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TEM investigations of laser texturized polycrystalline silicon solar cell

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ABSTRACT

Purpose: The presented in this paper research results concern investigation of phase transformation of the surface structure of polycrystalline silicon solar cell. The surface of boron doped polycrystalline silicon wafers were texturised by means of diode-pumped pulsed neodymium-doped yttrium aluminium garnet laser crystal (Nd:YAG). Investigations were carried out on transmission electron microscope (TEM) to observe the changes that occurred after laser treatment of the surface layer. Changes in microstructure of the surface layer of solar cells under the influence of the laser beam are presented using the analysis phase and dislocations present in the microstructure. Observations were carried out on prepared thin foils. Moreover, diffraction patterns from selected regions of textured wafers were solved to qualify phase transformations under influence of laser beam.

Design/methodology/approach: Investigations were carried out on the Transmission Electron Microscope JEM 3010 supplied by JEOL with 300 kV accelerating voltage equipped with an electronic camera configured with a computer. The microstructure was obtained in the bright field image as well dark field working in a magnification range of 10000x to ca. 100000x. Phases identification was performed by means of selected area diffraction (SAD) method, where for diffraction pattern calculations the computer software "Eldyf" was used, kindly supplied by the Institute of Materials Science, University of Silesia.

Findings: The research included analyze of the influence of laser treatment conditions on geometry, roughness and size of laser made surface texture of silicon wafer applied for solar cells.

Research limitations/implications: Paper contributes to research on silicon surface processing using laser beam.

Practical implications: Conducted investigations may be applied in optimisation process of solar cell surface processing.

Originality/value: The range of possible applications increases for example as materials for solar cells placed on building constructions, elements in electronics and construction parts in automobile industry.

Keywords: Amorphous materials; Surface treatment; Silicon; Solar cell; Laser treatment

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MATERIALS

1. Introduction

Fossil fuels such as coal, oil and natural gas are the three different forms of fuels that are widely used. They are formed by the process of anaerobic decomposition of organic matter under the surface of the earth for millions of years. Large scale use of fossil fuels started since industrial revolution. Today, they are the cheapest sources of energy available for the use of both personal as well as commercial purposes. Statistics show that almost three-fourth of the demands of the energy in the world is fulfilled by fossil fuels. The main disadvantage of fossil fuels is that they are non-renewable sources of energy. According to predictions the fossil fuels resources may be depleted by 2050. Additionally, combustion of fossil fuels increases the air pollution and greenhouse effect [1-6].

Increase in energy demand resulting in everlasting environment pollution and greenhouse effect is the reason for development of renewable sources of energy. Furthermore, world energy crisis stimulates researching of environmental friendly energy sources. Solar energy is one of these energy sources that has been intensively developed recently [7-12].

A photovoltaic cell is a device in which there proceeds a direct conversion of solar radiation energy into electrical energy. Silicon is the most frequently commercially used material for solar cells production. Up to date more than 90% of the solar cells manufactured is produced on silicon basis. Solar cells are made either of monocrystalline silicon wafers or of polycrystalline silicon wafers. Polycrystalline material is somewhat less expensive than monocrystalline, but the grain boundaries in polycrystalline material results in reduced solar cell performance [11-14]. A typical silicon solar cell is shown in Figure 1.

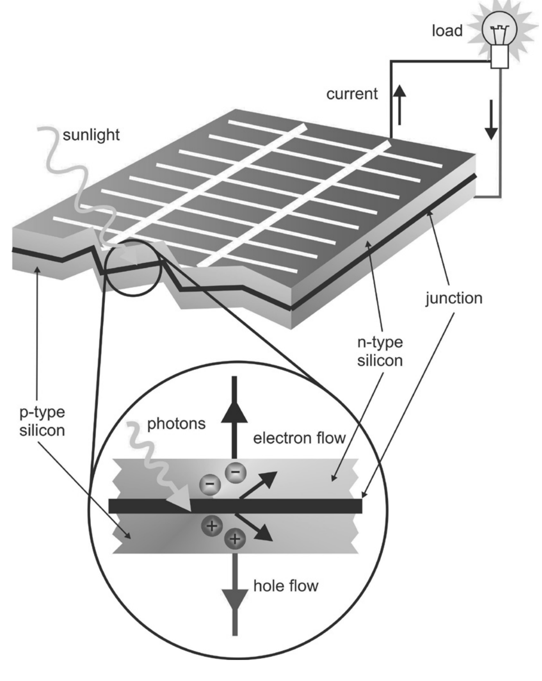


Fig. 1. Solar cell structure and working scheme [11-13, 15]

In photocells there is used a photovoltaic effect, in which photons generate voltage. This effect occurs in all semiconductors but with different intensity and for different ranges of radiation wavelengths. Photons, reacting with the electron or crystallic structure of a material, can produce such optical phenomena as [16-18]:

- absorption – the energy provided by photons is absorbed by the material,
- reflection – photons are rejected by the material, do not interact with the material electrons,
- transmission – photons emission by a material with the same energy, but even in the case of a transmission photons change the speed and refraction of the incidence angle occurs.

An extremely important factor which has an influence on the behaviour of photons in a material is the energy necessary to induce electrons to higher energy states. Photons with the energy higher than the energy corresponding to the value of energy break in a semiconductor can produce hole-electron pairs and participate in generating photocurrent of a photovoltaic cell [19, 20].

Solar cells made of monocrystalline and polycrystalline silicon are the most technologically advanced. Higher efficiency is achieved from a monocrystalline silicon cell, but the production of a base material is much more expensive. Solar cells are also made of amorphous materials, in which there is no such atoms orientation as in crystal lattice. Photovoltaic thin-film cells (with the thickness of about several micrometers, flexible and semi-transparent) are becoming increasingly important [11-13, 21].

A photovoltaic cell efficiency depends on: the properties of the material it is made of, solar cell production technology as well as the amount of the incident solar radiation. Surface texturing is one of the stages of producing a photovoltaic cell. The aim of surface texturing is to change the photons reflection angle of the surface, which allows them to be re-absorbed . There are many chemical methods of texturing the surface of monocrystalline silicon, but they are ineffective in the case of polycrystalline silicon because of the chaotic distribution of grains crystallographic orientation [22, 23]. In this work a laser was used as a device applied to shape the surface of polycrystalline silicon. High quality laser beams make it possible to use laser technology for processing which is impossible to carry out with any different techniques [24-26].

2. Material and methods

The material used for experiments was commercially available boron doped p-type polycrystalline silicon wafers obtained from the ingot by wire sawing of thickness ~330 μm, area 5 cm x 5 cm and resistivity 1 Ωcm. It is worth mentioning that particular attention has been paid to cleaning step after sawing in order to avoid contamination of substrate at the start of the cell manufacturing process.

Texturization was carried out by means of diode-pumped pulsed neodymium-doped yttrium aluminium garnet laser crystal (Nd:YAG). The main parameters of the laser used are: laser wavelength (λ = 1064 nm), maximum output power (P = 50 W), maximum speed of laser beam (v = 30 000 mm/s), pulse repetition frequency (from f = 100 Hz to f = 65 kHz).

The diffraction investigations and examination of the thin foils were made on the JEOL JEM 3010 transmission electron microscope at the accelerating voltage of 300 kV. The diffraction patterns from the transmission electron microscope were solved using a computer program.

3. Results and discussion

The laser processing was performed to produce a texture on the surface of the silicon plate sample. The occurrence of grooves on the samples was coming into existence by evaporation and remelting of the surface layer in direct contact to the laser beam.

Observations and investigations conducted using transmission electron microscope have revealed a polycrystalline microstructure

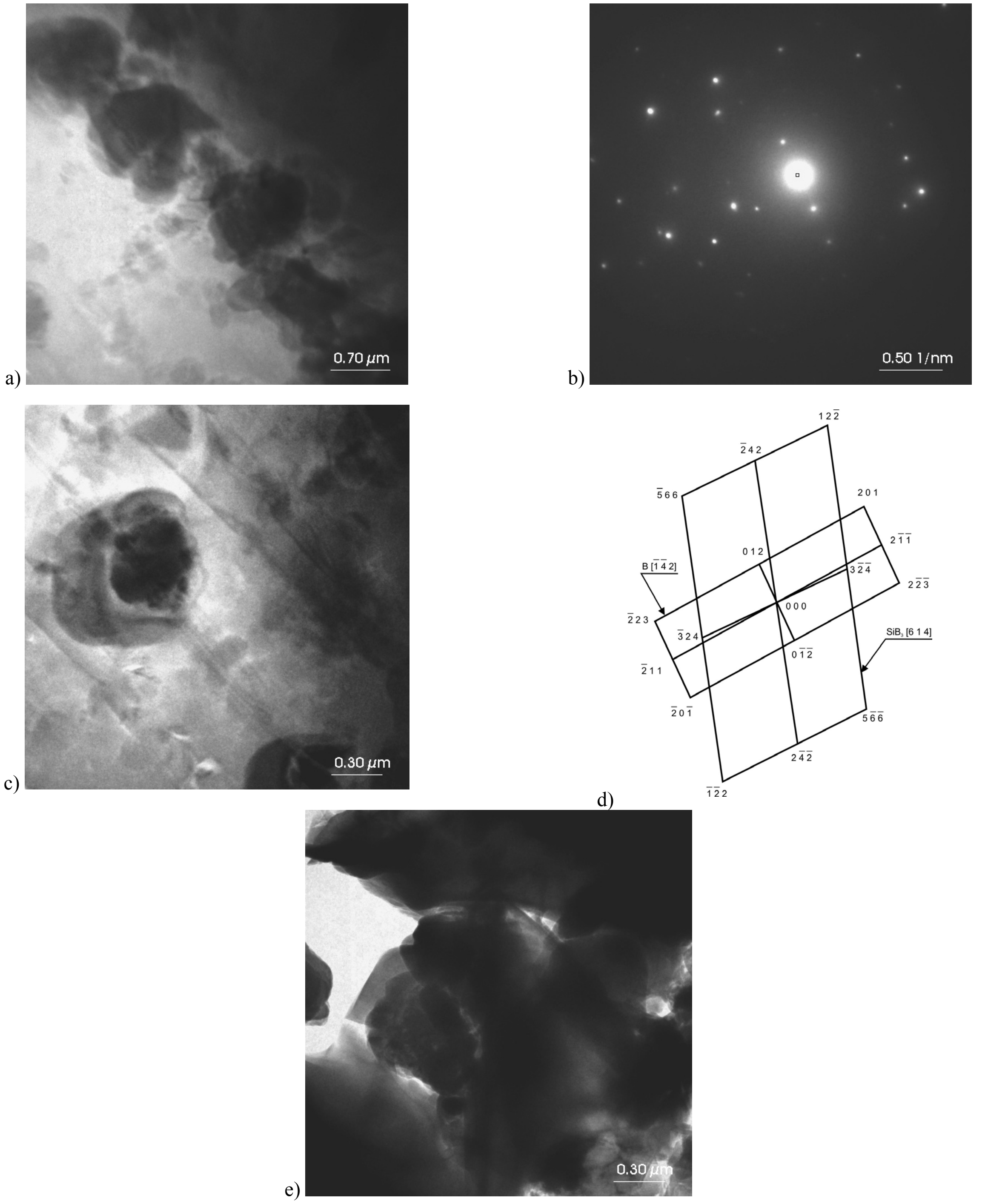


Fig. 2. TEM microstructure of the investigated material, a), c) bright field; b) diffraction pattern of the area in fig. a); d) diffraction pattern solution; e) dark field from reflex $0\bar{1}\bar{2}$ B (R3m)

of the boron doped silicon plate. This microstructure is a result of the laser beam operation onto the plate surface.

The traces of the laser impulses remaining in the structure are the first recognized laser beam effect in the investigated material. Figures 2a and 2c made in the bright field technique presents the precipitations observed in the microstructure. The micrographs are performed using small magnification (compared to the possibilities offered by the transmission electron microscope), nevertheless they already show traces of the laser beam.

Dark areas in a shape of smudges clearly visible in the micrograph performed in a bright field image are the effect of direct laser beam impact.

Diffraction pattern analysis of this area has allowed to identify two of the occurred phases (Fig. 2b).

The first one is crystallized boron in the rhombohedral crystal structure R3m and the spots as a result of electron beam diffraction on the planes zone $[\bar{1}\bar{4}2]$. The second identified phase is silicon boride SiB3 which chrysalises in the rhombohedral R3m crystal structure R3m and the spots are the results of a beam diffraction on the planes zone [614] (Fig. 2d).

In the Fig. 3a the boundaries between the amorphous areas are presented, whereon dislocations are visible coming into existence because of transformations occurred during remelting and amorphization of the area around.

This phase was identified as silicon boride (almost pure silicon with sporadically occurred boron inclusions) Si99B crystllised in the crystal structure Fd3m and the spots come from the planes zone with direction [1 4 2] (Fig. 3).

Moreover, as a result of the investigations performed by means of scanning electron microscope numerous crystalline structure line defects were observed – identified as mixed dislocation (Fig. 3c). Observations of the laser remelted areas are

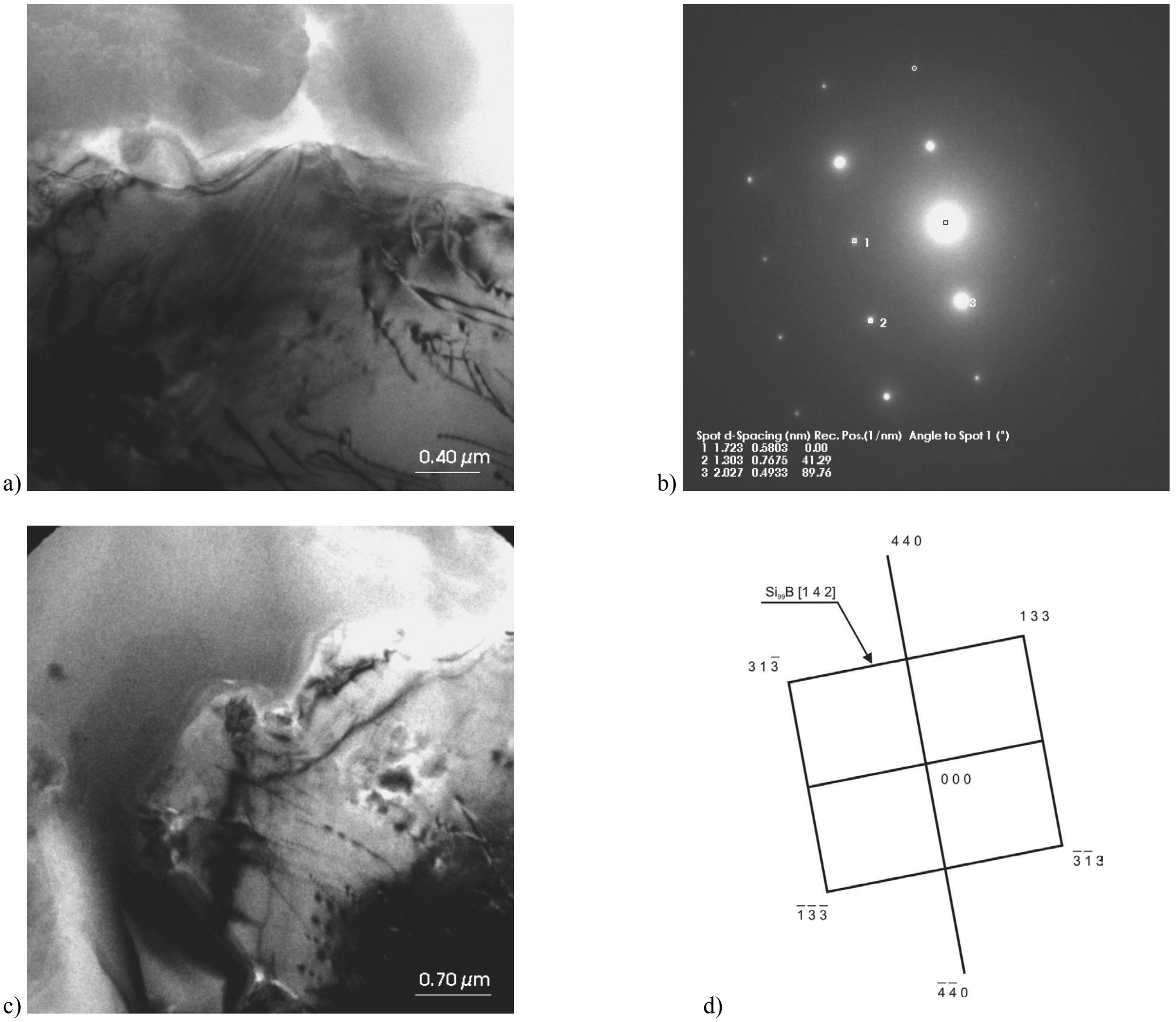


Fig. 3. TEM micrograph of boundary between amorphous and crystalline phases, a) and c) dislocations on crystalline phase; b) diffraction pattern from crystalline area in fig. a); d) diffraction solution pattern

characterised by occurrence of numerous dislocations, coming into existence by the laser beam application. Therefore the following phase transformation has occurred:

solid state → fluid state

and next as a result of cooling of the liquid micro areas:

fluid state → solid state

The precipitation in form of smudges is an effect of the direct impact of the laser beam, which has caused amorphization of this areas. This is also confirmed by dark field micrographs (Fig. 4a. – bright areas are crystalline, whereas dark areas are amorphous) and diffraction pattern (Fig. 4b).

A crystalline phase occurs between these amorphous areas. It was identified as boron crystallizing in the R3m crystal structure, with zone axis [1 9 4]. Precipitations (Figs. 5a and 5c) identified by means of diffraction pattern analysis as silicon boride (Figs. 5b and 5d.) SiB_3 crystallizing in the R3m crystal structure were also observed. The zone axis direction of these areas is [1 5 3].

The transformations are the reason for the tension accumulation in the analysed area which leads to generation of dislocation. Necessary tension τ_n for creation of dislocation is equal to [23]:

$$\tau_n = \frac{G}{4\pi e} \approx \frac{G}{30} \qquad (1)$$

where:
G – shape elasticity modulus,
e – base of a Napierian logarithm.

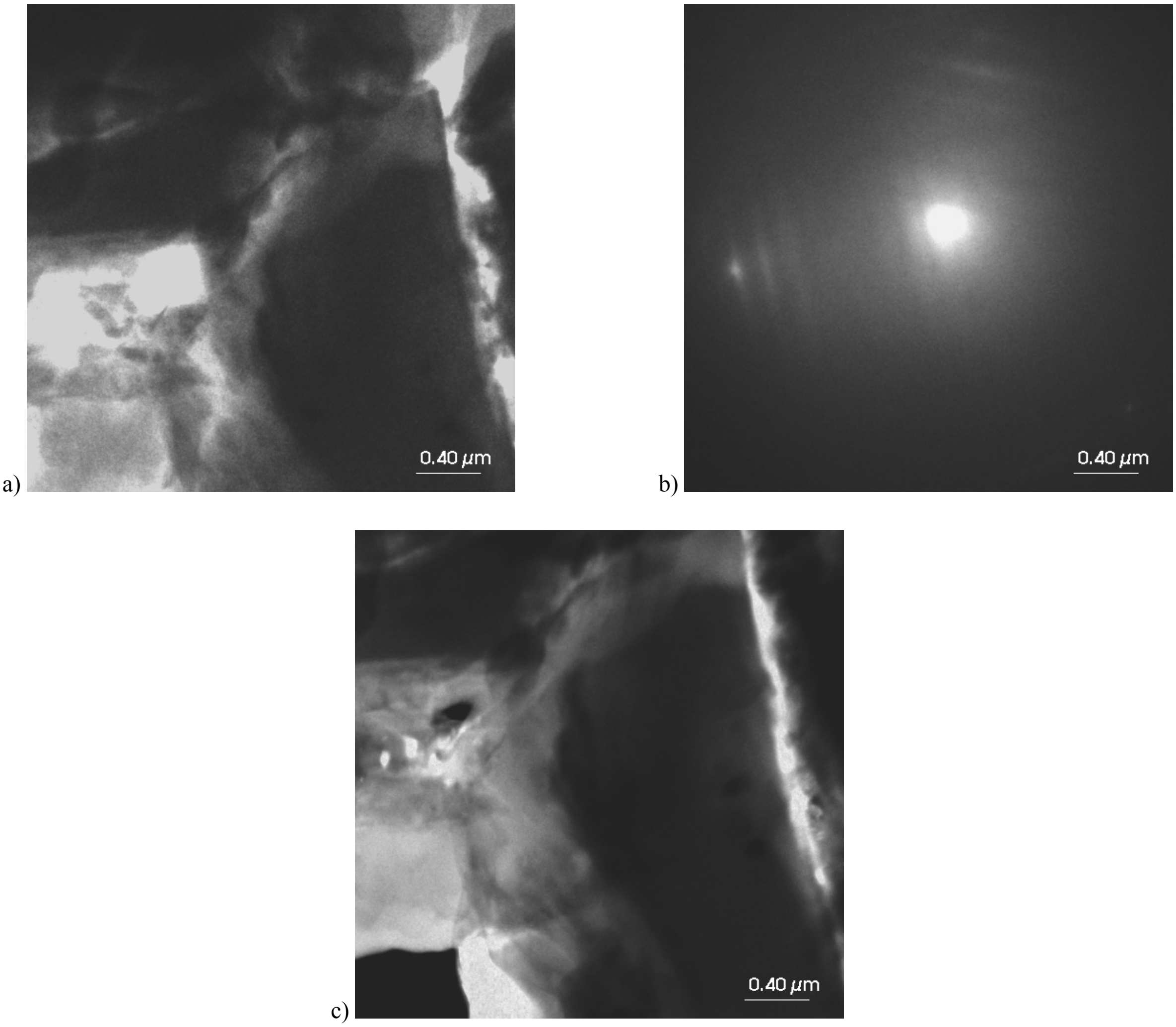


Fig. 4. TEM micrograph of boundary between amorphous and crystalline phases, a) and c) dislocations on crystalline phase; b) diffraction pattern from crystalline area in fig. a); d) diffraction solution pattern

Dislocation density is estimated on the basis of tension energy of the crystalline structure as well as on the dislocation tension energy and is equal [23]:

$$\rho_{\in} = \frac{k}{F}\frac{\left\langle \in^{2} \right\rangle}{b^{2}} \tag{2}$$

where:

$\langle \in^2 \rangle$ – rootmean-square strain,

F – correction factor that accounts for the mutual interaction energy of dislocations,

b – the Burgers vector of a lattice dislocation.

$$k = \frac{4\pi z C}{\ln(\frac{R}{r_0})} \tag{3}$$

z = 1 for screw dislocation,

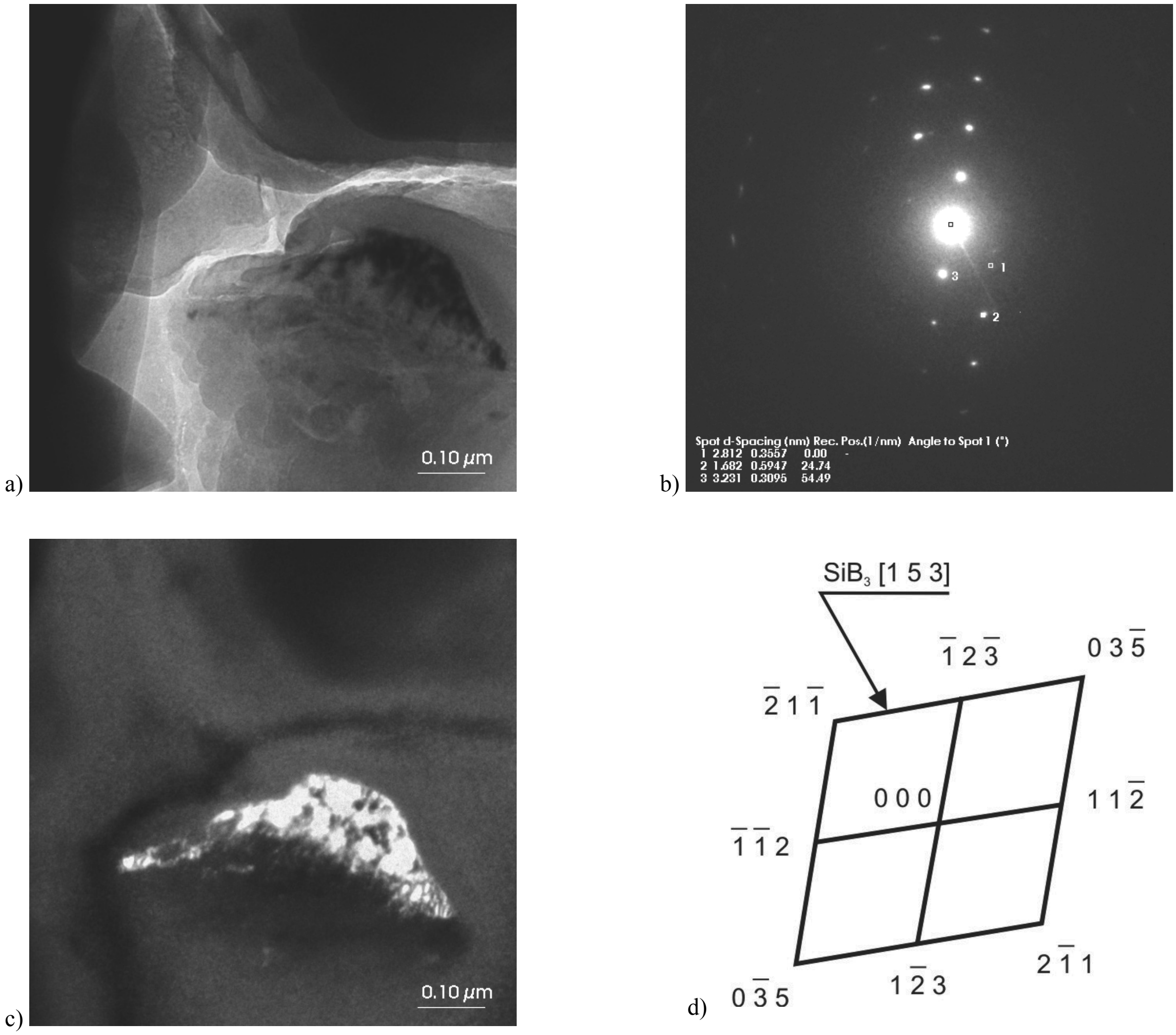
z=1-ν for edge dislocation,

ν - Poisson coefficient,

C – scaling constant in the range 4-7.5,

R, r_0 – outer and inner dislocation cutoff radii.

On the basis of the performed investigation using electron diffraction it was stated that the analysed phase is probably silicon boride (almost pure silicon with small amounts of boron inclusions) Si99B crystallizing in the $Fd\bar{3}m$ crystal structure spots as results of electron beam diffraction on the planes zone.



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Spot d-Spacing (nm) Rec. Pos.(1/nm)  Angle to Spot 1 (°)
 1  2.812  0.3557    0.00    -
 2  1.682  0.5947   24.74
 3  3.231  0.3095   54.49
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Fig. 5. Microstructure of the polycrystalline silicon wafer doped with boron, texturised using laser beam; a) bright field structure with visible traces of the impulse laser beam; b) diffraction pattern of the area in fig. a); c) dark field from reflex $1\bar{2}3$ SiB$_3$ (R3m); d) diffraction pattern solution

4. Conclusions

Solar power from photovoltaic cells is widely recognized as an integral part of a clean energy. Solar cells convert the absorbed sun light into electricity. One of the most direct ways to increase their efficiency is simply to reduce the surface reflection. Laser processing is a promising method for texturization of polycrystalline silicon. As a result of the laser beam influence on the polycrystalline silicon surface some changes on the surface layer could be observed. Bright field observations allow to state in the structure of the investigated material some traces of the laser impulses, and the diffraction pattern analysis has confirmed a structure change being the result of laser beam influence.

Laser beam has probably caused a remelting of the material in micro-areas. Next the fast cooled liquid transforms into the stable state that was a reason of generating of inner tensions in the material. Tensions causes the occurrence of line structure defects in form of dislocations.

Except this, as diffraction analysis shows a phase of pure boron B and silicon boride SiB3 crystallized in the R3m crystal structure as well as silicon boride with very small boron amount Si99B crystallized in the Fd3m crystal structure. All these phases were found in the working areas of the laser beam

The interaction between laser beam and polycrystalline silicon wafers causes local changes on the surface of processed material. Some of these changes appear only on the surface while the others penetrate into the bulk of the material. Detailed inspection of the laser processed surface revealed existence of amorphous regions. They were formed as a result of melting and solidification. Local changes of the state of aggregation introduced inner stresses into material resulting in linear defects (dislocations) in crystallographic structure of textured silicon [25].

Moreover, performed microscope observations revealed the precipitation of boron (R3m) and silicone boride (Fd3m).

As oil prices going up and seems this is going to keep that way, more and more attention is given to alternative energy sources. Probably solar energy is most attractive due to its nature.

A lot of different investigations are performed to improve solar cells performance. This paper was devoted to research in this area.

Laser texturized solar cells could represent a significant advance in photovoltaic energy technology. That might lead to construction of more efficient solar cells.

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