Contents list available at IJRED website

Int. Journal of Renewable Energy Development (IJRED)

Journal homepage: https://ijred.undip.ac.id

Research Article

Investigations on the Influence of Surface Textures on Optical Reflectance of Multi-crystalline Silicone (MC-Si) Crystal Surfaces-Simulations and Experiments

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Abstract MC-Si is the most widely used material for making solar PV cells. In spite of the considerable research on improving the conversion efficiency of MC-Si solar PV cells still it remains well within the range of 15-20%. Optical reflectance being the major loss of incident solar energy, efforts are being made to reduce the optical reflectance of solar cell surfaces. Among the several methods proposed, creation of well-defined surface topography on the cell surface remains a promising option. Micro/nano level features with various dimensions and distributions have been created on MC-Si crystal surfaces using a femto-second pulsed laser and the influence of surface topography on optical reflectance in the incident light wave length of 350 – 1000 nm have been studied and compared with the simulation results obtained using OPAL2 software. Experimental results indicate that surface textures on the wafer surface lead to the reduction of optical reflectance in the range of 20-35% in comparison with plain surface. Width of micro grooves have less significant effect on the optical reflectance in comparison with pitch between the micro grooves. Best reduction in reflectance is exhibited by the texture having a groove width of 30 μm and a pitch of 100 μm. A post texturing etching operation is found to have detrimental effect on the ability of micro/nano level features in decreasing the optical reflectance in the preferred wavelength of solar spectrum due to the flattening of nano level features created within the micro grooves due to laser texturing.

Keywords: Laser texturing, Surface texture, Etching Multi crystalline Silicone, Reflectance

Article History: Received: 24th May 2021; Revised: 26th Nov 2021 2021; Accepted: 28th Dec 2021; Available online: 10th January 2022
How to Cite This Article: Ullattil, S., Kakkarath, S., Sudheesh K., Viswambharanunnithan, V., Ramannair, S.P. (2022). Investigations on the Influence of Surface Textures on Optical Reflectance of Multi-crystalline Silicone (MC-Si) Crystal Surfaces-Simulations and Experiments. *Int. J.of Renew. En. Dev.*, 11(2), 375-383
https://doi.org/10.14710/ijred.2022.38538

1. Introduction

MC-Si is an attractive material for solar cells owing to its low production costs. Hence the use of MC-Si in the world photovoltaic industry is steadily increasing over the years. Abundant availability; high purity and comparatively high conversion efficiency are the major reasons for the dominance of crystalline silicon in the photovoltaic application. The performance of a solar cell is measured in terms of its efficiency at turning sunlight into electricity (Zhao *et al.* 1999) and this is influenced by several factors (Tripathi *et al.*, 2017). The efficiency of PV cells can be increased by a variety of methods like using photonic band gap materials, proper orientation of PV panels, reducing the temperature of PV cells, using anti reflection (AR) coatings and by texturing the surface of silicon wafer. The efficiency of silicon solar cell made of either mono crystalline or MC-Si material depends on the minimization of reflectance losses, since most of the sun light incident on the PV cell gets reflected back (Srivastava *et al.* 2015). The reflectance can be reduced by the process of texturization of the surface of silicon wafer. Micro features are generated on the surface of silicon wafer by various texturization techniques like acid texturization, etching in alkaline solutions, reactive ion etching (RIE) (Liu *et al.* 2014).

Black surface MC-Si wafer, which is generated by the nano-texturing using silver assisted wet chemical etching created an anti-reflective surface with less reflectance increases the photocurrent while reducing the open circuit voltage (Srivastava *et al.* 2012). Reactive ion etching minimized the loss of huge amount of silicon due to the saw damage and texturing (Yoo *et al.* 2013 and Yoo *et al.* 2011). The combination of acidic and RIE textured surface and high sheet resistance emitters gave a significant progress in the short wavelength optical response (Liu *et al.* 2014). Absorption of infrared rays from the incident sun light is shown to be enhanced by texturing both the front and back sides of the silicon wafers (Forbes, 2012). Honeycomb like textured surface created using a masked wet etching process demonstrated an enhancement in the conversion efficiency of solar cells (Hong 2016).

Most of the methods used for texturing mono crystalline silicon are inefficient for MC-Si due to the

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IJRED-ISSN: 2252-4940.Copyright © 2022. The Authors. Published by CBIORE

random distribution of grains having different crystallographic orientation (Gao *et al.* 2014). In such condition laser texturing is the better alternative to overcome this problem while using MC-Si wafer for PV cell fabrication. Laser surface texturing process is non-contact, which has better flexibility and good spatial resolution compared to other texturing methods (Sudeep *et al.,* 2014; Zeilke *et al.* 2012; Ruby et al. 2008). Various transverse modes influence the laser surface treatment as the lower order transverse mode suits the precision surface treatment and the higher depth texturing requires a higher order transverse mode (Dobrzański & Drygała 2007). The mechanism of light trapping in laser textured surface occurs through multiple reflections of sunlight within the micro patterns which leads to maximum achievable absorption of sun light (Iyengar *et al.,* 2010). Optical and electrical characteristics of laser textured silicon wafer are as good as conventional texturing methods (Malcolm, 2006 and Jeffrey, 2006). The major limitation of laser surface texturing is the formation of laser induced defects. This is due to the presence of heat affected zones in the vicinity of micro features which can have influence on the mechanical (Sudeep et al. 2014) and electrical properties (Dang *et al*., 2014; Pourakbar Saffar *et al.,* 2014; Binetti *et al.,* 2016). However, by using lasers having ultra-short pulse duration, this effect can be minimized. Another major laser induced effect on semiconductor is the thermally propagated dislocations which enhance minority carrier recombination within the silicon wafers (Dang *et al.* 2014). A decrease in open-circuit voltage and fill factor occur due to these lasers induced effects (Binetti *et al.* 2016). In addition to the above methods, new processing techniques including are also evolving for improving the performance of solar PV cells and energy storage (Hamdani *et al.,* 2022; Zhu *et al.,* 2012; Zhu *et al*., 2012; Reddy *et al.,* 2020)

It can be concluded from the literature review that laser texturing has potential to improve the conversion efficiency of MC-Si PV solar cells. However still research is ongoing by using novel creation of polydimethylsiloxane (PDMS) layers (Chuqi Yi *et al.* 2020) finding the best suitable shape of micro/nano features (Kim et al., 2021) which can impart beneficial effects and also through thermal processing (Jung *et al*., 2021) Understand the effects of laser induced defects on the performance of textured PV cells is also significant (Abdul Razak *et al.,* 2020). The additive-free acid-based texturing method to create uniform porous silicone layer is also reported (Sreejith *et al*., 2019). The wider commercial adoption of the technology has not come so far to the best of our knowledge despite the potential. Hence the objectives of the present work are to create micro grooves having laser induced periodic surface structures in them having the wavelength of the order of few nano meters enabling the multiple internal reflections and to study experimentally the parametric influence of features in terms of groove width and pitch on the reductions of optical reflectance in the solar radiation wavelength of interest i.e. 350-1000nm. Micro/nano level features on MC-Si wafer-suitable for production of PV cells are created with the help of a femto-second pulsed Nd-YAG laser and its optical reflectance have been studied with the help of a spectro-photometer having integrating sphere. Simulation studies have also been carried out before experiments to ascertain the influence of micro topography on optical reflectance for the range of light spectrum involved. Micro grooves of specific width and pitch having nano level periodic structures are found to have the ability to reduce the reflectance significantly of the order of 35% in comparison with the plain surface.

2. Materials and Methods

2.1 Simulation studies on the optical reflectance of MC-Si surface due to surface textures

We used OPAL 2 software which is an optical simulator that computes the optical losses associated with the front surface of a Si solar cell when exposed to sun light of required spectral range. This open source software is provided by PV Light house. For the defined structure of solar cell surface, the OPAL 2 calculates the reflection from the front surface, the absorption in the thin-film coatings and the transmission into the substrate over a selected range of wavelength of solar spectrum.

2.1.1 Geometric model of the Structure

The optical structure of a wafer, has been selected by, front and rear texture morphology, materials for surrounding material i.e. air, front thin film coatings and thicknesses i.e. SiN_x), substrate material and thickness (silicon wafer) and rear thin film coatings and thicknesses. Then the wafer ray tracer computes the optical losses and photo current generation in the given range of wavelengths. Front surface morphology of samples are designated by different sized micro features viz. v-grooves of different width in addition to the sample having planar front surface, which is considered as the reference sample. Then the optical losses from the front surface including reflectance, absorbance and transmittance are computed. The optical losses are computed over the wavelength range of 350nm to 1000nm.

2.1.2 Simulation procedure

Totally 50,000 rays are traced in the process of optical losses computation. Monte-Carlo algorithm is used in the simulation, which results in output uncertainties. These uncertainties are reduced by increasing the number of rays. This is achieved by convergence studies where the number of rays are progressively increased to 50,000 when the results are converged. The width of micro features are selected as 30, 40 and 50 µm respectively. The optical losses from the front surface of MC-Si samples that have a planar and textured with grooves are calculated at AM 1.5 standard conditions (Gulomov J *et al*., 2021). The air mass coefficient defines the direct optical path length through the Earth's atmosphere. AM 1.5 standard condition is defined corresponds to a solar zenith angle of $z = 48.2^0$.

For each sample, the percentage reflectance for each wavelength and corresponding graphs is obtained as output from the simulation software. Then the optical losses viz. effective reflectance and effective absorbance of each sample is determined using the formulae (1) and (2).

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$$R_{eff} = \frac{\sum_{350}^{1000} R(\lambda).N(\lambda).d(\lambda)}{\sum_{350}^{1000} N(\lambda).d(\lambda)} \quad (1)$$

$$A_{eff} = \frac{\sum_{350}^{1000} A(\lambda).N(\lambda).d(\lambda)}{\sum_{350}^{1000} N(\lambda).d(\lambda)} \quad (2)$$

Where R (λ) – % reflectance, A (λ) – % absorbance and N (λ) - the solar flux under AM1.5 standard conditions. In the calculation of effective reflectance, spectral irradiance of sun is taken to account.

2.2 Creation of surface textures on MC-Si wafer

The various processes carried out in stages during the experimental study are described herein. Work material used in the experiment, machining processes involved in the study like laser surface texturing, wet chemical etching, analysis of surface topography features and parametric studies are described followed by the effect of surface textures on the reflectance are explained.

2.2.1 Description of specimen

The work material used to study the effect of surface texturing on the surface reflectance is the boron doped p-type MC-Si wafer. Table 1 shows the specifications and Fig 1 shows the commercially polished and un-polished sides of MC-Si wafer that is taken as the work specimen.

2.2.2 Surface texturing

A femto second pulsed Nd: YAG laser has been used in the present study for texturing purpose. The selection of the type of laser was based on the literature (Malcolm & Jeffrey 2006) The laser parameters used for micro machining are indicated in Table 2. The initial attempt was to understand the correlation between laser parameters viz. number of pulses and the dimensions of the resulting micro/nano features. For this purpose, longitudinal micro grooves with definite pattern have been machined on the wafer surface. Dependence of number of passes of pulsating laser beam on the dimension of grooves created in patches on the surface of MC-Si wafer has been studied. The groove width for different number of passes is measured and analyzed by machining rectangular patches of micro-grooves on the circular disk-shaped specimen

2.2.3 Chemical etching

Wet chemical etching using 20% Potassium Hydroxide (KOH) solution is used. Etchant solution is a mixture of Potassium Hydroxide, Iso-propyl alcohol and distilled water. Concentrations of constituents are adjusted using the standard procedure. Etchant solution is prepared by mixing 20% wt. of KOH (117.645 g) in 500ml of distilled water. After the complete dissolution of KOH in water, 10% vol. of iso-propyl alcohol (63.6ml) is added to the mixture. The chemical etching process is carried out at a fixed temperature of 70^0C and for a time of 15 minutes. Here the sample is inserted into the solution at the time when the temperature reaches at 70^0C after proper masking. The layer of laser induced defects from the textured surface is removed through etching process. Thus, a uniform structured texture is obtained as a result of laser processing and subsequent etching process.

Table 1
Specifications of work specimen

Type	p-type MC-Si wafer
Dopant	Boron
Size	3 inches diameter
Orientation	(100) (hkl)
Thickness	275 µm
Resistivity	10 ohm-cm
Nature of surface	Single side polished

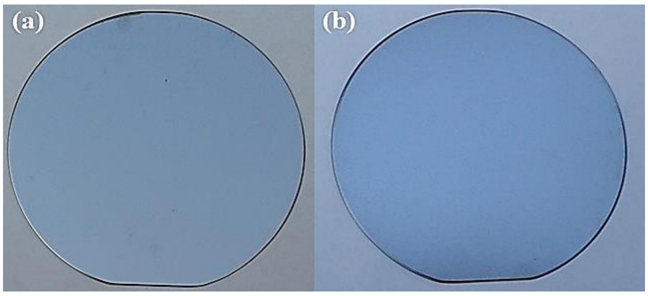

Fig. 1 MC-Si wafer sample a) polished side b) un-polished side

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Table 2
Laser parameters of pulsed Nd: YAG laser used in the experiment

Laser parameters	Corresponding values
Pulse repetition frequency	20 KHz
Laser wave length	1064 nm
Pulse duration	10 ns
Diameter of laser spot	7μm
Maximum power output	4.5 W

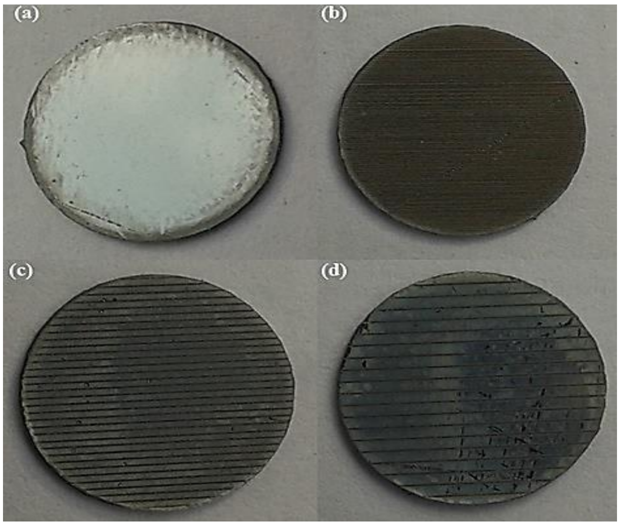

Fig.2 Samples that are a) plain b) textured with a groove width of 30μm and pitch of 100μm c) textured with a pitch of 300 μm and groove width of 30 μm d) textured with a pitch of 500 μm and groove width of 30 μm

2.3 Optical reflectance measurement

The two different parameters viz. groove width and pitch are fixed as 30 μm, 40 μm, 50 μm and 100 μm, 300 μm, 500 μm respectively for the evaluation of optical reflectance. Two identical samples are prepared for each groove width with a constant pitch of 100 μm. Similarly two identical samples for a fixed pitch with a constant groove width of 30 μm are also prepared. Among the two identical samples for each groove width and pitch, one sample is subjected to chemical etching to study the influence of etching on surface reflection in association with texturing. The samples are cut into a standard size of 1 cm diameter disk so as to enable the reflectance measurement. Fig 2 (a) - (d) shows the samples that are plain, textured with a groove width of 30 μm and pitch of 100 μm, textured with a pitch of 300 μm and textured with a pitch of 500 μm, both with a constant groove width of 30 μm respectively.

3. Results and Discussion

3.1. Analysis of the simulation results

Fig 3 (a) & (b) shows the percentage reflectance graphs obtained as output from the software for plain sample, samples having a grooved front surface morphology with a groove width of 30 μm, 40 μm and 50 μm respectively.

Consolidated results of effective reflectance and effective absorbance for all the sample specimen are calculated and indicated in Table 3. The results obtained from the Fig.3 and Table 3 show that the presence of surface micro features results in substantial decrease and increase in the value of effective reflectance and effective absorbance compared to the sample with planar surface topography. The results show the trend reported elsewhere (Dobrzański & Drygała, 2007)

The micro features created on the surface of MC-Si sample results in multiple hitting of same rays on the surface. This multiple hitting increases the quantity of absorbed photons. As a result, the effective absorbance increases and simultaneously the effective reflectance decreases. The results obtained from the graphs show that there is only a slight increase and decrease in effective reflectance and effective absorbance respectively for the case of width of micro features. This means the change in width of micro features has less significant effect on the reflection and absorption of light on crystalline silicon samples. That means the proportion of lights which enters each area accounting for the total area does not have a noticeable change.

Table 3
Laser parameters of pulsed Nd: YAG laser used in the experiment

Laser parameters	Corresponding values
Pulse repetition frequency	20 KHz
Laser wave length	1064 nm
Pulse duration	10 ns
Diameter of laser spot	7μm
Maximum power output	4.5 W

Table 4
Consolidated dimensions of micro grooves obtained

No of passes	Groove width before etching (μm)	Groove width after etching (μm)
2	21.5	25.9
4	33.3	37.1
6	38.1	43.2
8	43.3	46.3
10	46.3	50.9
12	52.2	53.8

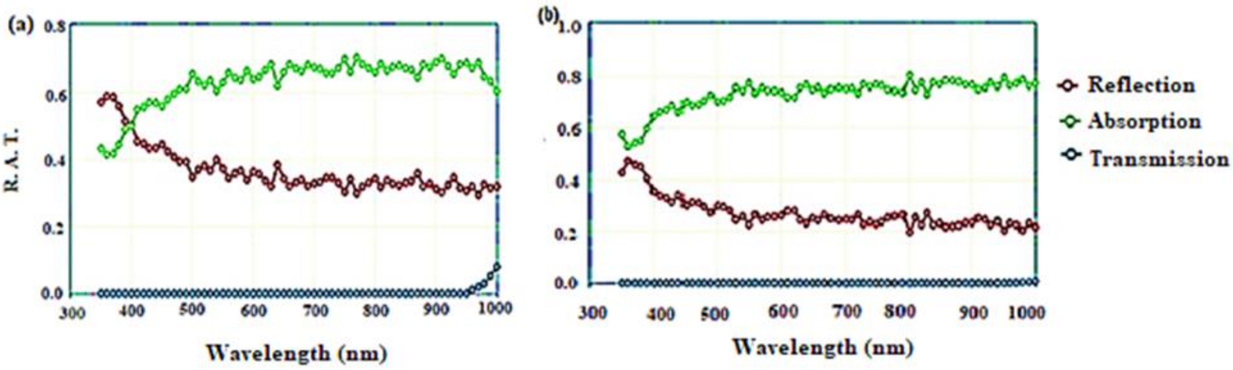

Fig 3. Percentage reflectance graphs for a) plain sample, (b) samples having a grooved front surface morphology with a groove size of 30μm

From the results reported herein, it is seen that the optical losses from the samples that have the presence of various surface micro features is less when compared with that of the sample having planar front surface. Increase in the size of micro features results in slight increase in effective reflectance and slight decrease in effective absorbance which indicates that the change in size of micro features has no significant effect on the absorption and reflection of light on crystalline silicon samples. It is inferred that the area coverage of groves is significantly less than the surface area of the Si samples. The change in effective area coverage due to the increase in width of grooves being negligible, do not contribute towards the increase in reflectance.

3.2 Analysis of surface topography features

Surface of the machined silicon wafer is analysed by using a 3D confocal microscope (Olympus LEXT OLS4000), to study the effect of laser machining parameters on the dimensions and shape of micro features.

Table 4 shows the consolidated dimensions of micro grooves (groove width), created by varying the number of passes. It is observed that the groove width ranges from 21.5 μm to 52.2 μm when the number of passes varied from 2 to 12. This is due to the continuous ablation of material from the surface during each pass by keeping the power constant. The crystal surface is etched for removing the bulges along the grooves resulted during the re-solidification of ablated molten Si.

Fig 4 (a) and (b) shows the surface topography images of the plain sample and the textured sample having a groove width of 30 μm and a pitch of 500 μm respectively. The grooves contain periodic surface structures of nanometre wavelength due to the laser matter interaction and re-solidification.

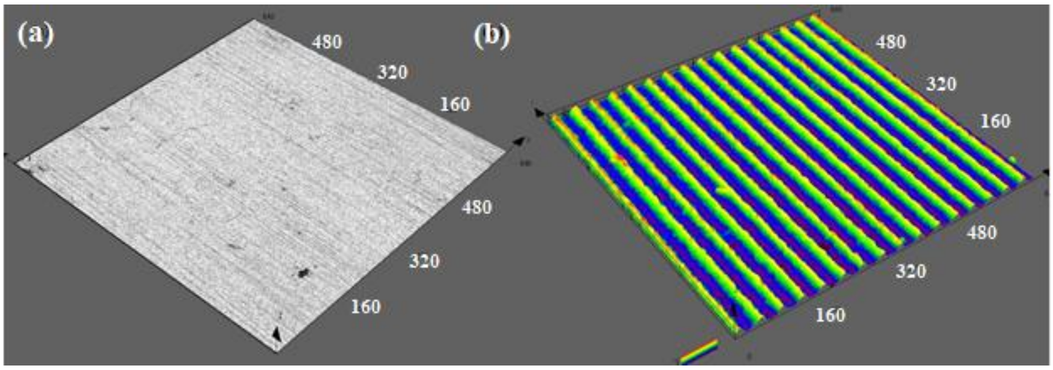

Fig.4 Surface topography images of a) Plain sample, textured samples with a groove width of b) 30 µm

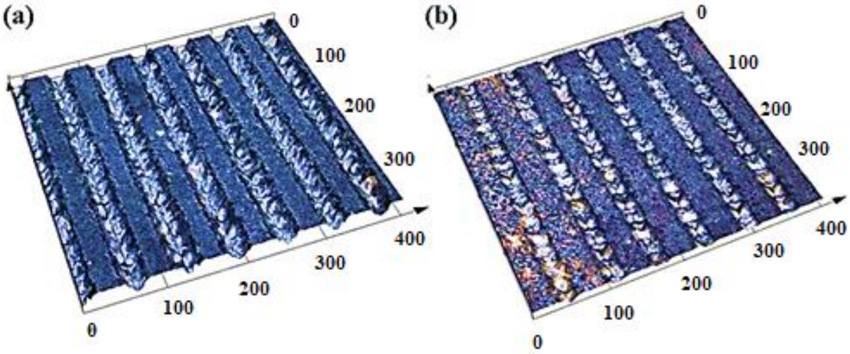

Fig.5 Surface topography images of a) textured and etched sample with a groove width of 30 µm b) textured and etched sample with a groove width of 40 µm

Similarly, Fig 5 (a) and (b) indicates the surface topography images of textured and etches samples with a groove width of 30 µm and 40 µm respectively. The etching process has resulted in removal of laser induced defects from the vicinity of grooves, but at the same time has resulted in flattening of the nano structures resulted due to melting and solidification of the Si material in the micro grooves due to interaction with high energy laser beam.

3.3. Reflectance measurement of prepared samples

The reflectance of both plain and textured silicon wafer samples are measured using Specord S600 UV-V spectrophotometer with an integrating sphere. The wavelength range has been selected as 350 to 1000 nm coinciding with the solar radiation spectral range corresponding to maximum energy.

3.3.1 Effect of groove width and pitch of textured surfaces on optical reflectance

Laser surface texturing creates grooves on the surface of silicon wafer, which enhances the number of absorbed photons through multiple internal reflections which results in a lower effective reflectance loss.

The reflectance curves for the plain sample and samples textured with a groove width of 30 µm, 40 µm, 50 µm and pitch of 100 µm, 300 µm, and 500 µm are shown in Fig 6 and Fig 7 respectively. The variation in reflectance against spectral range of 350-1000nm which is the range of interest in the case of solar PV cells are plotted and compared with plain specimen. The results reported are following the trends reported by (Dobrzański L.A. & Drygała, A. 2007) adopting specimen with textures where the patterned surfaces have exhibited significant reductions in reflectance in the 300- 1000nm wavelength region of spectrum.

The results obtained from the graphs indicate that the optical reflectance of the plain samples are much higher than all textured samples. The trend observed in the result is in line with the results reported in literature (Malcolm & Jeffrey 2006) where the reductions in reflectance is observed for the case of plain and textured samples with an increase in groove depth. It is also observed that the optical reflectance is minimum in the range of 500 – 650nm after which the reflectance tend to increase. This is due to the matching of nano feature wavelength (which is of the order of 500-650nm) with the wavelength of the radiation causing maximum internal reflections. Only a slight increase in reflectance is seen with the increase in groove width from 30µm to 50µm. This means that the change in width of textured grooves has less significant effect on the reflection of light from the MC-Si samples. The reflection area may change very little with the change in width of micro grooves. That means the proportion of light rays which enters into each groove does not have a noticeable change. Whereas the increase in pitch of grooves results in increase of optical reflectance in the range of 350 – 500nm and subsequently higher pitch has resulted in slight drop in reflectance, since the increase in pitch decreases the net surface area of textured region which has resulted in the escalation of optical reflectance, this effect appears profound in the lower wavelength range. Another effect is that of the wavelength of laser induced periodic surface structures (LIPSS) in the grooves. The wavelength of these LIPSS are of the order of a part of the wavelength of solar radiation. This effect appears more profound in the lower wavelength region of the spectrum as the wavelength of nano features are in the same order of 350nm-500nm. This causes light rays to undergo multiple internal reflections causing light to get absorbed rather than to get reflected.

3.3.2 Effect of etching of textured samples on optical reflectance

Table 5 shows the effect of chemical etching on optical reflectance of laser textured MC-Si wafer along with plain and textured non etched samples. From the graph it is seen that the post-laser texturing etching increases the optical reflectance of the samples because applied etching procedure causes the nano level textures to flatten out which enhanced reflectance. Literature reported that post laser texturing, longer etching time has resulted in increase in reflectance (Dobrzański & Drygała, 2007). The post texturing removal of laser ablated portions are to be removed in order to avoid surface recombination in solar cells however this has resulted in very less increase in reflectance (Abdul Razak *et al*., 2020).

From the results reported herein, it is seen that the optical reflectance of textured sample is less when compared with that of the plain sample which indicates that the surface textures reduce the optical reflectance of MC-Si wafer. Maximum percentage reduction in effective reflectance is achieved by texturing the samples with a groove width of 30 µm and pitch of 100 µm (35%). Similarly the lowest reduction in percentage reflectance is achieved by texturing with a pitch of 500 µm with a constant groove width of 30 µm (22.7%). These results indicate that laser surface texturing on the surface of MC-Si wafer leads to the reduction of optical reflectance in the range of 20-35%. Increase in groove width is found to have less significant effect on the effective reflectance whereas the increase in pitch of grooves results in increase in effective reflectance. For all sample pairs textured with same surface parameters, there is less percentage reduction in effective reflectance in comparison with their corresponding non etched samples

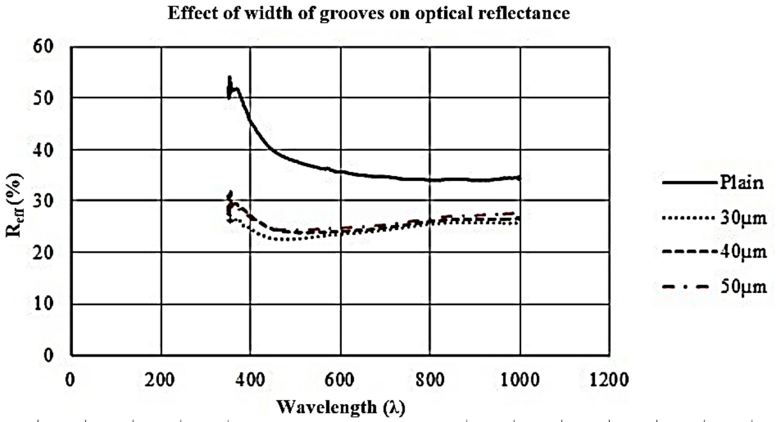

Fig.6. Effect of width of textured grooves on optical reflectance

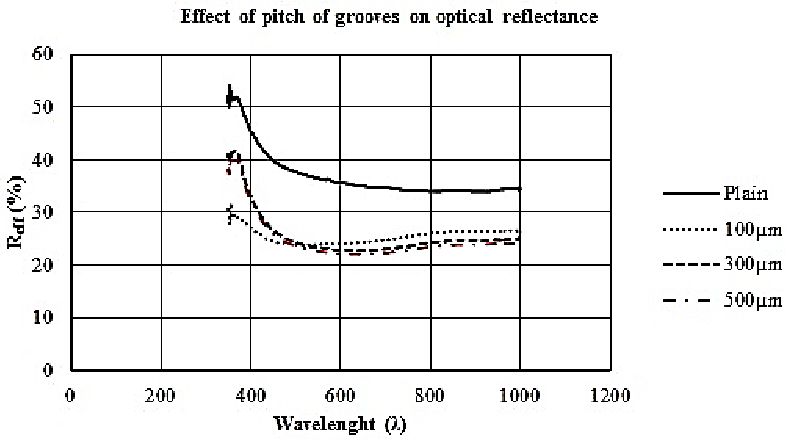

Fig.7 Effect of pitch of textured grooves on optical reflectance

Table 5
Percentage reduction in effective reflectance

Surface Parameter	Nature of Sample	R_{eff} (%)	% Reduction in optical reflectance due to laser texturing and etching process
Groove width (with constant pitch of 100 µm)	30 µm Textured	24.22	35
	30 µm Textured and Etched	25.41	31.8
	40 µm Textured	25.25	32.2
	40 µm Textured and Etched	28.82	22.6
	50 µm Textured	25.68	31
	50 µm Textured and Etched	28.1	24.5
Pitch (with constant groove width of 30 µm)	100 µm Textured	24.22	35
	100 µm Textured and Etched	25.41	31.8
	300 µm Textured	27.52	26.1
	300 µm Textured and Etched	30.6	17.8
	500 µm Textured	28.77	22.7
	500 µm Textured and Etched	35.86	3.75

4. Conclusion

The optical reflectance from the samples that have the presence of various surface micro features is less when compared with that of the sample having planar front surface (In the range of 20-35 %). Change in width of micro grooves has no significant effect on the reflection of light from the crystalline silicon samples whereas the increase in pitch of grooves results in an increase in effective reflectance. It is due to the significant decrease in effective area of textured surface due to increase in pitch. For all the pairs textured and etched with same surface parameters, there is higher reflectance in comparison with their corresponding non-etched samples. This could be due to the reason that etching flattened the laser induced periodic nano structures present in the micro grooves. The presence of this nano level features having a wavelength of the order of 450-600nm are responsible for the total internal reflection of the incident radiation having the spectral components in the range of 350-1000nm.

Acknowledgement

Authors gratefully acknowledge the financial grant from Kerala state council for science technology and environment wide ETP/13/2017/KSCSTE -12/08/2018 in carrying out the research work

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