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Surface texturing of multicrystalline silicon solar cells

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Manufacturing and processing

ABSTRACT

Purpose: The aim of the paper is to elaborate a laser method of texturization multicrystalline silicon. The main reason for taking up the research is that most conventional methods used for texturization of monocrystalline silicon are ineffective when applied for texturing multicrystalline silicon. This is related to random distribution of grains of different crystalographic orientations on the surface of multicrystalline silicon.
Design/methodology/approach: The topography of laser textured surfaces were investigated using ZEISS SUPRA 25 and PHILIPS XL 30 scanning electron microscopes and LSM 5 Pascal ZEISS confocal laser scanning microscope. The reflectance of produced textures was measured by Perkin-Elmer Lambda spectrophotometer with an integrating sphere. Electrical parameters of manufactured solar cells were characterized by measurements of I-V illuminated characteristics under standard AM 1.5 radiation.
Findings: A method of texturing of multicrystalline silicon surface using Nd:YAG laser appeared to be much more independent on grains crystallographic orientation compared to conventional texturing methods. Laser texturing makes it possible to increase absorption of the incident solar radiation.
Research limitations/implications: The major inconveniences are surface damage in the heat affected zone and depositing of foreign materials during laser treatment. Applied etching procedure allows for obtaining solar cells of high efficiency larger in relation to cells without texture.
Originality/value: This paper demonstrates that laser texturing has been shown to have great potential as far as its implementation into industrial manufacturing process of solar cells is concerned.
Keywords: Photovoltaics; Solar cells; Multicrystalline silicon; Texturization; Laser processing

1. Introduction

Renewable resources are clean or green energy sources that give much lower environmental impact than conventional energy sources. Renewable resources are attractive because they are replenished naturally – which means that they will never run out. Solar cells use the sun, a free and inexhaustible source of fuel, to produce emission-free electricity. In 2006, global cell production grew by 41% to 2520 MW [20, 23]. The crystalline silicon is the most important material in the photovoltaics today. According to predictions it will remain an important and dominant material in photovoltaics over the next 10-30 years, owing to its well recognized properties and its established production technology [17]. Crystalline silicon solar cells operate by absorbing light and using the discrete energy from the received photons to pump electrons to their exited state. The excited electrons migrate through the material's layers and produce an electrical current [6, 13]. There is no doubt that due to low production costs multicrystalline silicon is attractive substrate for solar cells. However, because of its worse electrical properties compared to monocrystalline silicon intense research is being performed to increase conversion efficiency of solar cells produced of multicrystalline silicon [11].

The exponential growth in the PV market and necessity of a material cheaper than monocrystalline silicon make multicrystalline silicon an important alternative. High-efficiency silicon solar cells need a textured front surface to reduce reflectance since optical losses due to reflectance of incident solar radiation are one of the most important factors limiting their efficiency. Texturing of monocrystalline silicon is usually done by etching in alkaline solutions [7, 12, 14, 24, 26]. These methods are inefficient for multicrystalline silicon due to the presence of random crystallographic grain orientations and high selectivity of etching along specific directions [9, 24, 26].

There are three different kinds of texturization techniques for multicrystalline silicon solar cells which are currently under investigation for implementation in a production line:

- acid texturization [25, 27],
- reactive ion etching [8],
- mechanical texturization [5, 10].

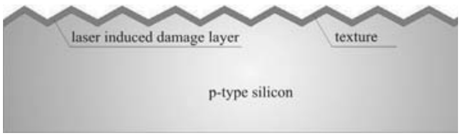
Each of them has some advantages and drawbacks. The application of etches based on $HF\text{-}HNO_3$ induces difficult reproducible results due to random distribution of grains of different crystallographic orientation on the surface of multicrytalline silicon and necessity of precise control of temperature as well as composition of etches. Reactive ion etching creates a needle-like surface, on which screen printing is difficult, but this problem can be overcome by an additional wet chemical etching step. However, the additional alkaline etching step brings the disadvantage of a reduced gain in reflectance. Mechanical texturing may be effective, but has some limitations related to textured material. It cannot be applied specially for thin, wraped, and fragile materials.

The possible way to overcome this problem is the use of laser processing. Strongly coherent and monochromatic laser beam focused to small spot produces high power densities. High quality laser beams make it possible to use laser technology for processing which is impossible to carry out with any different techniques. The wide range of applied power and power densities available from lasers and the possibility of accurate laser beam control are features which contribute to its successful application in many different aspects of surface processing. Energy delivered by focused laser beam is changed into electron, thermal and mechanical energy influencing the surface of workpiece. Such interaction results in evaporation and removal of the thin material layer in the form of neutral atoms and molecules, positive and negative ions from material surface exposed to laser radiation [1, 15-19, 21-22].

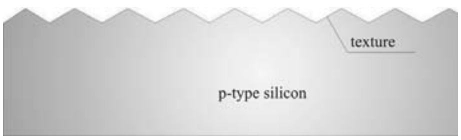
The laser processing is very promising technique for texturing multicrystalline silicon due to the contactless treatment. Moreover, texture of different patterns can easily be implemented on the treated surface without any additional masking [2-4]. In the paper a method of laser texturing has been developed as a possible solution to the problem of texturing multicrystalline silicon.

a) multicrystalline silicon wafers obtained by wire sawing

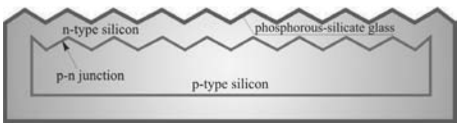
b) saw damage removal



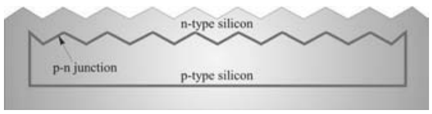
c) laser surface texturization



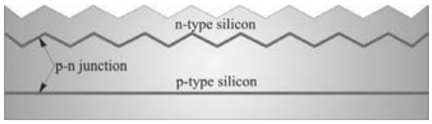
d) laser induced surface damage removal



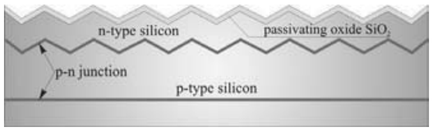
e) phosphorous diffusion



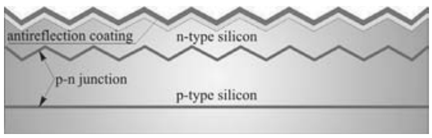
f) phosphorous-silicate glass removal



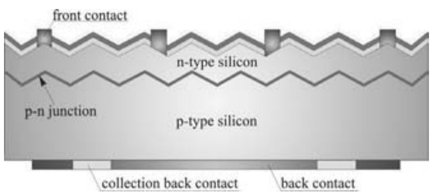
g) junction insulation



h) passivation



i) antireflection coating deposition



j) screen-printing and co-firing of metal contacts

Fig. 1. Applied technology of multicrystalline silicon solar cells

2. Material and experimental procedure

Material used as a substrate was "as cut", p-type, boron-doped multicrystalline silicon wafers manufactured by casting method. Experiments were carried out on wafers of thickness ~330 μm, area 5 cm x 5 cm and resistivity 1 Ωcm. Damage on the surface induced by wire-cutting was removed by etching in 20% KOH solution at 80°C. Typically, about 11 μm of distorted material were etched away creating damage-free surface.

To minimize reflection losses from the front surface texturization of wafers by means of ALLPRINT DN50A Q-switched Nd:YAG laser was performed. Successive grooves were scribed with constant spacing within consecutive scanning the wafer surface by laser beam in the opposite directions. Many trials for different values of laser parameters were carried out. On the basis of these trials optimum parameters of laser treatment were adjusted and assumed to take the following values: maximum output power (P = 50 W), speed of laser beam v = 20 mm/s, pulse repetition frequency f = 15 kHz. The texture consisting of parallel grooves with spacing of 90 μm was produced.

A top layer of material of various thickness was removed by wet etching in 20 %KOH at 80°C performed just after laser texturization. The topography of laser textured surfaces were investigated using ZEISS SUPRA 25 and PHILIPS XL 30 scanning electron microscopes. The reflectance of produced textures was measured by Perkin-Elmer Lambda spectrophotometer with an integrating sphere. The illuminated I-V parameters were measured under standard AM 1.5 radiation. Figure 1 shows the main steps of technology of multicrystalline silicon solar cells.

3. Results and discussion

Alkaline solutions exposing crystallographic (111) planes are usually used to produce textures in the form of random pyramids in (100) monocrystalline silicon to reduce the reflectivity from the front surface of silicon solar cells. In respect of multicrystalline substrates these etches are less practicable for texturing due to the various crystallographic grain orientations.

Texture produced on (100) silicon surface by etching with 40 % KOH:IPA:DIH$_2$O and volume ratio 1:3:46 in 15 minutes at temperature 80°C is depicted in Fig. 2. On the surface of this crystallographic orientation randomly distributed pyramids of reproducible dimensions were produced. 3D topography of this alkaline texture obtained from confocal laser scanning microscope is depicted in Fig. 3.

Additionally, with extending time of alkaline etching, steps of significant height are formed at the grains borders (Fig. 4). It is the main limitation in applying this etch for texturing multicrystalline silicon.

A detailed inspection of scanning electron microscope micrographs of cross-sections of laser textured wafers revealed that grooves are irregular in shape with positive ridges at both rims (Fig. 5).

Detailed analysis of SEM micrographs revealed redeposited residues of expelled silicon which could be seen at rims of the grooves (Fig. 6). Moreover, residues of solidified material were found far beyond the groove rims (Fig. 6). This is the result of interaction of laser beam with the treated surface. After the absorption of short laser pulses of high peak intensities silicon is heated up so that the surface is partially molten.

If the absorbed energy is sufficiently high some of the material is explosively evaporated from the molten layer. The recoil pressure of evaporated material and the plasma plume formed in this process ejects a part of molten layer. As a result of this violent expulsion of the material the deposition of solidified silicon droplets, both inside and outside of the groove can be observed (Fig. 6).

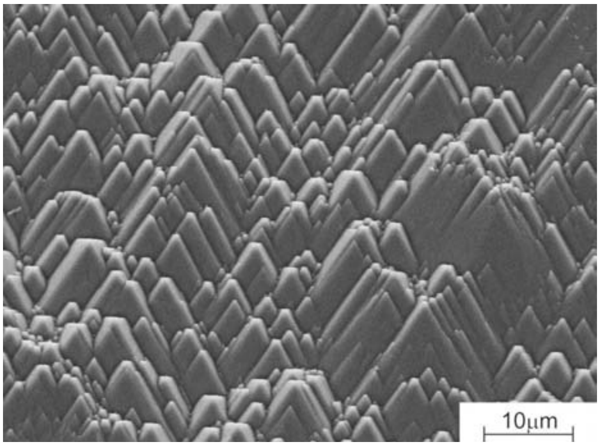


Fig. 2. SEM micrograph of texture formed on (100) silicon surface by etching with 40 % KOH:IPA:DIH$_2$O and volume ratio 1:3:46 in 15 minutes at temperature 80°C

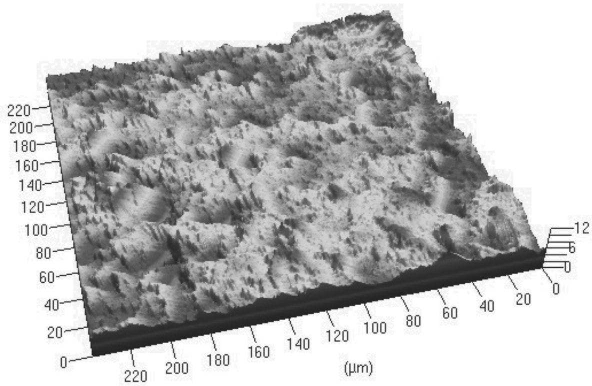


Fig. 3. 3D confocal laser scanning microscope topography of texture formed on (100) silicon surface by etching with 40 % KOH:IPA:DIH$_2$O and volume ratio 1:3:46 in 15 minutes at temperature 80°C

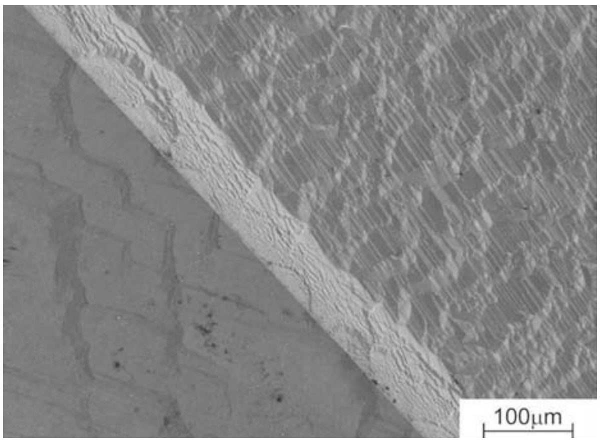


Fig. 4. SEM micrograph of alkaline texture at the grains boundary

Bottom and sidewalls of laser scribed grooves are covered with molten, not evaporated and resolidified material. Solar cells manufactured from laser textured wafers that were not etched shown very low conversion efficiency (Tab. 1). It was a result of detrimental influence of laser induced defects on the operation of solar cells. Therefore, post laser processing etching was performed to remove laser damaged layer. With the increase of thickness of removed layer positive ridges were etched off and textured surface was smoothened away (Fig. 7).

Furthermore, the angle between sidewalls increased resulting in formation of so-called V-grooves (Fig. 8). In the bottom of the grooves may be observed regions of regular shape dependent on crystallographic orientation of substrate. As a result of laser processing and subsequent etching texture of uniform structure was obtained (Fig. 8).

Solar cells manufactured from laser textured wafer that were not etched demonstrate extremely low efficiency. This is the result of damages introduced into the top layer of the material during laser texturing. These damages have detrimental influence on the operation of solar cell and reduce its performance mainly through increased recombination and/or junction shunting. Fortunately, it appears that detrimental influence of laser induced damage on the solar cells performance may be successively mitigated by post – laser processing etch procedure. Applied etching step enable to remove layer of laser induced defects from the textured surface. Many trials have been performed to adjust etch concentration and thickness of removed layer. It can be observed that with the increase of thickness of removed layer efficiency of solar cell grows but at the same time the effective reflectance increase as well. Consequently, post-laser texturing etching improves electrical properties of textured material but deteriorates its optical properties. That is why the proper adjustment of thickness of removed layer must be a trade of balancing these properties of solar cells.

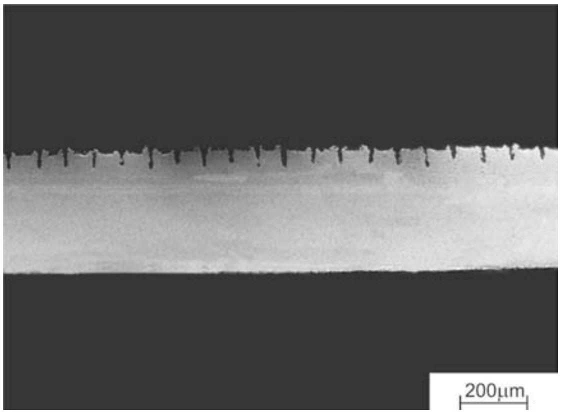


Fig. 5. Cross-section of the wafer with laser texture corresponding to parallel grooves produced with scanning speed of laser beam equal to 20 mm/s and spacing 0.09 mm

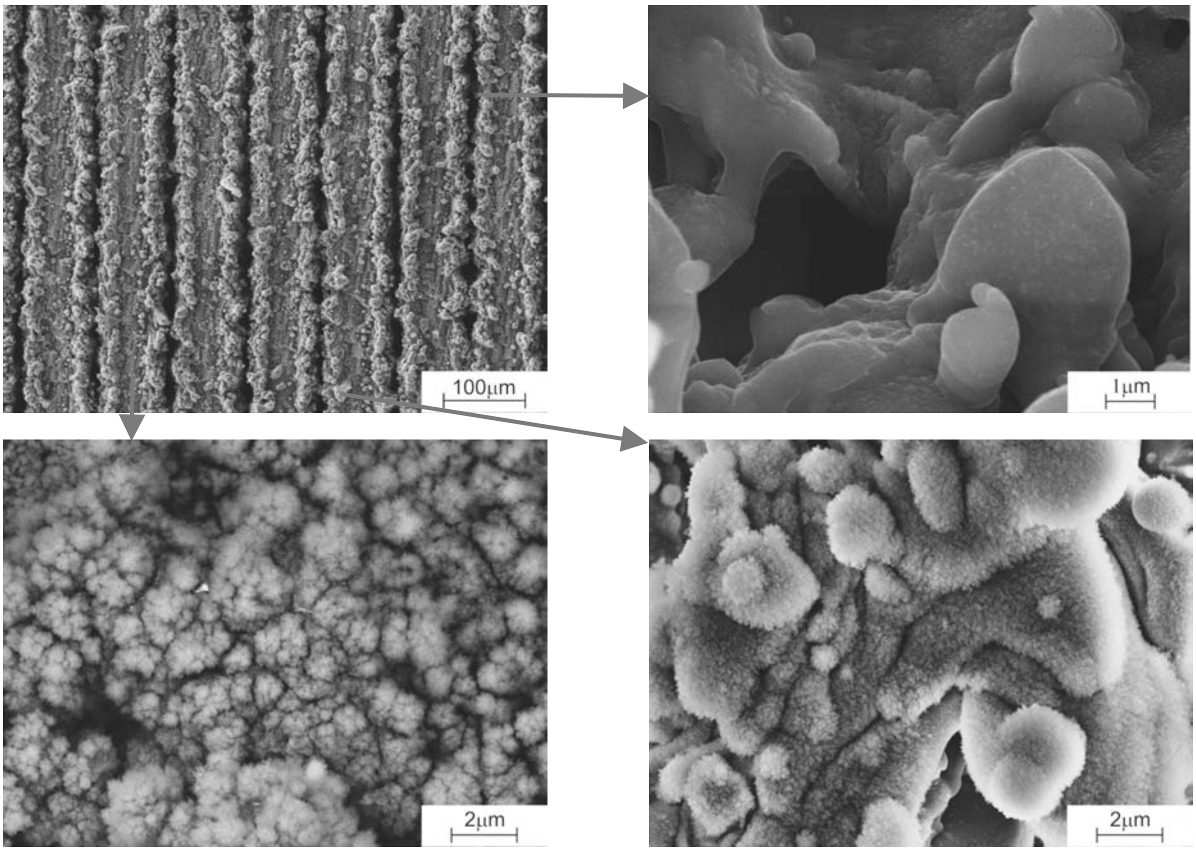


Fig. 6. SEM micrographs of laser texture corresponding to parallel grooves produced with scanning speed of laser beam equal to 20 mm/s and spacing 0.09 mm

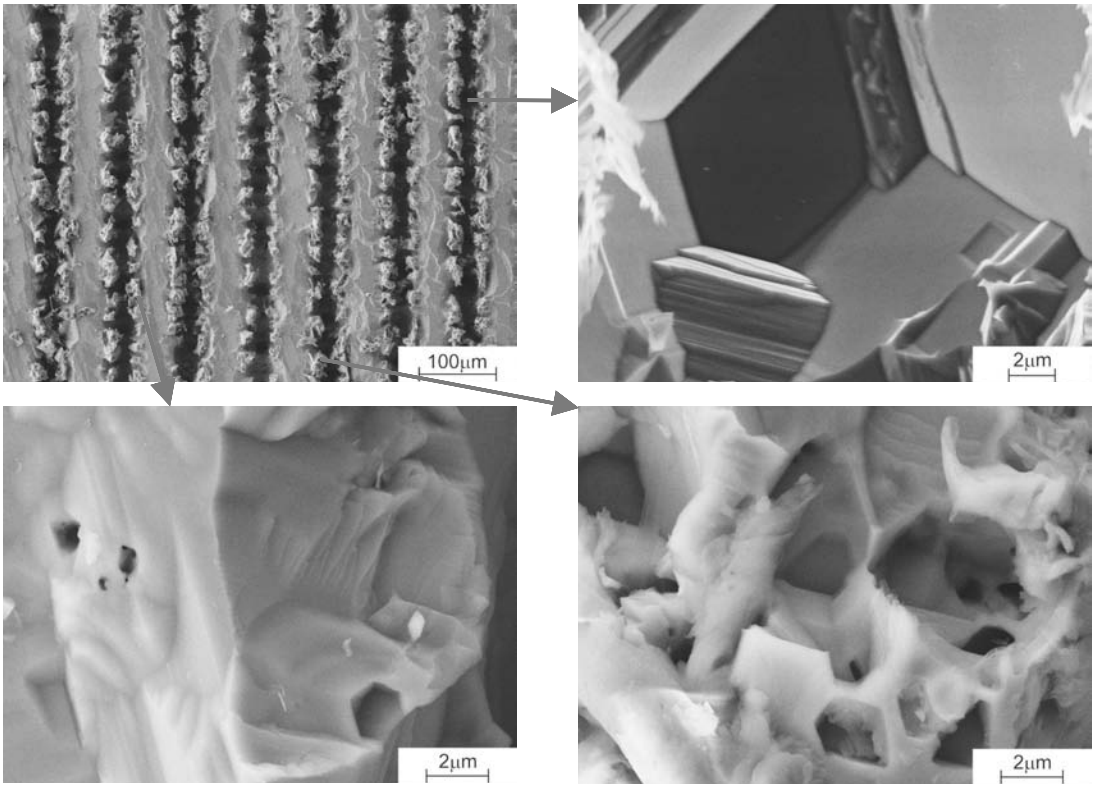


Fig. 7. SEM micrographs of laser texture corresponding to parallel grooves produced with scanning speed of laser beam equal to 20 mm/s and spacing 0.09 mm after removal of 20 µm distorted layer

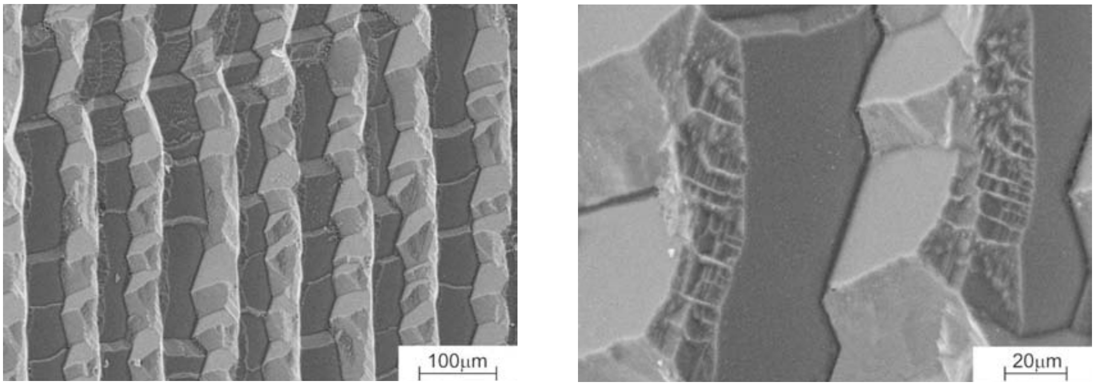


Fig. 8. SEM micrographs of laser texture corresponding to parallel grooves produced with scanning speed of laser beam equal to 20 mm/s and spacing 0.09 mm after removal of 80 µm distorted layer

Table 1.
Effective reflectance for textured wafers after removal of laser induced damage layer of different thickness and conversion efficiency of corresponding solar cells

Texture type	Thickness of removed by etching layer [µm]	Effective reflectance R_{eff} [%]	Efficiency E_{ff} [%]
Without texture	-	34.08	10.21
Laser texture	-	13.96	0.56
Laser texture after removal of laser induced damage layer	20	17.49	2.02
	40	20.53	6.85
	60	23.78	9.44
	80	28.53	10.51

4. Conclusions

The paper presents results of multicrystalline silicon texturization by means of Nd:YAG laser. The best solar cells manufactured from the laser-textured wafers with texture corresponding to parallel grooves after removal by etching of 80 μm of laser damage layer demonstrate 10.51 % efficiency. Laser processing of crystalline silicon surface is interesting alternative in comparison with chemical texturization methods. It gives possibility of precise surface processing independent on grains crystallographic orientation. However, laser surface treatment introduce defects into the top layer of processed material that deteriorate performance of the solar cells. Fortunately, aplied post-laser texturing etching step makes it possible to remove distorted layer and improve efficiency of corresponding solar cells. It can be drawn a conclusion that obtained results are significant from the development of photovoltaics viewpoint. It seems that presented laser texturing method may be successfully incorporated into production line of high-tech multicrystalline silicon solar cells.

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