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Technical Communication

A New Approach to Characterizing Surface Texturing of Crystalline Silicon Wafers for High Efficiency Solar Cells Application

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Surface texturing of crystalline silicon (c-Si wafers) wafers is a frequently used technique in high efficiency solar cells processing to reduce the light reflectance. Measuring the surface texturing result is important in the manufacturing process of high efficiency solar cells because the surface texturing of c-Si wafers is sensitive to the performance of reducing front reflection. Traditional approach for measuring surface roughness of texturing of c-Si wafers is atomic force microscopy. The disadvantage of this approach include long lead-time and slow measurement speed. To solve this problem, an optical inspection system for rapid measuring the surface roughness of texturing of c-Si wafers is proposed in this study. The incident angle of 60° is a good candidate for measuring surface roughness of texturing of c-Si wafers and y = -188.26x + 70.987 is a trend equation for predicting the surface roughness of texturing of c-Si wafers. Roughness average (Ra) of texturing of c-Si wafers (y) can be directly determined from the peak power density (x) using the optical inspection system developed. The results were verified by atomic force microscopy. The measurement error of the optical inspection system developed is approximately 0.94%. The saving in inspection time of the surface roughness of texturing of c-Si wafers is up to 87.5%.

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Keywords: Optical inspection system, Texturing of c-Si wafers, Surface roughness

1. Introduction

Surface texturing of crystalline silicon (c-Si wafers) wafers is a frequently used technique in high efficiency solar cells processing to reduce the light reflectance [1-3]. Many successful methods based on texturing c-Si wafers surface utilizing alkaline solution, such as potassium hydroxide (KOH) [4] or sodium hydroxide (NaOH) [5] have been reported. These surface textures enhance the light trapping capability by reducing both reflectivity of lights trying to escape from the cells and coupling of lights into the cells [6-9]. Generally, the surface texturing of c-Si wafers is sensitive to the performance of reducing front reflection. Thus, measuring the surface texturing result is important for large-volume production of high efficiency solar cells in photovoltaic industry.

Conventionally, atomic force microscopy (AFM) is widely accepted as the standard to characterize the surface roughness of a sample due to the high spatial resolution of measurement [10, 11]. However, this approach includes certain disadvantages including long lead time before measurement, low measurement speed, and the significant influence of the radius of the stylus tip on the surface-roughness parameters. Meanwhile, the mechanical contact between the stylus and sample often causes damage. It is well known that the light scattering method has the main advantage of reliability and simplicity [12, 13]. To solve this problem, an optical inspection system for rapid measurement of the surface roughness of texturing of c-Si wafers is developed in this study. The effects of incident angle on the measurement accuracy of the surface roughness of texturing of c-Si wafers are discussed. The applicability of the surface-roughness value obtained using the optical inspection system developed is investigated and compared with AFM. The measurement error of the optical inspection system developed is also discussed.

2. Experiment

Fig. 1 shows a schematic illustration of the sample structure. The substrate is a (100)-oriented crystalline silicon wafer and has a size of about 10 ×10 mm^2. Before surface texturing, the samples were etched in 10% hydrofluoric acid (HF) to remove native oxide and rinsed in deionized water. The samples were then etched in KOH solutions and the experimental conditions for texturing of c-Si wafers were summarized in Table 1. The KOH solution was heated with a temperature-controlled hot plate and the temperature of the KOH solution could be controlled with an accuracy of ±5 ℃. After the etching process, the results of surface texturing were characterized using an AFM (Digital Instruments, Dimension 3100) in tapping mode at a scan rate of 1 Hz. The sampling area is chosen to be 3 μm ×3 μm. The rectangular Si tip operated at a resonant frequency of 322.656 kHz was applied as a probe at a spring constant of 40 N/m. All micrographs have been scanned in constant force mode at ambient temperature and pressure.

Fig. 2 shows a schematic illustration of the experimental setup for measuring the Ra (average value of surface roughness) surface roughness of texturing of c-Si wafers. A linear polarization He-Ne laser (output power 15 mW, Melles Griot 25-LHP-151-249) was used as a probe laser. The laser beam was directed to the sample with at an incident angle Θ, which was measured from the sample surface normal, and finally captured by the photodiode (frame rates= 30 fps), which was connected to a computer. The optical inspection system was placed on an anti-vibration optical table. The samples were mounted on a three-axis translation stage which allows the measured point of the sample to be accurately manipulated using a LabVIEW^{TM}-based interface. In order to ensure consistency of measurement, the measured position was chosen to be at the center of the sample surface for both the optical measurement and AFM measurement. The size of the incident laser beam is smaller than that of the sample. The peak power density scattered from the texturing of c-Si wafers was recorded using a powermeter (wavelength 260-1100 nm, OPHIR), which was connected to a computer. The measured time for each sample was fixed at 15 seconds. The maximum incident angle is 70° due to experimental limitations. Five incident angles used frequently, at 30°、45°、60°、65°、70° [14-18], were employed for evaluating the surface roughness of the texturing of c-Si wafers.

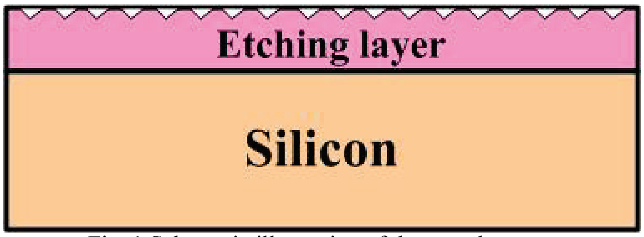


Fig. 1 Schematic illustration of the sample structure.

Table 1 Experimental conditions for texturing of c-Si wafers using KOH etching.

Sample No.	1	2	3	4	5	6	7
KOH (wt %)	0.5	0. 5	0. 5	1	1	1	2
Etching time (min.)	5	10	15	5	10	15	15
Temperature (℃)	90						

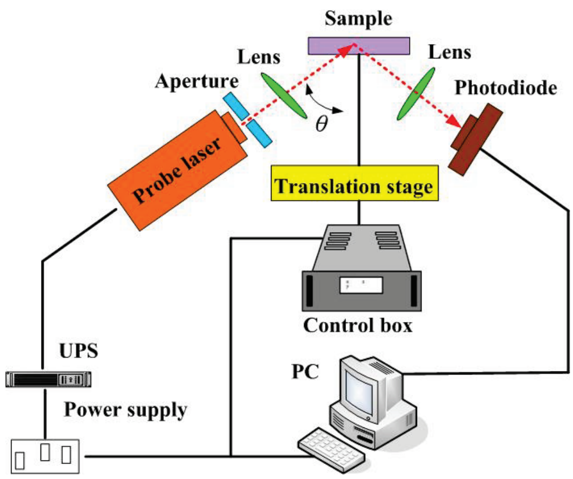


Fig. 2 Schematic illustration of the experimental setup for measuring surface roughness of texturing of c-Si wafers. Θ stands for the incident angle of the probe laser.

3. Results and discussion

To investigate the relationship between the scattered peak power density and surface roughness of the texturing of c-Si wafers, five samples (sample No. 2, 3, 4, 5, and 6) were investigated by both the optical method and the AFM measurement. Fig. 3 shows a sample with an isotropic surface and surface roughness (Ra) of 68.59 nm. Ra indicates the average value of surface roughness of texturing of c-Si wafers. To investigate the optimized incident angle for measuring the surface roughness of the texturing of c-Si wafers, five different incident angles (30°, 45°, 60°, 65°, and 70°) were selected. Before the optical measurement, a warm-up time of at least 30 minutes for probe laser is required [19-21]. Fig. 4 shows the peak power density as a function of measured time at different incident angles. The absorption of the sample for the He-Ne probe lase can be neglected because the value is very small. Two phenomena can be observed from these results. Firstly, texturing of c-Si wafers with different surface roughnesses in the nanometer (nm) scale can be accurately characterized based on the difference in the scattered peak power density. This means that there are statistical relations between surface roughness of texturing of c-Si wafers and the scattered peak power density from a rough surface. It is in good agreement with the primary assumption of the light scattering method, showing that Ra is significantly less than the wavelength of the He-Ne probe laser [22]. Secondly, there is less variation in the peak power density of the incident angle of 60°. The maximum variation of the peak power density values of different measurements is less than 1.01 %. This means that high repeatability of surface roughness measurement can be obtained using the proposed method. Fig. 5 shows surface roughness as a function of peak power density for different incident angles. Five trend equations can be obtained according to the curve fitting method. In general a higher R^2 value (maximum value=1) means a better accuracy of the trend equation [23]. As can be seen, the R^2 value of incident angle of 60° is close to 1. This result reveals that the incident angle of 60° is a good candidate for characterizing surface roughness of texturing of c-Si wafers and $y = -188.26x + 70.987$ is a trend equation for predicting the surface roughness of texturing of c-Si wafers.

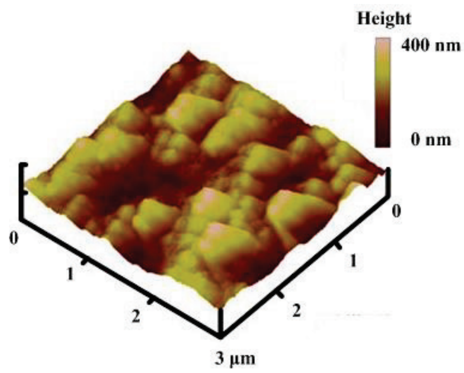
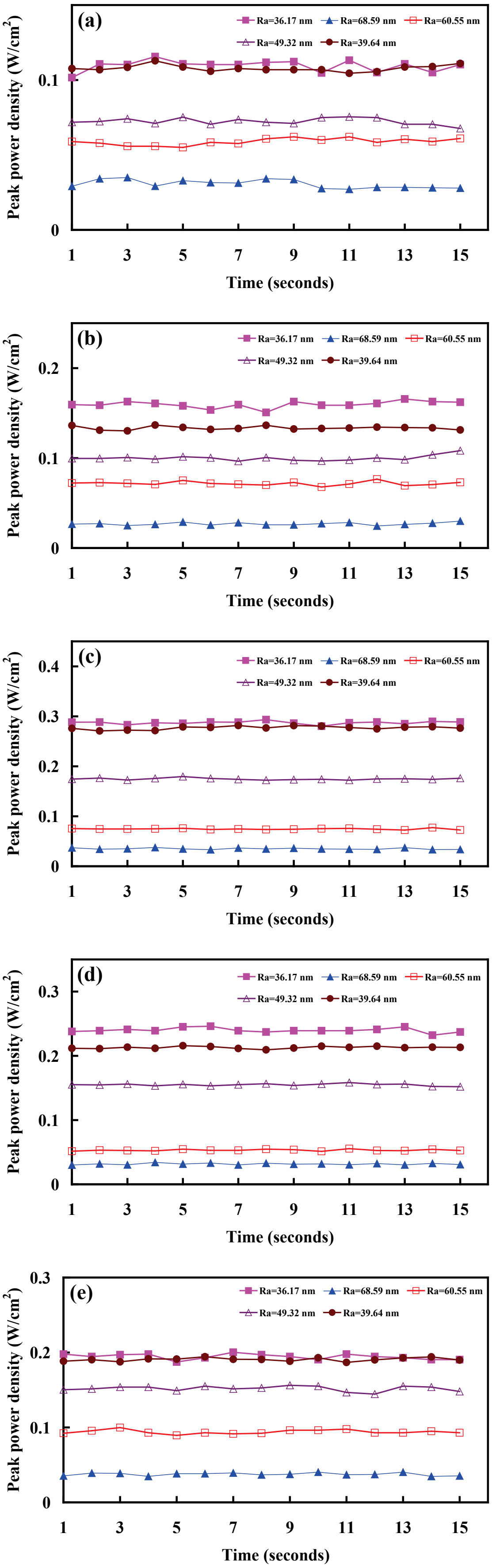


Fig.3 AFM image of texturing of c-Si wafers at an Ra surface roughness of 68.59 nm.

Fig. 4 Peak power density as a function of measured time at an incident angles of (a) 30°, (b) 45°, (c) 60°, (d) 65°, and (e) 70°.



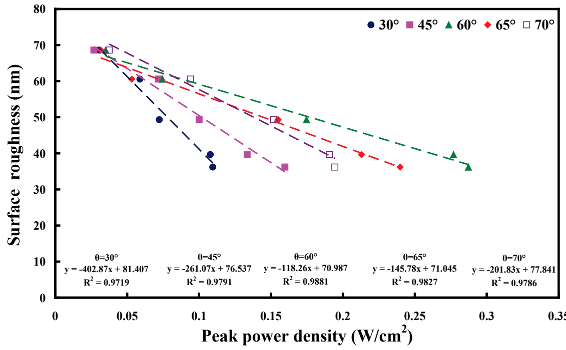


Fig. 5 Surface roughness as a function of peak power density at five different incident angles. Solid line indicates the trend equation to predict surface roughness of texturing of c-Si wafers.

To evaluate the measurement error of the optical inspection system developed, two samples (sample No. 1 and 7) were further investigated by both the optical method and the AFM measurement. Fig. 6 shows the results of surface roughness measurement obtained by the optical inspection system developed and the AFM measurement. The surface roughness of texturing of c-Si wafers obtained by the AFM measurement are 46.58 nm and 51.04 nm, while the result obtained by the optical inspection system developed at an incident angle of 60° are 45.93 nm and 50.67 nm. It is evident that the surface roughness of the texturing of c-Si wafers obtained by the optical inspection system show much better agreement with those obtained by AFM measurements. The measurement error is approximately 0.94%.This is confirmed by the corresponding AFM image shown in Fig. 7. This result reveals that the optical inspection system is highly accurate for measuring surface roughness measurement of texturing of c-Si wafers in the angstrom range. In general, the total working time for measuring surface roughness of texturing of c-Si wafers by AFM is approximately 40 minutes. However, the total working time is drastically reduced to approximately 5 minutes by the optical inspection system developed. It is noted that the saving in the inspection time of the surface roughness of texturing of c-Si wafers is up to 87.5%. In addition, the present experimental setup and measurement procedures are relatively simple and have fewer measurement-environment requirements. With the further use of motorized precision translation stages, the measurement process can be used for on-line and real-time quality control in the production of self-cleaning glasses. Thus this method provides better results than traditional attempts and it offers many advantages, such as high measurement speed and simplicity in experimental setup compared to traditional light scattering method [24], and non-destructive interaction. In addition, this optical system could be used for online inspection in the fabrication process of large-area solar cells when the etching process is changed to the method proposed by Chu et al. [25].

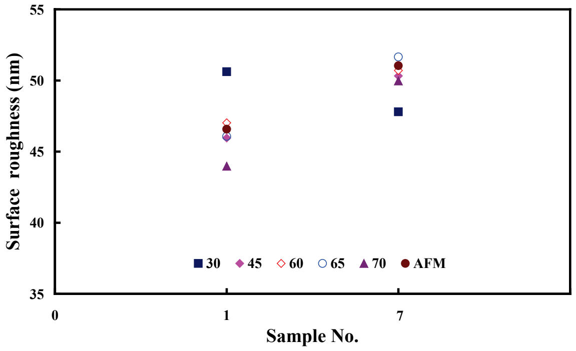


Fig. 6 Surface roughness obtained by the optical inspection system developed and the AFM measurement.

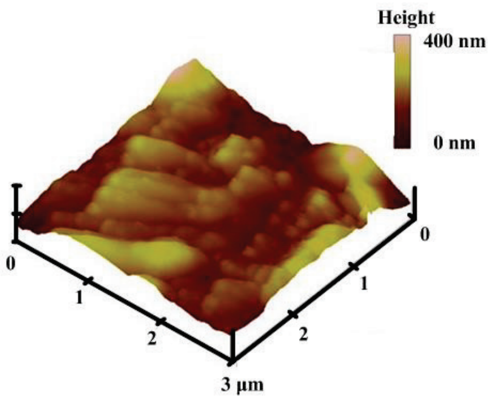


Fig. 7 AFM image of texturing of c-Si wafers at an Ra surface roughness of 46.58 nm.

4. Conclusions

An optical inspection system for rapid surface roughness evaluation of surface texturing results of c-Si wafers using KOH etching has been developed in this study. The advantages of this inspection system include high measurement speed and simplicity in experimental setup. The result obtained shows that surface roughness measurement of texturing of c-Si wafers in the nm scale can be accurately determined using the optical inspection system developed. An incident angle of 60° has been proved to be a good candidate for determining the surface roughness of texturing of c-Si wafers. Surface roughness of texturing of c-Si wafers (y) can be directly deduced from the peak power density (x) using the trend equation of $y = -188.26x + 70.987$. The measurement error of the optical inspection system developed is approximately 0.94%. The saving in inspection time of the surface roughness of texturing of c-Si wafers is up to 87.5%. This system can be used for the on-line and real-time quality control in the process for surface texturing of c-Si wafers using KOH etching.

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