Understanding the effects of picosecond laser texturing of silicon solar cells on optical and electrical properties

Anup Sharma and Deepak Marla*

Department of Mechanical Engineering,
Indian Institute of Technology Bombay,
Powai, Mumbai, 400076, Maharashtra, India
Email: anup.sharma@iitb.ac.in
Email: dmarla@iitb.ac.in
*Corresponding author

Abstract: Surfaces of silicon-based solar cells are modified to reduce reflectivity and enhance the absorption of light. Texturing using ultra fast lasers is a potential technique for surface modification of solar cells. In order to fabricate superior surfaces with low reflectivity and optimised 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 minimise 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 6%. In addition, the electrical behaviour of the textured surface was simulated using finite-difference time-domain (FDTD) method. The simulated results of current density and power generation suggest that rectangular-shaped gratings have higher current density and power as compared to those obtained for wave-like gratings.

Keywords: laser texturing; picosecond laser; silicon solar cell; reflectance; FDTD simulations.

Reference to this paper should be made as follows: Sharma, A. and Marla, D. (2022) 'Understanding the effects of picosecond laser texturing of silicon solar cells on optical and electrical properties', *Int. J. Materials Engineering Innovation*, Vol. 13, No. 1, pp.23–32.

Biographical notes: Anup Sharma is a research scholar in the IIT Bombay-Monash Research Academy. He received his MTech in 2019 from Department of Mechanical Engineering, IIT Bombay. His research revolves majorly around laser processing and presently he is involved in modelling the process of laser interaction with atom probe tomography specimen.

Deepak Marla is an Assistant Professor in the Department of Mechanical Engineering at IIT Bombay, India. He obtained his Bachelor's and PhD from IIT Bombay in 2007 and 2013, respectively. He also worked as a post-doctoral researcher at the University of Illinois at Urbana Champaign and Technical University of Denmark. His research interests include laser materials processing, electrochemical machining, electric discharge machining, and modelling and simulation in manufacturing.

This paper is a revised and expanded version of a paper entitled 'Picosecond laser based surface texturing of silicon for anti-reflective properties' presented at Lasers in Manufacturing Conference 2019, Munich, Germany, 24–27 June 2019.

---

1 Introduction

Silicon wafer based solar cells are one of the most widespread renewable energy generation technology presently. In order to increase the amount of light absorbed by the solar cells, the top surface of the silicon wafers is micro-textured. Surface reflectance is caused by an abrupt change refractive index. These textures induce forward scattering by creating a gradual change in refractive index and hence drastically reduce reflectance.

There are multiple approaches to create textures on the surface of silicon wafer including chemical, mechanical and even non-conventional methods like electro-discharge machining (EDM) (Rahang and Patowari, 2015). Also, methods like electrochemical micro texturing (Patel et al., 2019) are gradually gaining traction. Conventionally, mono-crystalline silicon wafers are textured using alkaline-based anisotropic chemical etching methods (Abdullah et al., 2016). 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 (Park et al., 2015). HF and HNO_3 are presently used for surface texturing of multi-crystal silicon solar cells (Nandy et al., 2017). These acidic texturisation methods are exothermic in nature and difficult to control; also, reagents like HF are extremely hazardous to use, and strict safety norms are required (Gangopadhyay et al., 2007). Enormous amount of water is required for rinsing after wet acidic chemical etch steps (Cotter et al., 2013), therefore optimising the operations towards minimal water consumption is vital both from the environmental and from the economic points of view.

Front surface textures on the silicon wafers, although reduce reflectivity of the surface, increase the surface area and subsequently the sites for recombination increases. A surge in charge recombination is detrimental to the power generation and hence leaves the texturing exercise as inconsequential. Textures created with chemical etching methods cannot be substantially altered and hence difficult to optimise. Li and Yu (2011) studied the effect of different types of surface structures such as nano-pillars and nano-cones on the efficiency of crystalline Si-based solar cells. Lasers provide a fast and precise way of engineering a surface with a variety of features (Ma et al., 2014). Therefore, laser texturing can prove to be an efficient way of dealing with these complications. Moreover, the elimination of hazardous gases and chemicals makes it an environment friendly option as well. Researchers have pointed out the use of pulsed laser in surface texturing via two techniques: direct ablation using nanosecond lasers (Zolper et al., 1989) and by using ultra fast lasers by Binetti et al. (2016) and Horn et al. (2012), and by Fauchet and Seigman (1982) in the picosecond and sub-picosecond range. Similar approach of using femtosecond pulsed laser for creating micro-dimples was adopted by Ezhilmaran et al. (2019), in order to texture piston rings with moly-chrome coatings. With laser texturing, a multitude of surfaces can be generated including both projections and depressions as demonstrated by the authors here.

Although short pulsed, nanosecond lasers induce a significant amount of thermal damage in the surface as compared to picosecond lasers and hence cannot be considered as an optimised solution for solar cell applications where the thickness of the substrate is generally less than 200 μm. Conversely, work by Her et al. (1998) and Yilbas et al. (2015) showed that femtosecond pulsed lasers induce little to no thermal damage at all on the substrate and can create a variety of surface structures with better absorption properties. However, for large volume industrial applications like solar cells, the capital and running cost may not be commercially feasible. Picosecond lasers can create surface structures in a wide range of size with significantly reduced thermal damage as compared to nanosecond laser. Along with better economic viability, picosecond laser can prove to be a more practical option.

In order to fabricate superior surfaces with low reflectivity and optimised electrical performance, it is essential to understand the impact of texture characteristics. In this work, silicon wafers are textured using picosecond laser to create diverse surface structures to reduce reflectance. Co-relation between the size of the textures and laser parameters with reflectance has been made to understand the effect of geometry and process parameters for their fabrication. Finite-difference time-domain (FDTD) simulations are carried out to measure the electrical performance of the gratings, current, and power generation characteristics.

2 Materials and methods

The experiments were carried out on a passively Q-switched picosecond laser (Model SpitLight 600-10 Special Nd:YAG, InnoLas Laser GmbH) of wavelength 532 nm and a pulse width of 650 picosecond to generate textures on the surface of monocrystalline 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 is 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 influence of the machine as well as the scanning speed. The laser is scanned over the surface as shown in Figure 1 along a zig-zag path. Each circle in the image represents the ablation due to a single pulse. As the pulsed laser scans the surface, several pulses overlap. A constant pitch is maintained between two consecutive scanning lines. The pitch is also varied such that the scanning lines overlap. The size and shape of the textures are governed by pitch and number of pulses falling at a given point. The laser parameters are varied to generate different textures on the Si surface. Table 1 gives the details about the parameters used in the experiments.

The laser textured samples were then characterised for two crucial attributes:

1 the size and geometry of the surface structures

2 the reflectance of the different textured regions obtained.

The surface characterisation was done using a 3D optical profilometer and scanning electron microscope (SEM).

Figure 1 Schematic showing the scanning path of laser used

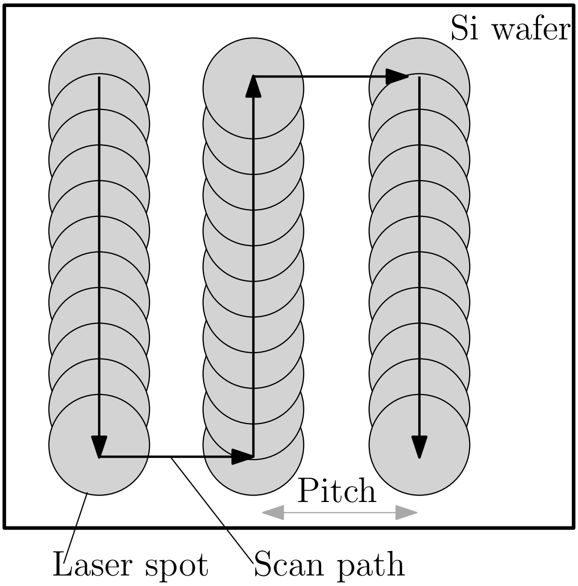


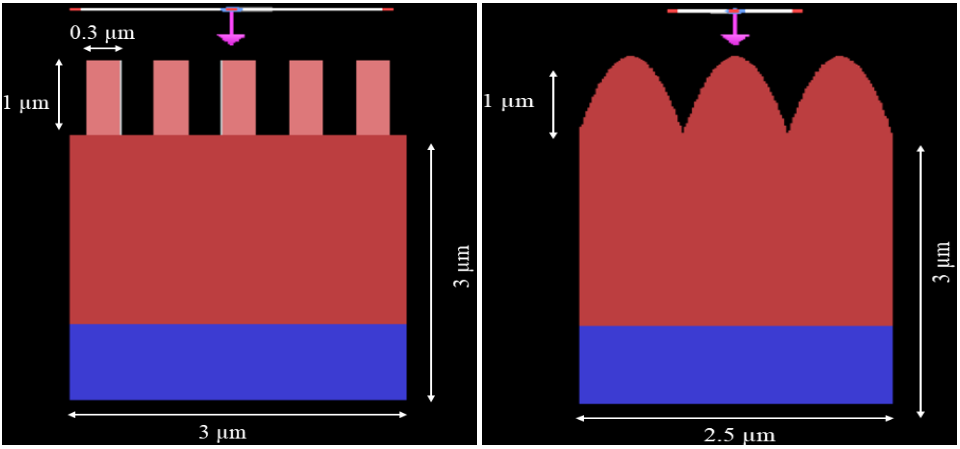
Table 1 Range of laser parameters used in the experiments

Parameters	*Range*
Pulse energy	60 μJ
Wavelength	532 nm
Scanning speed	10 to 100 mm/s
Pulses per spot	15 to 350
Repetition rate	22.5 to 45 kHz
Pitch	40 to 50 μm

3 Simulation of electrical properties

Martins et al. (2013) suggested that textures increase the area of the front surface which nullifies the optical enhancement effect achieved due to improved forward scattering. Therefore, to determine the aggregate consequences of the surface textures, electrical properties are required. FDTD method was utilised to model the power and current generation behaviour of textured silicon surface using a commercial solver named *Lumerical* (FDTD and device module). 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 obtained. This behaviour of two 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. The following two geometries were considered for simulation other than plane (flat) surface as depicted in Figure 2. The first geometry [Figure 2(a)] selected is analogous to the shapes of grooves, and the second geometry selected [Figure 2(b)] is similar to the peaks and valleys obtained during the experiments (depicted in Figure 3).

Figure 2 Shapes of the textures considered in the FDTD simulation (see online version for colours)



(a) (b)

The FDTD method is a state-of-the-art method for solving Maxwell's equations in complex geometries. A three-dimensional FDTD numerical method is employed to rigorously model the light absorption over thin film silicon solar cells. The following equations were solved, over the geometries shown in Figure 2 and under the incident light conditions mentioned above.

$$\nabla \times \vec{E} = -\frac{\partial B}{\partial t}$$

$$\nabla \times \vec{H} = \frac{\partial D}{\partial t}$$

Here, B is the magnetic field ($B = \mu H$) expressed as the product of permeability (μ) and magnetising field (H). Also, D is the displacement field ($D = \epsilon E$) expressed as the product of permittivity (ϵ) and electric field (E). The value of refractive index varies with the distance from the base of the surface projections and hence at all nodes of the mesh, refractive index is calculated.

4 Results and discussion

The results of the experiments and simulations are described in this section as per the measured surface textures and reflectance, and simulated electrical properties.

4.1 Surface topography

Diverse textures were fabricated by varying the laser process parameters. It was observed that with pulse energy constant, scanning parameters such as number of pulses per spot and pitch play a major role in modifying the textures. A three-dimensional profile image of one of the samples is depicted in Figure 3. On the basis of these obtained profiles, the geometries for simulation were selected.

The average peak size of the samples varied from 1 µm to 40 µm, however the higher sizes of 10 µm and beyond does not serve any purpose due to a large increase in surface area and shadow effect. The spacing of the peaks varied with the pitch distance of the subsequent scan lines, and height was found to be a direct outcome of number of pulses hitting per spot.

Figure 3 3D image of a textured sample showing the surface profile (see online version for colours)

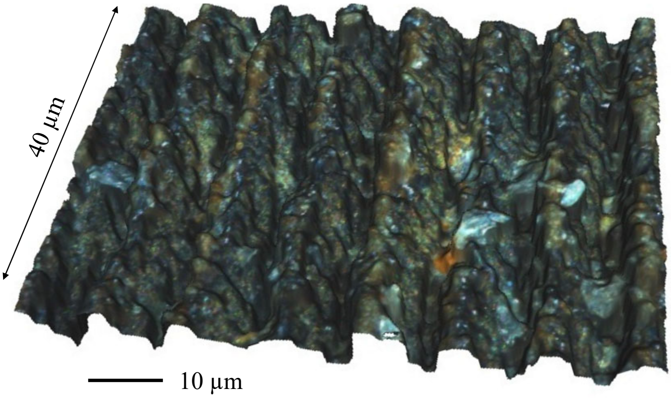
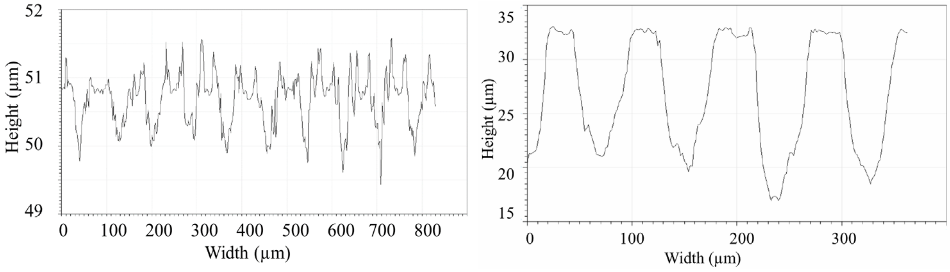


Figure 4 Cross-section profile of samples processed at two scanning speeds with a pitch of 40 µm, (a) scanning speed of 100 mm/s (b) scanning speed of 10 mm/s



(a) (b)

Figure 4(a) illustrates the cross-section of the surface textures obtained with scanning speed of 100 mm/s and pitch of 40 µm, with a spot diameter staying constant at 90 µm. With such high scanning speed, the number of incident pulses per spot is low and hence the small peak to valley distance (~1 µm). When the scanning speed is reduced to 10 mm/s, the number of pulses per spot increases and hence the size of the structures. The structures in this sample are the more uniformly distributed that can be inferred from Figure 4(b).

4.2 Reflectance

The reflectance of a surface is a function of the wavelength of the incoming light. The lowest values of reflectance obtained was around 6% at a specific value of wavelength as shown in Figure 5. It is also important to note the pattern of reflectance value as it drops until almost the visible range of wavelength and increases gradually thereafter. The variation in reflectance is caused by the size and distribution of the surface textures along different samples which in turn are caused by the modifying laser parameters. Therefore, in order to understand the impact of process parameters, they need to be mapped to the reflectance values. It can be a seen in a simple trend in Figure 6, that the value of reflectance reduces with increase in number of pulses incident on the surface. Although it represents a generic trend, it should not be taken on its face value. As the number of pulses per spot increase, the size of the structures increases as a result of higher amount of material removal. Damage to the surface also increases with number of pulses. Figure 6(b) shows a trend where reflectance decreases with increase in size of surface structures up-to a point and starts increasing thereafter. Therefore, it is crucial to keep the size of the surface structures around 10 µm as a thumb rule.

Figure 5 Reflectance values of the sample with respect to wavelength at 350 pulses per spot and average size of the structures at around 9 µm

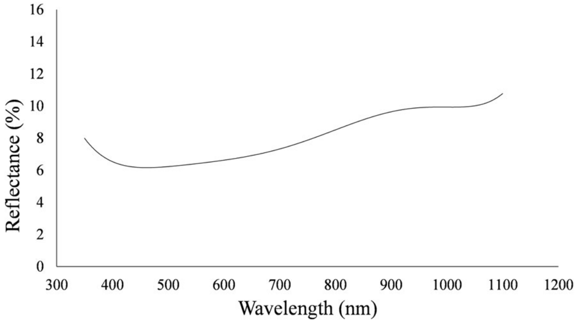
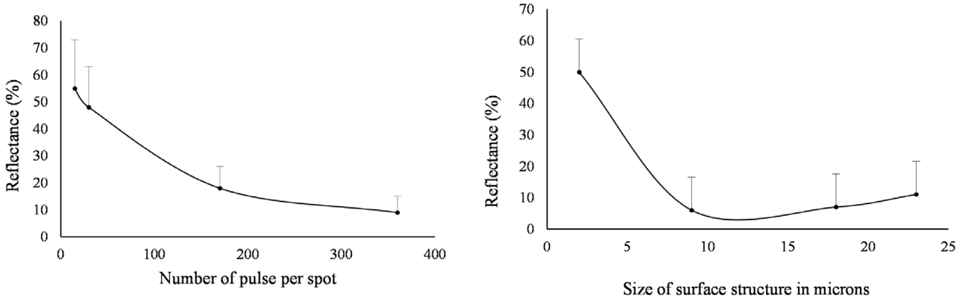


Figure 6 Variation in reflectance with, (a) number of pulses per spot (b) size of surface structures



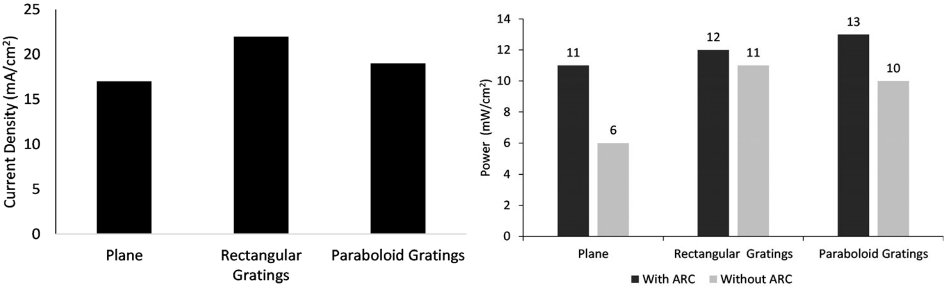
(a) (b)

4.3 Electrical properties

The electrical performance of the textures was simulated for two properties, the maximum power generated and current density. Figure 7 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 current density (J), the rectangular gratings appear to have an edge over the wave gratings and planar surface conditions.

The electrical simulations clearly suggest that 2D gratings can perform much better than no surface feature (i.e., smooth surface) due to its superior optical behaviour (measured in experimentation). Another point that can be inferred here is that although the optical performance is much enhanced, the electrical 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 electrical perspective.

Figure 7 Simulated values of (a) current density and (b) power density for different types of surfaces



(a) (b)

5 Conclusions

Picosecond lasers can be used to generate textures on Si wafer to enhance optical performance for applications in solar photovoltaics. In this work, 2D textures of different sizes and shapes were fabricated by varying the process parameters such as scanning speed and pitch, which is distance between two consecutive scanning lines. The shape of the textures resembled square and wave-like gratings with sizes between 1–40 µm that were strongly influenced by scanning speed and pitch. The shapes of the textures were close to square gratings at lower values of scanning speed. The observed reflectivity varied with different kinds of textures, with a minimum value of as low as 6%. The minimum reflectance decreased with a decrease in scanning speed for the range of values considered in this work. The obtained reflectance when mapped with the size of the textures suggested that their size should be around 10 µm for optimal optical performance. The simulated values of electrical properties using FDTD simulations for square and wave-like gratings reveal that both current density and power generation is higher when the structures resemble wave-like gratings. Therefore, it is concluded that for a optimal optical and electrical properties, the textures should be square gratings with sizes of the features around 10 μm.

Acknowledgements

The authors would like to express their gratitude towards NCPRE, Indian Institute of Technology Bombay and Prof Duraiselvam (Department of Production Engineering, National Institute of Technology Trichy) for extending their help in conducting the experiments. The authors would also thank Professor Suhas Joshi (IIT Bombay) for his valuable suggestions and feedback on the work.

References

Abdullah, M.F., Alghoul, M.A., Hameed, N., Nilofar, A., Shideh, A., Yatim, B. and Sopian, K. (2016) 'Research and development efforts on texturization to reduce the optical losses at front surface of silicon solar cell', *Renew. Sustain. Energy Rev.*, December, Vol. 66, pp.380–398.

Binetti, S., Le Donne, A., Rolfi, A., Jäggi, B., Neuenschwander, B., Busto, C., Frigeri, C., Scorticati, D., Longoni, L. and Pellegrino, S. (2016) 'Picosecond laser texturization of mc-silicon for photovoltaics: a comparison between 1,064 nm, 532 nm and 355 nm radiation wavelengths', *Applied Surface Science*, Vol. 371, pp.196–202.

Cotter, J.P., Zeimpekis, I., Kraft, M. and Hinds, E.A. (2013) 'Improved surface quality of anisotropically etched silicon {111} planes for mm-scale optics', *Journal of Micromechanics and Microengineering*, 21 October, Vol. 23, No. 11, p.117006.

Ezhilmaran, V., Vasa, N.J., Vijayaraghavan, L. and Krishnan, S. (2019) 'Femtosecond laser assisted generation of micro-dimples on moly-chrome film for improving its tribology', *International Journal of Precision Technology*, Vol. 8, Nos. 2–4, pp.261–278.

Fauchet, P.M. and Seigman, E. (1982) 'Surface ripples on silicon and gallium arsenide under picosecond laser illumination', *Appl. Phys. Lett.*, 1 May, Vol. 40, No. 9, pp.824–826.

Gangopadhyay, U., Dhungel, S.K., Basu P.K., Dutta S.K., Saha, H. and Yi, J. (2017) 'Comparative study of different approaches of multi-crystalline silicon texturing for solar cell fabrication', *Sol. Energ. Mat. Sol. Cells*, 15 February, Vol. 91, No. 4, pp.285–289.

Her, H.R., Finlay, R.J., Wu, C., Deliwala, S. and Mazur, E. (1998) 'Microstructuring of silicon with femtosecond laser pulses', *Appl. Phys. Lett.*, Vol. 73, No. 12, pp.1673–1675.

Horn, A., Kalmbach, C.C., Moreno, J.G., Schütz, V., Stute, U. and Overmeyer, L. (2012) 'Laser-surface-treatment for photovoltaic applications', *Phys. Procedia*, Vol. 39, pp.709–716.

Li, J. and Yu, H. (2011) 'Texturing of crystalline Si thin film solar cells via nanostructure to boost efficiency', *International Journal of Nanoparticles*, Vol. 4, Nos. 2–3, pp.284–306.

Ma, Y., Si, J., Sun, X., Chen, T. and Hou, X. (2014) 'Progressive evolution of silicon surface microstructures via femtosecond laser irradiation in ambient air', *Appl. Surf. Sci.*, 15 September, Vol. 313, pp.905–910.

Martins, E.R., Li, J., Liu, Y., Depauw, V., Chen, Z., Zhou, J. and Krauss, T.F. (2013) 'Deterministic quasi-random nanostructures for photon control', *Nat. Commun.*, 24 October, Vol. 4, No. 1, pp.1–7.

Nandy, S., Bhattacharya, S., Das, S., Jana, S. and Gangopadhyay, U. (2017) 'Multicrystalline silicon texturing by novel bi-component etching solution', *Mater. Today Proc.*, Vol. 4, No. 14, pp.12671–12677.

Park, K.M., Lee, M.B. and Choi, S.Y. (2015) ‘Investigation of surface features for 17.2% efficiency multicrystalline silicon solar cells’, *Sol. Energy Mater. Sol. Cells*, 1 January, Vol. 132, pp.356–362.

Patel, D.S., Jain, V.K., Shrivastava, A. and Ramkumar, J. (2019) ‘Electrochemical micro texturing on flat and curved surfaces: simulation and experiments’, *The International Journal of Advanced Manufacturing Technology*, Vol. 100, No. 5, pp.1269–1286.

Rahang, M. and Patowari, P.K. (2015) ‘Application of masking technique in EDM for generation of rectangular shaped pattern’, *International Journal of Precision Technology*, Vol. 5, No. 2, pp.140–156.

Yi, Y., Guo, W. and Peng, Y. (2018) ‘Enhancement of light trapping for thin film solar cells’, *MRS Adv.*, May, Vol. 426, pp.1–6.

Yilbas, B.S., Ali, H., Khaled, M., Al-Aqeeli, N., Abu-Dheir, N. and Varanasi, K.K. (2015) ‘Characteristics of laser textured silicon surface and effect of mud adhesion on hydrophobicity’, *Applied Surface Science*, 1 October, Vol. 351, pp.880–888.

Zolper, J.C., Narayanan, S., Wenham, S.R. and Green, M.A. (1989) ‘16.7% efficient laser textured, buried contact polycrystalline silicon solar cell’, *Appl. Phys. Lett.*, Vol. 55, No. 22, pp.2363–2365.