most beneficial) effective reflection coefficient, nonetheless, the efficiency of the so produced solar cells is sharply falling. Taking into account the strategic development of the (C) technology, a stormy environment where it is situated is the biggest issue. The environment offers multiple opportunities coming from a very attractive, prospective area of future industrial applications as well as multiple inconveniences connected with intense global competition and broad alternative quests for effective solar production technologies such as: etching in acidic solutions, reactive ion etching, mechanical texturisation and with a use of a diamond edge. The results of foresight-materials science research presented in this chapter are part of a broader project [39] aimed at selecting the priority innovative technologies of materials surface engineering and setting the directions of strategic development, as discussed in a series of publications, in particular [40-44].

References

1. MatVis. C. Dreher, Manufacturing visions: A holistic view of the trends for European manufacturing, in: M. Montorio, M. Taisch, K.-D. Thoben (eds.), Advanced Manufacturing. An ICT and Systems Perspective, Taylor & Francis Group, London, 2007.
2. Gennesys. H Dosch, M.H. Van de Voorde (eds.), Gennesys. White Paper. A New European Partnership between Nanomaterials Science & Nanotechnology and Synchrotron Radiation and Neuron Facilities, Max-Planck-Insititut für Metalforschung, Stuttgart, 2009.
3. NANOMAT, www.nanomat.eitplus.pl.
4. FORGOM, www.foresightgom.pl.

5. FOREMAT, Technology Development Scenarios of Modern Metallic, Ceramic and Composites Materials. Reports of Project Co-Operators, B. Gambin, W. Łojkowski, A. Świderska-Środa (eds.), Unipress Publisher, Radom, 2010 (in Polish).
6. FORSURF, www.forsurf.pl 2009-2012 (in Polish).
7. A.D. Dobrzańska-Danikiewicz, E-foresight of materials surface engineering, Archives of Materials Science Engineering 44/1 (2010) 43-50.
8. A. Goetzberger, V.U. Hoffmann, Photovoltaic solar energy generation, Springer Verlag, Berlin, 2005.
9. M.A. Green, Photovoltaics: technology overview, Energy Policy A 28 (2000) 989-998.
10. R.W. Miles, K.M. Hynes, I. Forbes, Photovoltaic solar cells: An overview state-of-the-art cell development and environmental issues, Progress in Crystal Growth and Characterization of Materials 51 (2005) 1-42.
11. R.H. Kozłowski, B.M. Zakiewicz, Large capacity energy from Geo-Plutonic formation for power plants with zero CO_2 emissions, Journal of Achievements in Materials and Manufacturing Engineering 43/2 (2010) 790-795.
12. A. Goetzberger, J. Luther, G. Willeke, Solar cells: past, present, future, Solar Energy Materials and Solar Cells 74/1 (2002) 1-11.
13. 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.
14. L.A. Dobrzański, Engineering materials and materials design. Fundamentals of materials science and physical metallurgy, Second Edition extended and supplemented, WNT, Warsaw, 2006 (in Polish).
15. A.D. Dobrzańska-Danikiewicz, Foresight methods for technology validation, roadmapping and development in the surface engineering area, Archives of Materials Science Engineering 44/2 (2010) 69-86.
16. H.J. Möller, C. Funke, M. Rinio, S. Scholz, Multicrystalline silicon for solar cells, Thin Solid Films 487 (2005) 179-187.
17. M. Lipiński, Silicon nitride for photovoltaic application, Archives of Materials Science and Engineering 46/2 (2010) 69-87.
18. J.A. Dziuban, Technology and application of micromechanical silicon and silicon-glass structures in microsystems technique, Wrocław University of Technology Publishing House, Wroclaw, 2004 (in Polish).
19. I. Zubel, Silicon anisotropic etching in alkaline solutions III: On the possibility of spatial structures forming in the course of Si(100) anisotropic etching in KOH and KOH+IPA solution, Sensors and Actuators A: Physical 84/1-2 (2000) 116-125.
20. R. Einhaus, E. Vazsonyi, R. Mertens, Isotropic texturing of multicrystalline silicon wafers with acid texturing, Proceedings of the 26^{th} IEEE Photovoltaic Specialists Conference, Anahiem, 1997, 167-170.

21. M. Lipiński, S. Bastide, P. Panek, C. Levy-Clement, Porous silicon antireflection coating by electrochemical and chemical etching for silicon solar cell manufacturing, Physica Status Solidi A 197 (2003) 512-517.
22. E.S. Marstein, H.J. Solheim, D.N. Wright, A. Holt, Acid texturing of multicrystalline silicon wafers, Proceedings of the 31st IEEE Photovoltaic Specialists Conference, Florida, 2005, 1309-1312.
23. C. Gerhards, C. Marckmann, R. Tolle, M. Spiegel, P. Fath, G. Willeke, Mechanically V-textured low cost multicrystalline silicon solar cells with a novel printing metallization, Proceedings of the 26th IEEE Photovoltaic Specialists Conference, Anaheim, 1997, 43-46.
24. W.A. Nositschka, C. Beneking, O. Voigt, H. Kurz, Texturisation of multicrystalline silicon wafer for solar cells by reactive ion etching through colloidal masks, Solar Energy Materials and Solar Cells 76 (2003) 151-166.
25. L.A. Dobrzański, M. Musztyfaga, A. Drygała, Selective laser sintering method of manufacturing front electrode of silicon solar cell, Journal of Achievements in Materials and Manufacturing Engineering 42/2 (2010) 111-119.
26. L.A. Dobrzański, J. Domagała, T. Tański, A. Klimpel, D. Janicki, Laser surface treatment of magnesium alloy with WC powder, Archives of Materials Science and Engineering 30/2 (2008) 113-116.
27. A. Klimpel, A. Rzeźnikiewicz, Ł. Janik, Study of laser welding of copper sheets, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 467-470.
28. A. Lisiecki, A. Klimpel, Diode laser surface modification of Ti6Al4V alloy to improve erosion wear resistance, Archives of Materials Science and Engineering 32/1 (2008) 5-12.
29. A. Lisiecki, A. Klimpel, Diode laser gas nitriding of Ti6Al4V alloy, Archives of Materials Science and Engineering 31/1 (2008) 53-56.
30. L.A. Dobrzański, J. Domagała, T. Tański, A. Klimpel, D. Janicki, Laser surface treatment of cast magnesium alloys, Archives of Materials Science and Engineering 35/2 (2010) 101-106.
31. T. Maruyama, J. Bandai, S. Osako, Reflection at transparent V-grooved surface, Solar Energy Materials and Solar Cells 64/3 (2000) 261-268.
32. L.A. Dobrzański, T. Tański, L. Čížek, Z. Brytan, Structure and properties of magnesium cast alloys, Journal of Materials Processing Technology 192-193 (2007) 567-574.
33. L.A. Dobrzański, M. Bonek, A. Klimpel, A. Lisiecki, Surface-Layer's Structure of X40CrMoV5-1 steel remelted and/or WC alloyed with HPDL laser, Materials Science Forum 437-438 (2003) 69-72.
34. L.A. Dobrzański, M. Bonek, E. Hajduczek, A. Klimpel, A. Lisiecki, Comparison of the structures of the hot-work tool steels laser modified surface layers, Journal of Materials Processing Technology 164-165 (2005) 1014-1024.
35. L.A. Dobrzański, T. Tański, L. Čížek, Heat treatment impact on the structure of die-cast magnesium alloys, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 431-434.

36. M Lipiński, P. Panek, H. Czternastek, The influence of surface modification on crystalline silicon solar cells, Molecular Physics Report 36 (2002) 123-126.
37. B.S. Richards, Single-material TiO_2 double-layer antireflection coatings, Solar Energy Materials and Solar Cells 79/3 (2003) 369-390.
38. A.D. Dobrzańska-Danikiewicz, A. Drygała, Foresight methodology application for laser texturing of silicon surface, Proceedings of the 8th Ukrainian-Polish Conference of Young Scientists "Mechanics and Computer Science", Abstract of scientific paper, Khmelnitsky, Ukraine, 2011, 156-157.
39. A.D. Dobrzańska-Danikiewicz, Computer Aided Foresight Integrated Research Methodology in Surface Engineering Area, work in progress.
40. A.D. Dobrzańska-Danikiewicz, E. Jonda, K. Labisz, Foresight methods application for evaluating laser treatment of hot-work steels, Journal of Achievements in Materials and Manufacturing Engineering 43/2 (2010) 750-773.
41. A.D. Dobrzańska-Danikiewicz, T. Tański, S. Malara, J. Domagała-Dubiel, Assessment of strategic development perspectives of laser treatment of casting magnesium alloys, Archives of Materials Science Engineering 45/1 (2010) 5-39.
42. A.D. Dobrzańska-Danikiewicz, K. Lukaszkowicz, Technology validation of coatings deposition onto the brass substrate, Archives of Materials Science Engineering 46/1 (2010) 5-38.
43. A.D. Dobrzańska-Danikiewicz, E. Hajduczek, M. Polok-Rubiniec, M. Przybył, K. Adamaszek, Evaluation of selected steel thermochemical treatment technology using foresight methods, Journal of Achievements in Materials and Manufacturing Engineering 46/2 (2011) 115-146.
44. A.D. Dobrzańska-Danikiewicz, K. Gołombek, D. Pakuła, J. Mikuła, M. Staszuk, L.W. Żukowska, Long-term development directions of PVD/CVD coatings deposited onto sintered tool materials, Archives of Materials Science Engineering 49/2 (2011) 69-96.