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Picosecond Laser Based Surface Texturing of Silicon for Anti-Reflective Properties

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Abstract

Surfaces of Silicon-based solar cells are modified to reduce reflectivity and enhance the absorption of light. Texturing using ultrafast lasers is a potential technique for surface modification of solar cells. In order to fabricate superior surfaces with low reflectivity and optimized electrical performance, it is essential to understand the impact of texture characteristics. In this work, two dimensional surface textures were fabricated on Silicon surface using a picosecond laser operated at different laser parameters and the reflectance was measured. The experimental data was used to identify the set of optimal laser parameters and dimensions of surface structures to minimize the surface reflectivity of Silicon. The height of the structures obtained were around 10 μm with a spacing of 25 to 30 μm. As a result, a wave like profile was generated, which can enhance the absorption of photons on the surface and hence reduce reflectivity. Using this technique, the surface reflectivity was reduced to as low as 5 %. In addition, the electrical behavior of the textured surface was simulated using finite difference time domain (FDTD) method. The current density and power generation characteristics of the textures were obtained and were found to be comparable with existing technology of anti-reflective coatings.

Keywords: Surface texturing; Picosecond pulsed laser; Silicon wafers; Reflectivity; Current Density and power generation

1. Introduction

Light manipulation is of crucial significance in multitude of engineering applications. Solar Energy for long has been looked upon as one of the most viable solutions for the energy security challenges and climate change issues due to prolonged use of fossil fuels around the globe. Worldwide, silicon wafer-based solar cells contribute to around 92% of the total production of photovoltaic cells [1]. A major cause of concern regarding the efficiency of these solar cells is the reflectance of silicon, an average of 30% of incident light is

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lost via reflection from the front surface. Researchers have shown the use of ultrafast lasers for surface structuring of silicon, although there's a need to comprehensively study the impact of these structures on the reflectivity of silicon.

Silicon wafer based solar cells are either made of mono-crystal silicon or poly-crystal silicon. As the name suggests mono-crystal silicon is comprised of just one single crystal and hence it's easier to structure its surface using conventional alkaline based anisotropic chemical etching methods [2]. Such an approach is not feasible for poly or multi-crystal silicon as it contains multiple crystals with different orientations. Multi crystalline silicon being economical and easier to manufacture is a more widespread choice for solar cells as of today [3]. HF and HNO_3 are used presently for surface texturing of multi-crystal silicon solar cells [4]. These acidic texturization methods are exothermic in nature and difficult to control, also reagents like HF are extremely hazardous to use and strict safety norms are required [5] also quite a large volume of water is required for rinsing after acidic wet chemical etch steps [6], therefore optimizing the operations towards minimal water consumption is vital both from the environmental and from the economic points of view. Surface texturization of top layer of silicon is an accepted technique to boost light absorption [7] for photovoltaic devices.

Laser surface texturing can prove to be an efficient way of dealing with the complications mentioned above as lasers provide a fast and precise of way of engineering a surface with varieties of features [8]. Moreover the elimination of hazardous gases and chemicals makes it an environment friendly option as well. Researchers have pointed out the use of laser in surface texturing via two techniques i.e. by direct ablation using nanosecond lasers [9] and by using ultrafast lasers [10,11] in the picosecond and sub-picosecond range. As ablation using nanosecond lasers technique involves removal of material via melting it tends to introduce Heat Affected Zone (HAZ) and other thermal defects on the surface which can be eliminated by the use of picosecond laser.

With ultrafast lasers, a multitude of surface structures can be generated [10] and there have been works reported [12-16] where laser textured silicon surfaces have shown better optical properties in both air and water [17-20]; still a standard operating procedure of industrial acceptance is unaccounted for. However just the optical assessment without the electrical properties is not satisfactory enough to arrive at a conclusion regarding the usefulness of the surface structures. In this work, a picosecond laser is used to create 2 dimensional gratings on silicon surface and the reflectance was measured. FDTD simulations are carried out to measure the electrical performance of the gratings, current and power characteristics were measured.

2. Experiments

The experiments were carried out on a passively Q switched laser of wavelength 532 nm and a pulse width of 650 picosecond to generate textures on the surface of silicon wafers with thickness 280 +/- 20 μm. The pulse energy of the machine was constant at 60 μJ and with the spot size being 90 μm the fluence comes out to be a fixed value of around 1 J/cm^2 The maximum frequency of the pulses is 45 kHz and the variation in power is directly proportional to change in frequency. Hence the heat input is varied with the change in frequency or the number of pulses. The spot size kept constant and the stage is only permitted to move in x-y plane with a maximum velocity of 500 mm/s. The processing parameters were constrained by the fluence of the machine as well as the scanning speed. Here the criteria for parameters were governed by overlap of the subsequent pulses and the number of pulses falling at a given point. As stated earlier these two are the most influencing parameters on the heat input on the substrate. The number of pulses used in the experiments ranged from 15 to 350 with a repetition rate varying from 22.5 kHz to 45 kHz. A simple raster scan strategy was employed to scan the silicon wafer surface. Table 1 gives the details about the parameters used in the experiments. The laser textured samples were then characterized for two crucial attributes, first the size and geometry of the surface structures and secondly for the reflectance of the different textured regions obtained. The surface characterization was done using a 3D optical profilometer and SEM (Scanning Electron Microscope).

Table 1. Process Parameters Used

Parameters	Number of Pulses/spot	Repetition Rate(kHz)	Line Spacing (μm)	Scanning Speed (mm/s)
Set 1	35	22.5	50	50
Set 2	15	22.5	40	100
Set 3	175	22.5	40	10
Set 4	350	45	40	10

3. Simulating the Electrical Performance of the textures

Textures increase the area of the front surface [21-23] which nullifies the optical enhancement effect [2, 12] achieved due to improved forward scattering. Therefore, to determine the aggregate consequences of the surface textures, electrical simulations are required. Finite Difference Time Domain method was utilized to model the power and current generation behaviour of textured silicon surface using a commercial solver named *lumerical* (FDTD and DEVICE). Rectangular and wave like gratings were assessed using a perpendicular planar light source of wavelength ranging from 400 nm to 700 nm. During this process the number of electrons and holes produced in the semiconductor is calculated and subsequently the current density is calculated. This behaviour of 2 dimensional textured surfaces is compared with that of a planar silicon cell. For simplicity sake it is assumed that rate of generation of an electron hole pair is equivalent to rate of absorption of photons, i.e. each photon will trigger the generation of an electron and a hole.

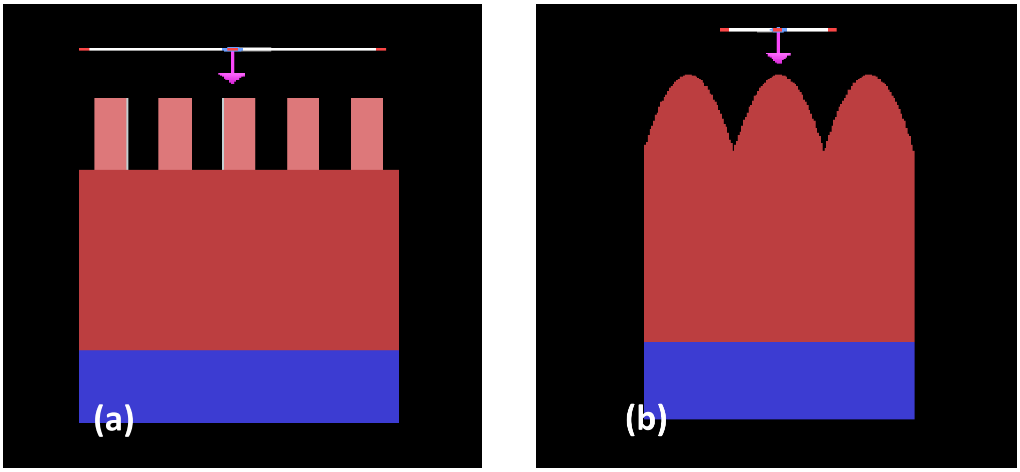

Fig.1. Surface texture designs used for modelling electrical behaviour of the solar cell formed with (a) rectangular and (b) wave gratings. The pink arrow on the top represents the direction of the incident light.

4. Results and Discussion

4.1. Surface Topography

Fig. 2 shows the sample after picosecond laser processing. Here, a single side polished silicon wafer, was textured with 5 different parameter set as mentioned in table i.e. 5 squares of size 20mm x 20mm were made on the sample. Multiple ZETA microscope scans of the same sample were taken to ensure comprehensive measurement of the samples; suitable statistical methods were used to finalize the final values of measured quantities. A sample microscopic 3D profile is shown in the below.

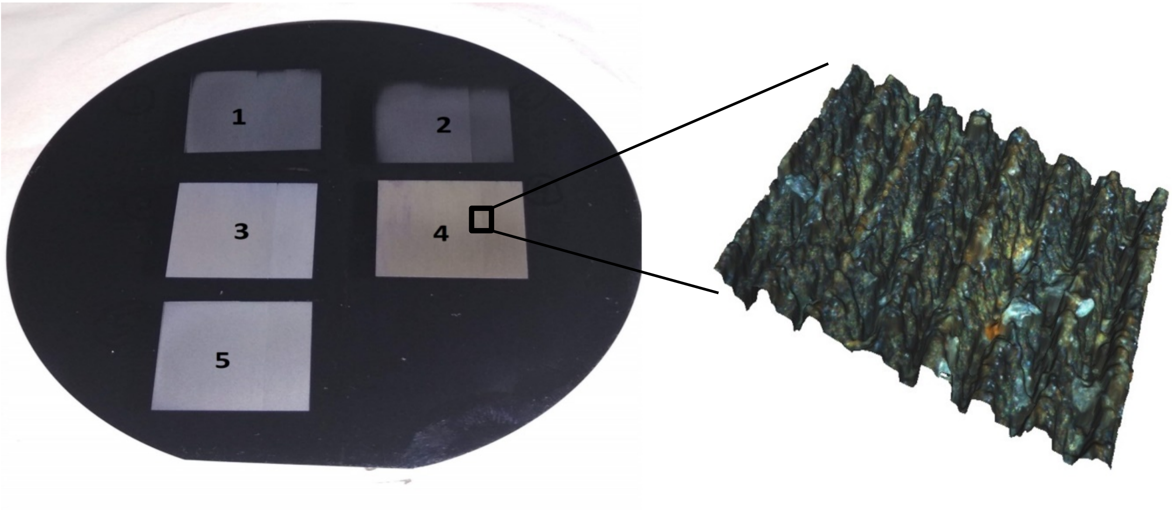

Fig.2. Silicon Wafer with different region of textures formed using different set of laser parameters. A microscopic image of the formed texture is shown on the side, using a 3D profilometer.

The average peak size of the samples varied from 1 µm to 40 µm, however the higher sizes of 10 µm and beyond doesn't serve any purpose due to high increase in surface area and shadow effect. It is certain that these structures are not self-organized or laser induced periodic surface structures (LIPSS), but these are direct write laser textures. There can be two aspects of such an outcome, either the fluence is not high enough or the pulse is not short enough. When the fluence is not high enough for ablation through a single pulse, and multiple pulses are used for machining, then the mechanism is a combination of both melt expulsion and coulomb explosion.

4.2. Reflection of the Samples

The reflectance of silicon samples were measured on a spectrometer with a wavelength range from 300 nm to 1200 nm. Sample 1 (where parameters set 1 was used) possessed the highest amount of reflectance, almost touching the bare silicon values. The optical performance of sample 3 was at par with chemical etching methods, with reflectance ranging from 10-15% throughout the visible range of wavelength.

Sample 4 had the best performance optically; the reflectance values achieved were under 7% for most part of the visible region. One result which contradicts the known literature was the third sample where the sample dimensions were around 800 nm i.e. of the order of wavelength of light. However the reflectance of this sample was very high as compared to other samples.

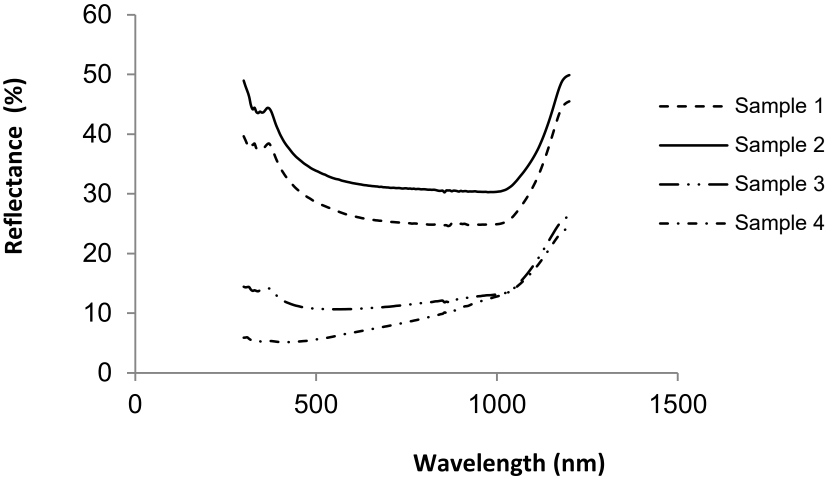

Fig.3. Amount of incident light reflected from each sample surface as measured with a spectrometer. The reflectance is a function of wavelength of incident light.

As the process parameters vary, the size and design of textures also fluctuate. This change in the texture in turn affects the reflectance, therefore the trends of variation of reflectance with number of laser pulses per spot and average peak height of the textures are shown below in Fig. 4. It can be a seen in a simple trend that the value of reflectance reduces with increase in number of pulses indenting on the surface. Although it represents a generic trend, it should not be taken on its face value. Damage to the surface also increases with number of pulses. Fig. 4(b) shows a trend where reflectance decreases with increase in size of surface structures up-to a point and starts increasing thereafter. However these are discreet data points and further comprehensive experimentation is required to interpolate data points from this curve.

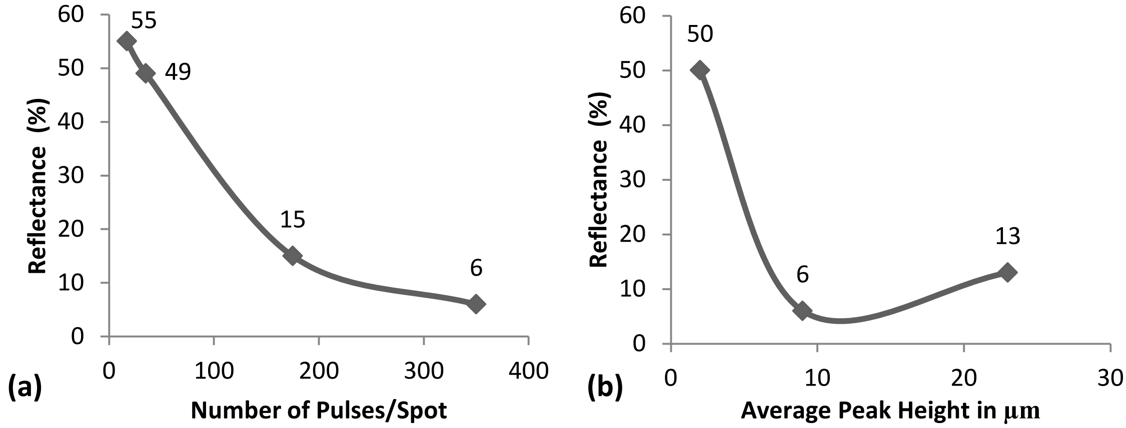

Fig.4. (a) Reflection v/s pulses per spot plot (b) Reflection v/s Average peak height of the textures

4.3. Simulation Results

The electrical performance of the textures was simulated for two properties, the maximum power generated and current density. Fig. 5 presents the results of generated power/cm^2, for both with and without the use of anti-reflection coating (ARC). It can be observed that the difference in power generation for the two types of gratings is smaller than the plane surface. It can be accounted for by the fact that such gratings are anti-reflective in nature and absorb more photons as compared to plane surface. Although the generation is still lower than the ones with ARC, which can be attributed to the enhanced recombination effect in the silicon wafer due to increased surface area by gratings. With J_{sc} (Current density), the square gratings appear to have an edge over the wave gratings and planar surface conditions.

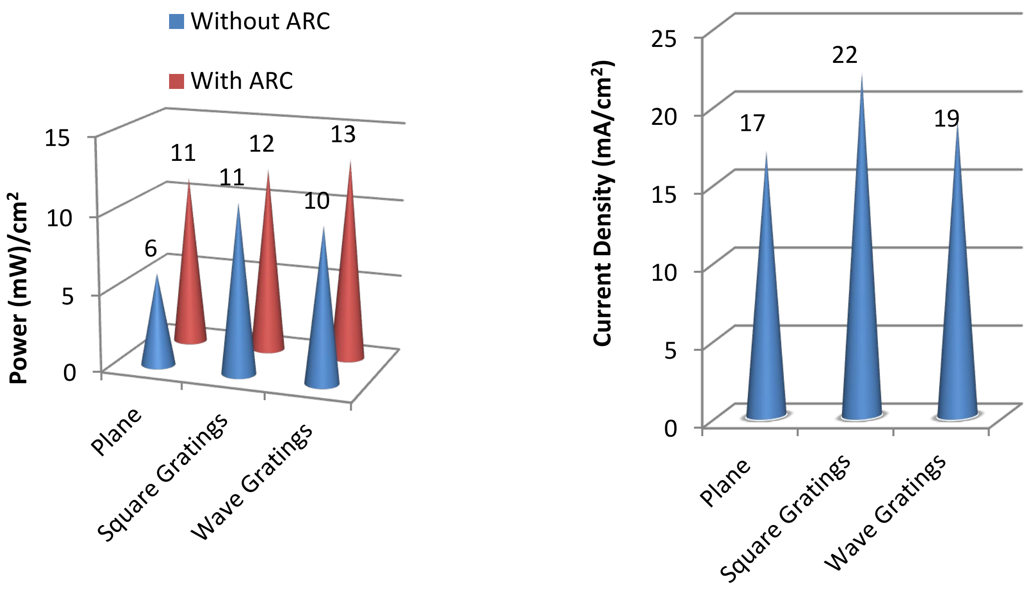

Fig.5. The power and current density plots from the simulations data, square gratings perform better than other surface features taken in consideration

The elctrical simulations clearly suggest that 2D gratings can perform much better than no surface feature (i.e. smooth surface) due to its superior optical behviour (measured in experiementation). Another point that can be infered here is that although the optical performance is much enhanced, the elctrical results are restricted due to increased surface area of the gratings. There is a scope to identify and develop better structures, in both 2 and 3 dimensions which can perform better in both optical and elctrical perspective.

5. Conclusions

Two dimensional surface structures were created using picosecond pulsed laser processing and its reflectance was measured. Electrical properties were assessed using simulations and results were compared with anti-reflective coatings.

Based on the research carried out and with the backdrop of literature reviewed, we can firmly conclude that reflectance of silicon surface can be suppressed adequately with two dimensional gratings of appropriate size and profile, formed with laser processing. The reflectance value measured with wave gratings was around 6%. Although just the reflectance values are not sufficient to determine the usefulness of the textures, electrical performance of the surface structures must be evaluated as the power generation is hampered by increased surface area created by surface textures. In this case, 2d square gratings were found be better off than planar and wave type surface in simulations, however still not as competent as anti-reflective coatings generally used in solar cells. Future scope lies in generating three dimensional surface structures optimized for both optical and power generation capabilities.

References

1. Photovoltaic Report. Fraunhofer ISE; 2015
2. M. F. Abdullah *et al.*, "Research and development efforts on texturization to reduce the optical losses at front surface of silicon solar cell," *Renew. Sustain. Energy Rev.*, vol. 66, pp. 380–398, 2016.
3. K.M. Park, M.B. Lee, S.Y. Choi, Investigation of surface features for 17.2 % efficiency multi-crystalline silicon solar cells, Sol. Energy Mater. Sol. Cells 132 (2015) 356-362.
4. S. Nandy, S. Bhattacharya, S. Das, S. Jana, and U. Gangopadhyay, "Multicrystalline Silicon Texturing by Novel Bi-Component Etching Solution," *Mater. Today Proc.*, vol. 4, no. 14, pp. 12671–12677, 2017.
5. Gangopadhyay U, Dhungel SK, Basu PK, Dutta SK, Saha H, Yi J. Comparative study of different approaches of multi-crystalline silicon texturing for solar cell fabrication. Sol Energ Mat Sol Cells 2007;91:285.9.
6. J P Cotter, I Zeimpekis, M Kraft, E A Hinds, Improved Surface Quality of Anisotropically Etched Silicon {111} Planes for mm -scale Integrated Optics.
7. Guy Beaucarne, Patrick Choulat, B.T. Chan, Harold Dekkers, Joachim John and Jef Poortmans, IMEC, Belgium Etching, texturing and surface decoupling for the next generation of Si solar cells
8. Y. Ma, J. Si, X. Sun, T. Chen, and X. Hou, "Progressive evolution of silicon surface microstructures via femtosecond laser irradiation in ambient air," *Appl. Surf. Sci.*, vol. 313, pp. 905–910, 2014.
9. J.C. Zolper, S. Narayanan, S.R. Wenham, M.A. Green, 16.7 % efficient laser textured, buried contact polycrystalline silicon solar cell, Appl. Phys. Lett. 55 (22) (1989) 2363-2365.
10. S. Binetti *et al.*, "Picosecond laser texturization of mc-silicon for photovoltaics: A comparison between 1064 nm, 532 nm and 355 nm radiation wavelengths," *Appl. Surf. Sci.*, vol. 371, pp. 196–202, 2016.
11. A. Horn, C. C. Kalmbach, J. G. Moreno, V. Schütz, U. Stute, and L. Overmeyer, "Laser-Surface-Treatment for Photovoltaic Applications," *Phys. Procedia*, vol. 39, pp. 709–716, 2012.
12. P M Fauchet and E Seigman. Surface ripples on silicon and gallium arsenide under picosecond laser illumination Appl. Phys. Lett. 40, 824 (1982)
13. T. H. Her, R. J. Finlay, C. Wu, S. Deliwala, and E. Mazur, "Microstructuring of silicon with femtosecond laser pulses," *Appl. Phys. Lett.*, vol. 73, no. 12, pp. 1673–1675, 1998.
14. C.H. Crouch, J.E. Carey, J.M. Warrender, M.J. Aziz, E. Mazur, F.Y. Genin, Comparison of structure and properties of femtosecond and nanosecond laser-structured silicon, Appl. Phys. Lett. 84 (2004) 1850-1852.
15. Y. Yi, W. Guo, and Y. Peng, "Enhancement of light trapping for thin film solar cells," *MRS Adv.*, vol. 426, no. May, pp. 1–6, 2018.
16. V.V. Iyengar et al. Solar Energy Materials and Solar Cells 95 (2011) 2745-2751
17. L. Forbes Solar Energy 86 (2012) 319-325
18. Large scale micro structuring on silicon surface in air and liquid by femtosecond laser pulses M. Ulmeanu etal. Applied Surface Science 258 (2012) 9314-9317
19. Formation of femtosecond laser induced surface structures on silicon: Insights from numerical modeling and single pulse experiment. 9488 T.J.-Y.Derrien et al./ Applied Surface Science 258 (2012) 9487--9490
20. B.S. Yilbaset al. Applied Surface Science 351 (2015)880--888
21. E. R. Martins *et al.*, "Deterministic quasi-random nanostructures for photon control," *Nat. Commun.*, vol. 4, pp. 1–7, 2013.

22. Serra H Altinoluk et al. , Light trapping by micro and nano-hole texturing of single-crystalline silicon solar cells Energy Procedia 92 (2016) 291-296
23. Quan ji Wang and Weidong Zhou , Direct fabrication of cone array microstructure on mono-crystalline silicon surface by femtosecond laser texturing Author links open overlay panel Optical Materials 72 (2017) 508e512