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Enhanced Solar Cell Efficiency via Reflectance on Silicon Wafers: Laser Texturing vs. Anisotropic Etching

(Kecekapan Sel Suria yang Dipertingkatkan melalui Pantulan pada Wafer Silikon: Tekstur Laser lwn. Goresan Anisotropik)

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ABSTRACT

Due to its high refraction index, silicon (Si) reflects a significant amount of solar light of more than 37% of the sun's spectral range, particularly when it does not strike the surface perpendicularly. This effect consequentially reduces solar cell efficiency due to electrical and optical losses. Surface texturing is essential for increasing the cells' photon-trapping and absorbing capabilities to improve the efficiency of low-performance solar cells. In this study, pulsed Nd:YAG lasers are used to texturize surfaces of silicon wafers. This procedure is quicker and easier and does not produce waste or pollutants. However, there are some disadvantages to laser texturing; one is that it may lower solar cell efficiency if the damaged layer caused by the laser texturing is not removed. In this study, the laser damage layer is washed off with potassium hydroxide (20%), also known as KOH. This paper also compares the reflectance of laser texturing and wet chemical etching on surfaces of crystalline silicon wafers. The PerkinElmer Lambda 950 UV-VIS-NIR Spectrophotometer results indicate that laser texturing obtains a reflectance of 1% before and 9% after KOH treatment, in contrast to wet chemical etching, which has a reflectance of 16%. Laser texturing showed some efficiency, especially when texturing silicon wafer surfaces in parallel patterns, with a conversion efficiency of about 5% and grid patterns at 7.5%. This successful outcome demonstrates that laser texturing gives silicon solar cells a good alternative to traditional texturing techniques.

Keywords: Anisotropic etched; laser texturing; pulsed Nd:YAG laser; reflectance; silicon solar cells

ABSTRAK

Disebabkan indeks biasan yang tinggi, silikon (Si) memantulkan sejumlah besar cahaya matahari lebih daripada 37% daripada julat spektrum matahari, terutamanya apabila cahaya tidak mengenai permukaan secara tegak. Kesan ini secara tidak langsung mengurangkan kecekapan sel suria disebabkan oleh kerugian elektrik dan optik. Penteksturan permukaan adalah penting untuk meningkatkan keupayaan penyerapan dan perangkapan foton bagi meningkatkan kecekapan sel suria yang berprestasi rendah. Dalam kajian ini, laser Nd:YAG berdenyut digunakan untuk mentekstur permukaan wafer silikon. Prosedur ini lebih cepat dan mudah serta tidak menghasilkan sisa atau bahan pencemar. Walau bagaimanapun, terdapat beberapa kelemahan pada penteksturan laser; salah satunya adalah ia boleh mengurangkan kecekapan sel suria jika lapisan yang rosak akibat penteksturan laser tidak dibuang. Dalam kajian ini, lapisan kerosakan laser dibersihkan dengan kalium hidroksida (20%), yang juga dikenali sebagai KOH. Kertas ini juga membandingkan pantulan penteksturan laser dan pengukiran kimia basah pada permukaan wafer silikon kristal. Keputusan daripada Spektrofotometer PerkinElmer Lambda 950 UV-VIS-NIR menunjukkan bahawa penteksturan laser memperoleh pantulan sebanyak 1% sebelum dan 9% selepas rawatan KOH, berbanding dengan penteksturan kimia basah yang mempunyai pantulan sebanyak 16%. Penteksturan laser menunjukkan kecekapan tertentu, terutamanya apabila penteksturan permukaan wafer silikon dalam corak selari dengan kecekapan penukaran kira-kira 5% dan corak grid pada 7.5%. Hasil kejayaan ini menunjukkan bahawa penteksturan laser memberikan sel suria silikon alternatif yang baik kepada teknik penteksturan tradisional.

Kata kunci: Laser Nd:YAG berdenyut; pantulan; penteksturan anisotropik; penteksturan laser; sel suria silikon

INTRODUCTION

Light harvesting is one technique that is becoming more and more important for boosting the efficiency of solar energy conversion into electricity. It is crucial to have a system that continuously captures the most solar power when sunshine is present during the day (Ghani, Zainal Abidin & Othman 2023). Extensive research has been conducted on photon-trapping structures on various surfaces, such as substrates, cell surfaces, and active materials (Saive 2021). These included techniques like diffraction, interference, and resonant plasmonic phenomena, which involve the interaction of light waves in different ways to enhance a system's performance, like increasing light absorption in solar cells. It should be noted that solar cell efficiency is increased when the amount of solar light reflected from the surface is low. Bare silicon without any texturing on its surface has a reflection of about 37% in a wavelength range of 300-1100 nm (Nevenchannyy, Khoruzhiy & Kudryashov 2019). Therefore, surface texturing is a practical approach for increasing light absorption of silicon wafers through multiple internal reflections, which results in a lower effective reflectance loss (Dehghanpour et al. 2022). When the silicon wafer surfaces are textured, about 10% or more reflection loss can be reduced, hence making the surface rougher and darker. Consequently, light is absorbed near the p-n junction, where photons excite electrons in the conduction band to form an electron-hole pair, which is then converted into electric energy (Okamoto et al. 2023). Moreover, front surface texturing has been the subject of extensive research up to this point to lessen silicon reflection (Wang et al. 2016).

Theoretically, there are two primary purposes of texturing. First, texturing can make the light's path longer, so more photons can be trapped and absorbed. The absorbed photons will produce more charge carriers inside the cells and increase efficiency. Second, texturing can cause the surface and rear surfaces to have numerous internal reflections. Incident light inside the side can have longer a path length because of the reflection from textures formed on the front and back surfaces. In order to increase the length of the incident light path and increase the chance that reflected light would bounce back onto the surface rather than into the surrounding air, texturing techniques become more crucial and need to be applied to solar cells, especially thin film solar cells (Manzoor et al. 2020).

There are numerous techniques for texturing silicon wafer surfaces, including acid texturization, etching in alkaline solutions, reactive ion etching and laser texturing in order to help improve their light absorption and reduce reflection (Park et al. 2021). When the surface reflection is reduced, the surface can trap more photons and absorb them into the cells (Abdul Razak et al. 2020; Razak et al. 2020a). The popular one and still used today, is wet chemical etching. There are two techniques of chemical etching (Razak et al. 2020a). First is anisotropic etching, which is only suitable for monocrystalline silicon solar cells. Anisotropic etching uses an alkaline solution to etch monocrystalline silicon surfaces, resulting in a pyramid formed on silicon surfaces but not homogenous sizes. The second technique is an isotropic etching, which uses an acidic solution to etch a multi-crystalline silicon surface. An acidic solution is used for a multi-crystalline silicon surface because it has a random crystallographic orientation grain. This technique will create craters on the multi-crystalline silicon surface (Chen et al. 2018; Razak & Amin 2014; Razak et al. 2023). In addition, several methods, including reactive ion etching (Winderbaum, Reinhold & Yun 1997), plasma-enhanced chemical vapour deposition (PECVD) (Ma et al. 2023), and etching in acid vapours which contains HNO_3:HF (Ben Rabha et al. 2005) have been suggested for texturing multi-crystalline silicon solar cells. However, they are all limited in terms of creating an aspect ratio of textures. Besides, other disadvantages of chemical texturing is that it can pollute the environment because the solution waste takes time to decay, which is dangerous to human health, and many steps need to be applied for texturing silicon wafers (Nabil & Motaweh 2016). Because of these problems, researchers have developed new techniques, such as dry texturing, including mechanical texturing, such as focused ion beam etching (FIB) and femtosecond (fs) laser etching (Liu et al. 2022).

Mechanical texturing is very promising as an alternative texturing technique. The texture can be created precisely, fast and homogenous on all surfaces. Mechanical texturing can also work independently on surfaces by non-contact with the materials. Laser texturing is the best candidate for making texturing on a silicon wafer surface. Laser texturing has been used in silicon solar cell fabrication since the late 1960s to precisely cut solar cells with smooth edges and has also been applied for scribing on silicon solar cells (Jamaatisomarin et al. 2023). In 2007, the first laser texturing to textured silicon solar cells surfaces was reported (Dobrzański & Drygała 2007). They used laser texturing for multi-crystalline silicon as an alternative method to texturing silicon wafer surfaces because conventional chemicals and electrochemicals are not effective for multi-crystalline silicon wafers due to the presence of random crystallographic grain orientations, thus, making it higher selectivity of etching along specific directions (Macdonald et al. 2004; Papet et al. 2006; Yoo, Yu & Yi 2009). As a result, they found that with appropriate adjustment of process parameters (exposition time, translation of laser beam, pulse repetition frequency) they were able to obtain texture whose morphology appears to be very promising as far as reduction of reflectivity is concerned. Lee et al. (2023) reported that laser texturing reduces surface reflectance by creating microstructures that trap more light within the silicon wafer, thereby, increasing the optical path length and enhancing light absorption (Iyengar, Nayak & Gupta 2010). In some studies, laser texturing has been shown to reduce reflectance to below 10%, significantly increasing the short-circuit current density (Jsc) from 25.2 mA/cm^2 to

34.1 mA/cm², demonstrating the potential of laser texturing to enhance photovoltaic performance (Kato, Kurokawa & Soga 2022). Increasing the short-circuit current density can indeed enhance the efficiency of silicon solar cells due to enhanced light bouncing and absorption (Choi et al. 2015). This demonstrates that optimizing current density is a crucial factor in improving solar cell performance. When compared to traditional wet chemical etching, laser texturing is a contactless, precise, and environmentally friendly option for silicon wafer texturing. Unlike chemical etching, which is limited to monocrystalline silicon due to crystallographic limitations, laser texturing works on all silicon types, including multicrystalline, allowing for customisable patterns for improved light absorption (Radfar et al. 2018; Razak et al. 2020a). It minimises operational complexity and environmental effects by cutting waste, avoiding dangerous chemicals, and operating more quickly. Wet chemical etching, on the other hand, requires more procedures, longer processing durations and the disposal of hazardous waste (Vazsonyi et al. 1999). Because of these advantages, laser texturing is a better option for industrial applications, providing a balance between sustainability, efficiency, and scalability. Although laser texturing is very promising, this technique must add another step after it has been executed to remove the laser damage layer.

Laser texturing creates a damaged layer on the crystalline silicon surfaces. The damaged layer is caused by laser ablation on the silicon wafer, resulting in unwanted particles and an oxide layer (Razak et al. 2023). If the damaged layer is not removed from the silicon surfaces, the defects will create recombination on the surface where the incident light should be absorbed resulting in the reduced solar cells' efficiency (Dobrzański & Drygała 2007). However, this phenomenon can only happen if the silicon wafer surface has been covered with the damaged layer. To tackle these problems, some researchers already experimented by using a 20% KOH (Potassium Hydroxide) at 80 ºC in order to remove the laser-induced damaged layer (Radfar et al. 2018).

This paper discussed pulsed Nd:YAG laser as an alternative method to texture crystalline silicon wafer surfaces. A wet chemical etched texturing silicon wafer is used to compare the reflectance and efficiency with the laser texturing samples. An optical microscope, Field Emission Scanning Electron Microscopy (FESEM) SUPRA 55VP from ZEISS, perthometer and PerkinElmer Lambda 950 UV-VIS-NIR Spectrophotometer are used to observe the morphology, roughness and reflectance, respectively.

METHODS

In this experiment, a p-type crystalline silicon wafer with a 4 cm × 4 cm dimension, 0.5 Ω/cm resistivity, and 200 μm thickness was used. Two texturing techniques were performed separately on the silicon wafer samples: anisotropic wet-chemical etching (alkaline-based) and laser texturing using a pulsed Nd:YAG laser. The detailed fabrication process sequence of silicon solar cells is shown in Figure 1.

WET CHEMICAL ETCH: ANISOTROPIC WET-CHEMICAL ETCHING (ALKALINE BASED)

All the solutions are freshly prepared for the anisotropic wet-chemical etching (alkaline-based), as shown in Figure 2. The main chemicals are isopropyl alcohol (IPA), potassium hydroxide (KOH), and deionized water. Interestingly, solar cell manufacturers have used this alkaline wet-chemical etching in massive production for a decade (Hu et al. 2017). Before starting the etching, the silicon wafer was cleaned using a warm acetone bath for 10 min (the solution is heated to 55 °C before soaking the wafer in it), methanol for 2-5 min before rinsing it with deionized water and blow-drying it with nitrogen in order to remove unwanted surface particles and dust (Du, Zhao & Li 2023; Iqbal et al. 2022).

In the first etch solution of anisotropic wet-chemical etching, 120 g of potassium hydroxide (KOH), 200 mL of isopropyl alcohol (IPA) and 200 mL of deionized water were used. All the solution is mixed and stirred in one beaker. Then, the solution is heated at a temperature of 80 °C. After reaching 80 °C, the sample is immersed inside the solution for about 40 min. After that, the samples were rinsed with deionized water for 1 min. In another beaker, the 10% hydrochloric acid (HCl) solution is prepared. After the samples from the first solution step are completed, the samples are transferred to the second solution for 1 min. Then, the same samples were immersed in a 10% solution of hydrofluoric acid (HF) for 30 s to eliminate any metallic impurities or silicon oxide. After the etching is completed in the desired time, the samples are rinsed under the flowing deionized water and then blow-dried using nitrogen. To optically characterize the silicon wafer texture, a reflection measurement is conducted using a PerkinElmer Lambda 950 UV-VIS-NIR Spectrophotometer and an optical microscope, FESEM and perthometer are used to see the morphology and measure the roughness of silicon wafer surfaces, respectively. Previous studies demonstrate that anisotropic wet-chemical etching (alkaline-based) will create a pyramid texture on silicon surfaces (Hu et al. 2017).

PULSED Nd:YAG LASER TEXTURING

In the second experiment, silicon wafer surfaces are texturized using a laser rather than the conventional approach. The same type of silicon wafer was used. Laser texturing was performed using a pulsed Nd:YAG laser that had a wavelength of 1064 nm. The laser had a maximum average output power of more than 20 W and a pulse repetition frequency of 10 kHz. The beam delivery system included an F-theta scan lens, a high-speed galvanometric

Anisotropic wet-chemical etching (alkaline based) texturing
or
Pulsed Nd:YAG laser texturing

↓

Phosphorus $POCL_3$ Diffusion on front side

↓

Thermal SiO^2 growth

↓

Antireflection coating on both sides

↓

Ag/Al front side and Ag rear-side contact screen-printing

↓

Contacts firing in IR belt

FIGURE 1. Flow chart of the complete fabrication process of silicon solar cells

Acetone / Ethanol cleaning

- Acetone: 10 minutes (with solution temperature 55°C)
- Ethanol: 2-5 minutes

↓

Rinsed under flowing deionized water and blow-dry with nitrogen

↓

Anisotropic wet-chemical etching (alkaline based)

First solution

(Add all in one beaker) 120 g of potassium hydroxide (KOH), 200 ml of isopropyl alcohol (IPA), and 200 ml of deionized water.

- Heat the solution until it reaches the temperature, 80°C
- Soak the silicon wafer samples inside the solution for 40 minutes.
- After that, the samples are transferred to the second solution.

Second solution

For 1 minute, the samples were washed in deionised water. Then, the samples were put in a 10% HCl solution and left there for 1 minute

Third solution

The same samples were then immersed in a 10% solution of Hydrofluoric acid (HF) for 30 seconds to eliminate any metallic impurities or silicon oxide.

↓

Rinsed under flowing deionized water and blow-dry with nitrogen

FIGURE 2. Step-by-step anisotropic wet-chemical etching (alkaline based) for texturing silicon wafer surfaces

scanner, a beam expander with a 5× magnification, and an almost ideal mirror with a more than 99.5% reflection. The z-axis translation table system could be adjusted to set the laser aiming points. Table 1 displays the full specifications of the experimental system.

The components of the laser optical system include a diode laser alignment device, a laser resonator, a Q-switch, and a cast-iron base-mounted laser pump cavity with a Nd:YAG rod and a laser diode. The laser resonator has two mirror mounts, one for the front mirror and one for the back mirror. Approximately 100% of the laser beam at 1064 nm is reflected by the rear mirror coated in a multilayer dielectric film (hard coating). However, there is a 90% reflection of the 1064 nm laser beam from the front mirror. A multilayer dielectric film (hard coating) is also applied on its surface. In a laser optic system, the Q-switch plays a crucial role in the optics. In order to obtain high peak power, it passes or obstructs the laser beam at a specific frequency. This laser has an alignment unit built around a He-Ne laser beam (0.632 m), enabling visual alignment before laser operation. Q-switch is turned on during the texturing to give more energy to the laser beam and can texture deep lines on silicon wafer surfaces. Figure 3 shows the optical design of the beam that hits the silicon wafer via the quartz chamber. The size of the laser spot can be modified by adjusting the optic lens of the focusing beam system.

The sample was taped on the laser stage to avoid moving during laser texturing. Underneath the substrate, the sample was attached to the top of the X-Y translation table using black double tape. The X-Y translation table stage is powered by a stepper motor controller and controlled by a computer that has a LabView program. LabView programme allows the user to set their translation stage tracks and speeds. Additionally, it can direct the Q-switch and laser generator to emit lasers at specific spots. After being textured with a laser, the samples were cleaned with deionized water in an ultrasonic bath and dried with nitrogen gas under high pressure.

PULSE ENERGY CALCULATIONS

It is assumed that the power output of the Nd:YAG laser system remains constant. The pulse repetition rate is adjustable, and peak power, P_p is computed as (Hsiao et al. 2011):

$$P_p = \left(\frac{P_a}{\Delta T}\right) \tag{1}$$

ΔT represents the time for one pulse, where P_p stands for peak power, and P_a for average power. The following shows the result of ΔT from multiplying the laser pulse width, t by the pulse repetition frequency, PRF (Hsiao et al. 2011):

$$\Delta T = PRF \times t \tag{2}$$

After that, the formula from Equation (2) combined with Equation (1), as follows (Hsiao et al. 2011):

$$P_p = \left(\frac{P_a}{PRF\ x\ t}\right) \tag{3}$$

For the evaluation of laser energy, E_l is dependent on the area of laser irradiation, as shown in Equation (4) (Hsiao et al. 2011):

$$E_l = P_p \times t \tag{4}$$

Scattering incident light across textured surfaces can increase the absorption rate. When the textured surface is rough, and it can reduce reflection while increasing light trapping effectiveness (Oliver Nesa Raj & Prabhu 2023). In this investigation, the parameter ranges for the texturing of silicon wafer surfaces using a Pulsed Nd:YAG laser were determined by a literature review, the interaction of pulse energy with silicon wafer-based materials, and industrial applications (Abdul Razak et al. 2020; Razak et al. 2020b). The experiment results show that surface reflection values decrease as laser beam exposure times increase.

In this investigation, the following conditions were used to run the laser texturing on silicon wafers: (a) The laser pulse energy and scan speed were set to 84 J/p and 0.5 mm/s, respectively, to investigate the impact of the treatment path both before and after laser treatment, and (b) The laser texturing pattern designed in this study is a parallel pattern and grid pattern.

To be noted, a novel approach in this study, compared to previous research, is the integration of laser texturing with KOH to enhance light trapping and absorption in silicon solar cells. While Razak et al. (2023) primarily focused on optimizing laser fluence to control texturing depth, this research investigates the impact of KOH treatment and non-treatment after laser texturing and their influence on reflectance and efficiency.

Additionally, Knuettel, Bergfeld and Haas (2013) compared laser texturing techniques for thin-film silicon photovoltaics but did not explore crystalline silicon applications with advanced post-treatment. Our study fills this gap by demonstrating how laser-textured surfaces, when combined with KOH treatment, can effectively balance reduced reflectance and controlled surface roughness. This innovative combination of structured laser patterning and chemical post-processing sets a foundation for further advancements in cost-effective and scalable solar cell manufacturing.

RESULTS AND DISCUSSION

Figure 4 shows the scanning optical microscope images of the surface topographies of silicon wafer surfaces with three different techniques: anisotropic wet-chemical etched (alkaline based), laser texturing before KOH treatment and laser texturing after KOH treatment. All the images are taken using the same magnification. Figure 4(a) and 4(b) shows the crystalline silicon wafer sample after it has been etched at 80 °C in aqueous alkaline solution for 30 min. The pyramids' texture appears in microns, where the surface looks rough and turns black in our naked eyes.

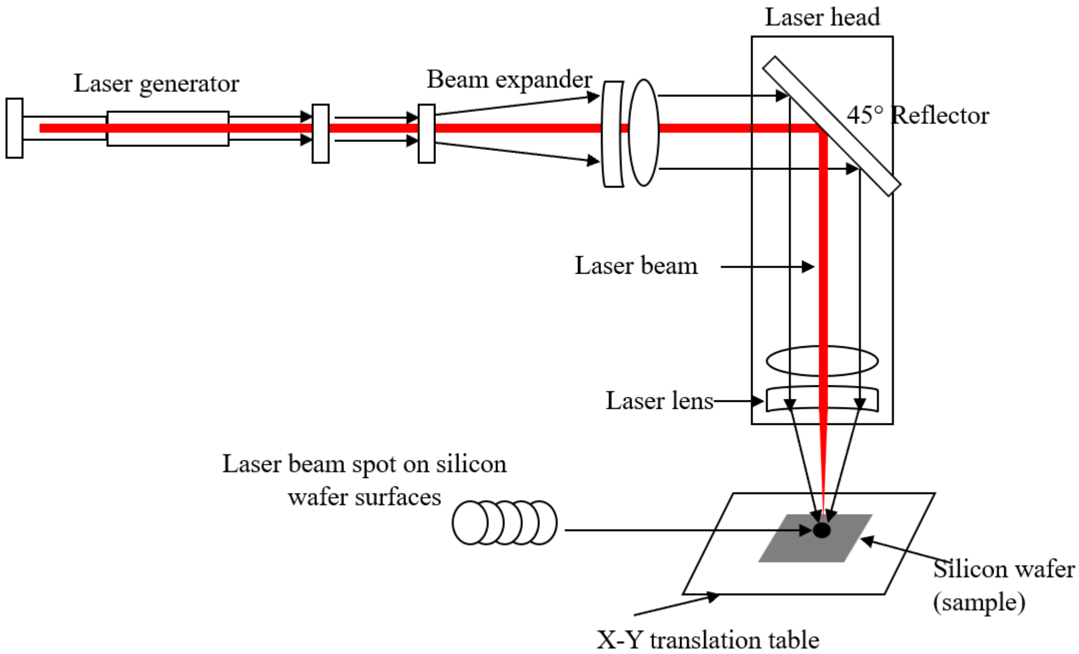

FIGURE 3. Pulsed Nd:YAG laser schematic diagram texturing silicon wafer surfaces

TABLE 1. Specification of parameters pulsed Nd:YAG laser processing system

Laser wavelength (nm)	1064 nm (near-infrared beam)
Beam quality	M2<6
Maximum output power (W)	50 W
Modulating Frequency kHz)	0.5 kHz ~ 50 kHz
Laser Output Instability	≤±3 %
Repetition rate	10kHz
Laser working material	Solid state laser
X-Y translation table speed	0 ~ 120mm/s
Spot Size	≤0.05 mm
Continuous operation hours	> 24h

The pyramids' size grows bigger when a longer etching time is used and more uniformly distributed, meaning all the surfaces are pyramid-textured. The pyramids' texture grew larger and more homogenous as time increased (Chen et al. 2018; Winderbaum, Reinhold & Yun 1997). The pyramid size obtained in this study is about 2 μm under the field emission scanning electron microscopy (FESEM), as shown in Figure 4(b), where a giant pyramid indicates a lower density of pyramids. Moreover, a pyramidal texture with an average size of 1-2 μm also exhibits low reflectance and a low surface carrier recombination rate, both of which enhance the performance of solar cells (Ben Rabha et al. 2005; Liu et al. 2022; Ma et al. 2023).

For laser textured on silicon wafer surfaces, the surface turns into a dark surface with very rough lines, as shown in Figure 4(c). These lines, however, contain a lot of unwanted particles after laser ablation on the silicon wafer surface. Figure 4(c) shows optical and field emission scanning electron microscope (FESEM) pictures of the laser spot and laser-induced damaged layer on silicon wafer surfaces, which occurred when a high number of laser pulses were applied. This laser-induced damaged layer must be removed to ensure silicon wafer surfaces receive the incident light and trap the photons (Jamaatisomarin et al. 2023). Based on the previous studies, these unwanted particles only can be removed using a KOH solution. After laser texturing, a 20% KOH solution is used to remove the residue. The sample is immersed for 2 minutes in the solution in order to obtain the clean samples. After removing the laser-induced damage layer, the laser texturing lines can be seen clearly on the surfaces, as shown in Figure 4(d).

The reflectance of crystalline silicon surfaces was measured after being textured. Three texturing techniques applied to crystalline silicon wafers in this study were characterized more to see different reflectance percentages of each other technique and roughness surfaces, with the goals of finding low reflectance and some conversion efficiency.

Figure 5 shows the results of reflectance tests performed on silicon wafers before and after laser damage layer removal, following anisotropic wet-chemical etching (alkaline-based) and pulsed Nd:YAG laser texturing. Using a PerkinElmer Lambda 950 UV-VIS-NIR Spectrophotometer, the samples were held in the 0° port and exposed to an incident beam of light through the 180° port in order to determine the reflectance. A baffled detector is used to measure the total reflected radiation when it is spatially integrated by the sphere. It is important to note that spectrometers with an integrating sphere are often used to measure reflections on samples that have thin-film coatings, non-flat surfaces, or different surface topologies. This is because the reflections are accurately captured and measured without the need for extra optical elements (Van Nijnatten 2014). The integrating sphere uses a two-beam setup, with one beam hitting the sample perpendicular to the surface and the other at an angle. The light absorption was determined using the Kubelka-Munk theory from the diffuse reflection coefficient (Nobbs 1985). For reflection measurements, the reflectance wavelength ranges from 200 to 1200 nm, which includes the ultraviolet, visible, and near-infrared spectrums. From Figure 5, the reflectance from the laser texturing before KOH solution treatment is low compared to those after KOH treatment and anisotropic wet chemical etching (alkaline-based). The lower reflectance is because the surface after laser texturing is very rough and contains a laser damage layer on the top, which consists of unwanted particles. The laser texturing treated with KOH showed a reflectance of about 9%, while laser texturing without treatment showed 1%. Compared with other samples, the wet chemical etched surface showed a reflectance of about 15%, while the bare silicon wafer showed 16%. Based on the reflectance results, the reflectance percentage dropped by 10% after being textured. The increase in reflectance percentage after laser texturing was treated with KOH solution is because the surface roughness has been reduced due to the removed laser-induced damaged layer. The reflection from the silicon solar cell surface after texturing was found to be decreased in the short-wavelength region and to be slightly increased in the long-wavelength part, resulting in a good agreement between theory and experiment (Manzoor et al. 2020). According to earlier research, the laser-induced damage layer needs to be taken off because the flaws will cause recombination on the surface where light should be absorbed, which will lower the efficiency of the solar cells (Gupta 2020).

Figure 6 shows the absorption and transmission of silicon wafer surfaces under various treatment conditions, including laser texturing before and after removing laser damage layers and anisotropic wet-chemical etching (based on an alkaline solution). The graph indicated that following laser irradiation, the surface absorbance in the 'blue' spectral range (<480 nm) increased from 0.7% to 2.5% in the 400-1000 nm spectral range. However, the absorbance decreased in the red wavelength of the visible spectrum thanks to low information content, which interferes with the modelling of spectral analysis (Vinčiunas et al. 2013). Furthermore, the absorption was reduced by up to 35% in the spectral range >850 nm and above, most likely as a result of the silicon surface melting. A 2% increase in absorption near the 380 nm wavelength was noted when the cell surface was exposed to a few laser pulses per region. The high aspect ratio texturing of the cell surface improves the coupling of solar light within the cell. Approximately 600 nm was the cell absorption that was most affected by this type of laser texturing (Lee et al. 2012). According to the reports, after exposing the area to 75 to 500 laser pulses each area, the absorption level dropped quickly and stayed low even as the pulse number increased. Because of this, the absorption characteristics may alter, mirroring the changes made to the silicon substrate. The changes were validated by surface roughness studies of the laser-textured silicon wafer presented in this article.

Optical transmission measurements cannot be made directly on silicon due to its high absorption in the 250-900 nm spectral range (Saive 2021). However, to determine the transmittance for surfaces texturized with silicon wafers, several research studies employed transmittance measurements. According to Figure 6's transmission measurements, the laser texturing tends to couple more infrared light out of the back of the wafer. Compared to random pyramid patterns made by anisotropic wet-chemical etching (alkaline-based), the laser texturing still absorbs more light despite this improved rear coupling. The higher absorption is because the laser-ablated pits have a conical shape, which decreases the performance of the silicon wafer by providing less quick coupling of light out the rear of the cell. This finding shows that the uneven conical shape of the pits makes the laser texture better at trapping light. As shown in Figure 6's graph, the laser texture reflected less light at shorter wavelengths than the upright random pyramids (Lee et al. 2012). Although the exact cause of this effect is not entirely known, it is believed to be caused by the variations in surface geometry or surface polish that arise from the use of various etching solutions.

Two fundamental models on wettability, notably the Wenzel and Cassie-Baxter models, were used to describe the effect of surface roughness. According to the Wenzel model (Katasho et al. 2015), the liquid droplet can be immersed anywhere on a rough surface. The roughness of the surface can improve the wettability measurement of the solid surface. Surface roughness increases hydrophobicity, which in turn increases surface area, and a hydrophobic

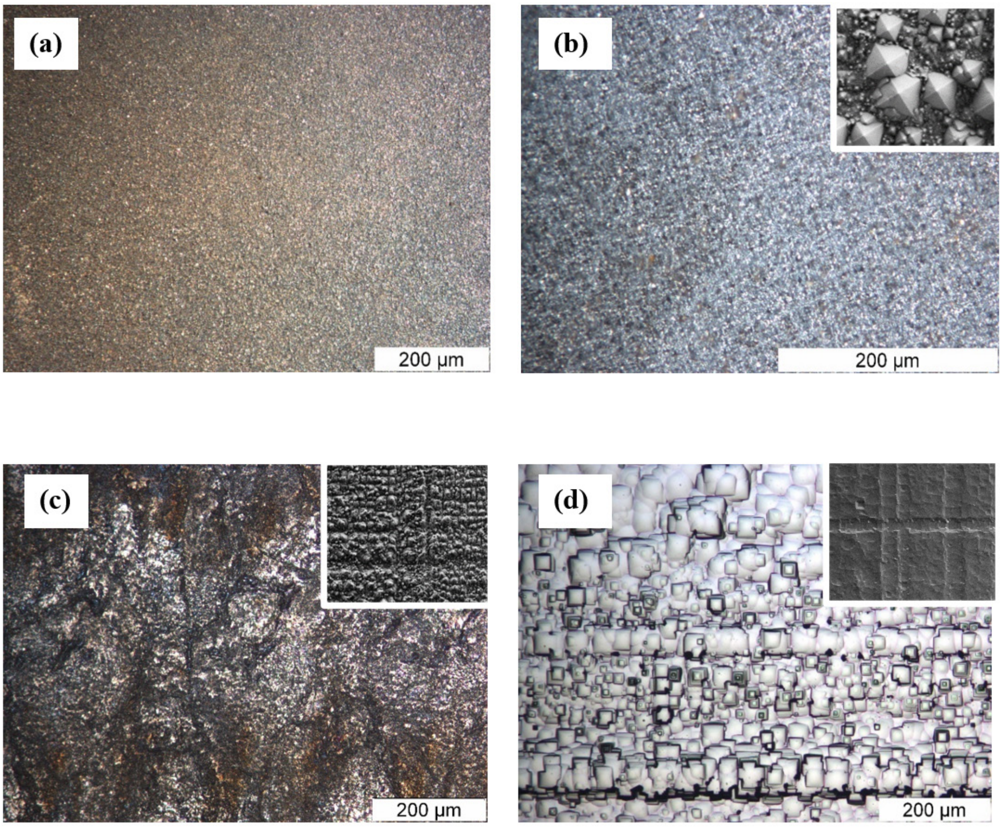

FIGURE 4. (a) Wet chemical etched (dark-field imaging), (b) Wet chemical etched (bright-field imaging), (c) Laser texturing before laser damage layer removal (bright-field imaging), and (d) Laser texturing after laser damage layer removal (Bright-field imaging)

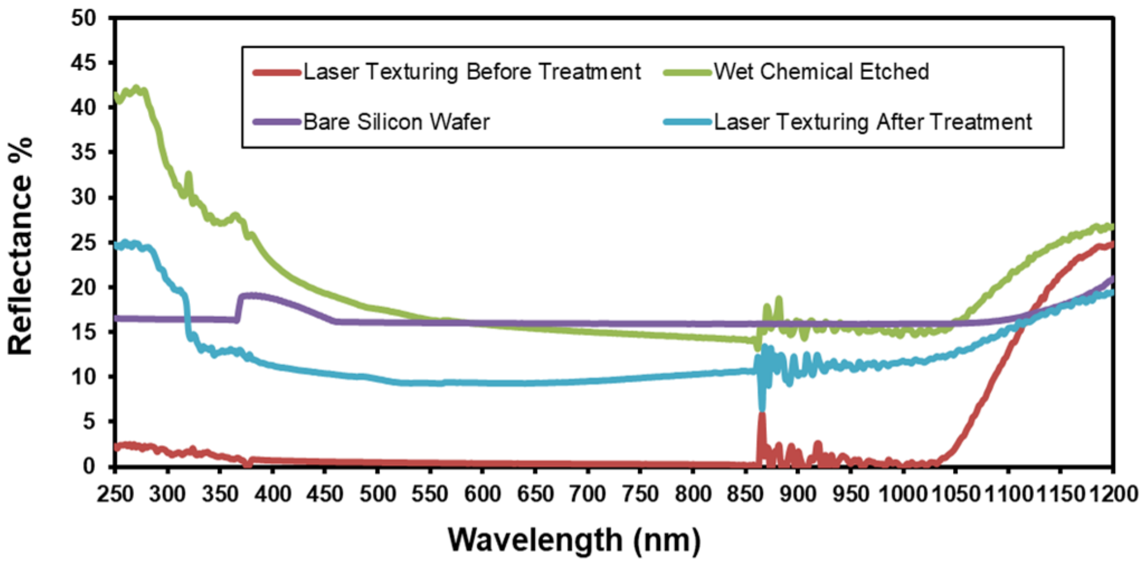

FIGURE 5. Reflection measurements of silicon wafers after alkaline etching solutions

surface traps air. The Cassie-Baxter model, on the other hand, states that hydrophobicity increases as roughness increases. It is likely that the final contact angles depend on how rough the surface is.

Surface roughness and morphology were more significantly affected by combinations of average laser power and scanning speed (Alsaigh 2024). Additionally, the average laser power must also be optimised to get the surface with the optimal wetting characteristic. However, due to the effects of texture width and depth, the laser scanning speed showed a significant impact on the surface roughness as well as the surface morphology. On top of that, increasing the pulse energy also increases the surface roughness. The optimal optimisation of the laser scanning speed is essential for the production of the finest wettable laser inscribed surface. Because of this, the surface of the silicon wafer that was texturized using a laser had the best wetting property (Li et al. 2021). Also, it shows that rough textures can make monocrystalline silicon wafers better at capturing light.

Table 2 summarises the reflection values obtained from different surface texturing processes on different types of silicon wafers in a comprehensive way. In order to reduce surface reflectance and maximise light absorption efficiency in solar cells made of silicon, these techniques are essential. Each approach is classified in the table according to the silicon wafer type, texturing methodology, chemical solution, and reflection percentage that was achieved.

Compared to untextured surfaces, Pulsed Nd:YAG laser textured surfaces have lower reflectances. The lower reflectance means that when the pulse frequency goes up, the roughness of the surface goes down and the reflection goes up. According to the pulse energy estimates, lower pulse repetition rates generate larger pulse energies, which in turn yield higher reflectivity. Table 3 summarizes the outcomes of laser surface treatment and wet chemical etching on silicon wafer substrates, including both acidic and alkaline treatments (Ben Rabha et al. 2005; Du, Zhao & Li 2023; Hu et al. 2017; Iqbal et al. 2022; Oliver Nesa Raj & Prabhu 2023; Radfar et al. 2018; Razak et al. 2020a). These investigations' results demonstrate that surface reflection values are over 10% at wavelengths between 300 and 1,300 nm. After the surface was laser-treated, anti-reflective coatings were applied, producing a rougher surface and decreased reflectivity without the need for chemical etching solutions.

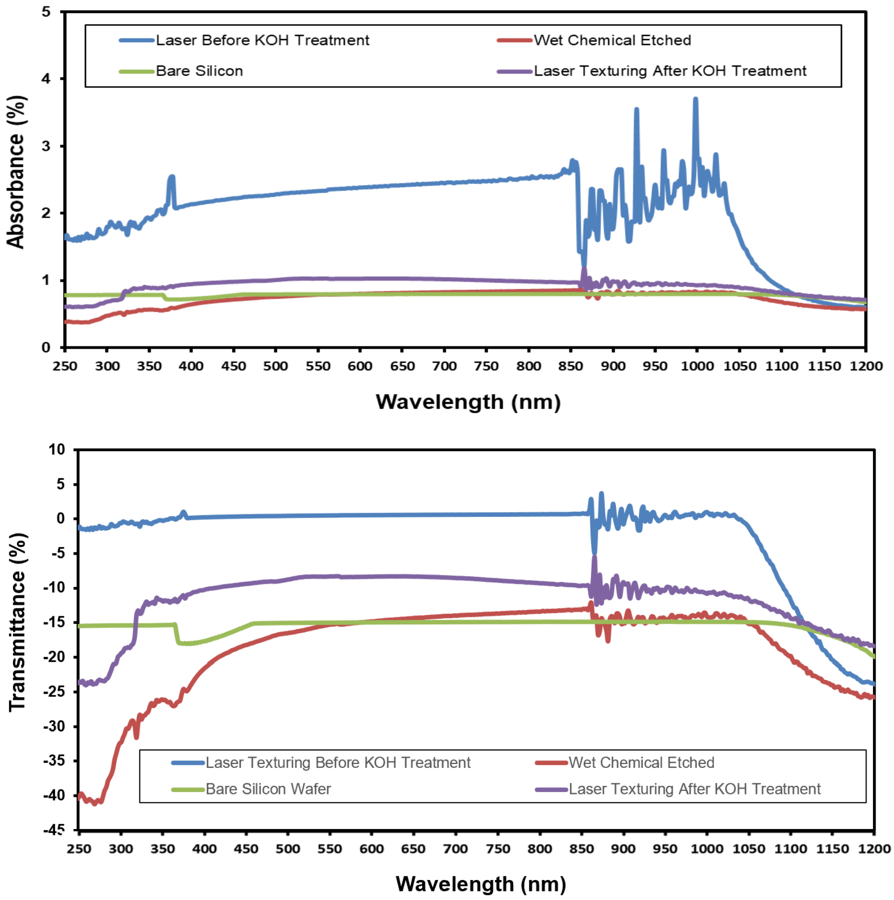

FIGURE 6. Absorbance and transmittance measurements of silicon wafers

TABLE 2. Summary of the reflection values under various surface textured methods

Author/year	Sample	Method	Solution	Medium	Reflection %
Park et al. (2003)	Multicrystalline silicon wafer	Acidic etching	H2So4, NaNO2, HF, and HNO3	n/a	9.8
Yoo et al. (2009)	P-type cz- silicon wafer	RIE	n/a	n/a SF6/O2	8.4 6
Vazsonyi et al. (1999)	Monocrystalline silicon wafer	Anisotropic etching	NaOH	n/a	14-12
Papet et al. (2006)	Silicon wafer	Anisotropic etching	TMAH	-	13
Winderbaum et al. (1997)	Polycrystalline silicon	RIE	CHF3	SF6/O2	Pyramid, 5.6 Groove, 7.9
Macdonald et al. (2004)	Multicrystalline silicon	Alkaline etching	KOH or NaOH	-	9.0*
		Acidic etching	HF/HNO3	-	8.0*
		Maskless RIE	-	-	3.9*
		Maskless RIE pyramids	-	-	-
Iyengar et al. (2010)	Silicon wafer	Ultrafast laser texturing	-	SF6	<5
Dobrzanski et al. (2007)	Monocrystalline silicon wafer	Nd:YAG laser treatment	KOH	-	<8.3-23.6
Hsiao & et al. (2011)	Monocrystalline silicon wafer	Nd:YAG laser treatment	-		<10
Our present	Monocrystalline silicon wafer	Optimization of Nd:YAG laser texturing	KOH	-	<5

H2So4 sulfuric acid, NaNO2 sodium nitrite, HF hydrofluoric acid, HNO3 nitric acid, NaOH sodium hydroxide, TMAH tetramethylammonium hydroxide, CHF3 trifluoromethane, KOH postassium hydroxide, SF6 sulfur hexafluoride, n/a not applicable
*with SIN AR coating

TABLE 3. Summary of reflectance and efficiency from laser and chemical texturing treatments on silicon wafers by various researchers

Surface Texture Treatment	Reflectance after Texturing (%)	Efficiency (%)	Author/ Source
Two-step Isotropic Alkali Etch + Metal-Catalyzed Chemical Etching (MCCE)	9.26% to 18.82%	18.02 to 18.63	Hu et al. (2017)
Anisotropic Wet-Chemical Etched (Alkaline based)	20	10.5	Razak et al. (2020)
Porous Silicon (Chemical Vapour Etching)	~15	~8.0	Ben Rabha et al. (2005)
Pulsed Nd-YAG laser Texturing; Grid Pattern (After KOH Treatment)	25	7.5	Razak et al. (2020)
Anisotropic KOH + NaOH + Na_2SiO_3	9.94 ± 0.43	-	Iqbal et al. (2018)
Nanosecond Fiber Laser Texturing (Different Dimple-textured pattern; circle and triangle	Circular: 18% to 30% Pyramid: 8% to 20%	-	Oliver & Prabhu (2023)
Pulsed Nd-YAG Laser Texturing; Parallel Pattern (After KOH Treatment)	25	5	Razak et al. (2020)

POST-TREATMENT AFTER LASER TEXTURING WITH KOH SOLUTION SHOWS A GREAT IMPACT ON THE ELECTRICAL PERFORMANCE

The volt-ampere properties of poly-Si solar cells that had been textured by lasers were tested using a solar imitator, which is a class AAA sun simulator used under standard test circumstances and illumination with an AM1.5 g spectrum. For volt-ampere measurements, grid and parallel laser texturing were characterized after KOH treatment and anisotropic wet-chemical etched (alkaline-based). It was known that laser texturing without KOH treatment results in increased recombination of minority carriers, thereby reducing the electrical performance of the cell. Consequently, this study did not compare the efficiency of silicon wafers subjected to laser texturing without KOH treatment, despite their low reflectance after the laser texturing process. Therefore, our previous research (Razak et al. 2023) reported the photovoltaic characteristics of a solar cell under different types of laser texturing patterns after KOH treatment compared with anisotropic wet-chemical etched (alkaline-based). However, the article did not provide a detailed analysis of the impact of KOH treatment compared to non-treatment on reflectance after laser texturing. They reported that laser texturing with a grid pattern after KOH treatment demonstrated an efficiency of about 7.5%, compared to laser texturing with a parallel pattern after KOH treatment, which was approximately 5%. Although anisotropic wet chemical etched texturing has demonstrated an efficiency of approximately 10.5%, laser texturing with grid patterns has the potential to replace this alkaline etching in the future. The lower efficiency of laser texturing in this study compared to the conventional wet chemical etched is because surface damage, microcracks, and defects increase electron recombination. Uneven surfaces result in unwanted light scattering and absorption losses, while adding effective passivation layers is difficult, resulting in further energy loss. Furthermore, heat from the laser process might damage the silicon structure, affecting charge carrier collection. When an entire poly-Si solar cell is texturized with a laser, changes happen in its photo-electrical properties that cause shunt formation (Vinčiunas et al. 2013). The current leakage through a broken passivation layer may be the cause of the shunt's resistance. Research has also shown that using a lower laser pulse energy during texturing might help reduce the detrimental effects of laser texturing on photovoltaic properties, as does decreasing the thickness of the damaged layer.

On the other hand, the laser texture outperformed the single-sided random pyramids and the double-sided random pyramids in terms of conversion efficiency. Light confinement at the infrared end of the spectrum and decreased reflection at the blue end of the spectrum contributed to this increase. An increase in the theoretical currents estimated for the laser texturing is directly proportional to the increase in absorption. The results indicate that the laser texture outperformed the random pyramid texture in terms of optical performance and that it might be a useful method for improving solar cell light trapping. It should be noted that the cells would have been encapsulated within a module for actual photovoltaic applications. Some of the reflected light that would otherwise be lost in this measurement could be absorbed by the glass encapsulant due to internal reflection (Hussein & Ismael 2022). Because of this effect, the difference in performance between the different types of textures would be reduced. Still, the laser texture would not be negatively affected in terms of its ability to trap light. Although laser texturing can minimise reflectivity, it may not always be as effective as conventional texturing methods, which use wet chemical etching. However, a novel method using Pulsed Nd:YAG laser for texturing silicon solar cell surfaces has been identified as an attractive option for low-cost solar cell production, despite the current limitations in efficiency, which could be used in future technologies as laser technology continues to improve (Barrio et al. 2021). Additionally, ongoing research into optimizing laser parameters and post-processing techniques holds promise for improving the efficiency of laser-textured silicon solar cells in the future (Radfar, Es & Turan 2020). In addition, the smaller solar cells, laser texturing can increase edge recombination, which leads to higher energy loss. However, if properly optimized, laser texturing can improve the efficiency of high-performance solar cells by enhancing light absorption. This results in a higher open-circuit voltage, better resistance to electrical losses, and more electricity generated from light, all of which contribute to better overall performance.

CONCLUSIONS

This study compares three techniques to make texturing on a silicon wafer surface. Laser texturing with KOH treatment produced lower reflectance than commonly used chemical etching. Hence, laser texturing can provide an alternative to replace the chemical technique. These techniques are very simple and effective ways to reduce surface reflection and as light trapping for crystalline silicon solar cells. To be noted, all the techniques used in this experiment are simple and low-cost, resulting in a perfectly textured surface. All of these texturing techniques provide incident light scattering through the entire surface.

In order to improve the optical performance of samples of monocrystalline silicon substrates, a pulsed Nd:YAG laser system is used to create a textured surface. To determine the most effective values for the process parameters governing laser surface texturing, a diverse value of laser machining speed rate, pulse intensities, repetition frequencies, and exposure times were investigated. It is noted that the devices were less useful if the laser damage layer was not removed, although it can textured homogenously on silicon wafer surfaces. Laser irradiation and ablation result in structural flaws that reduce the lifetime of photo-generated charge carriers, preventing them from reaching the p-n junction. As a result, the photovoltaic efficiency decreased.

Therefore, KOH treatment is crucial to removing the laser damage layer. A three-dimensional confocal laser scanning microscope was used to examine the surface roughness and morphology of the produced microstructures. Results from a UV-Vis spectrophotometer experiment show that rougher surfaces have better optical properties. Laser texturing decreased reflectivity from 40% to 10% without using chemical etching processes. This method is applicable to a wide variety of materials, including crystalline silicon, multi-crystalline silicon, and thin film silicon.

It has also been demonstrated that texturing silicon solar cells using a laser is an efficient way to improve the efficiency of both monocrystalline and multicrystalline silicon solar cells. Within the scope of this paper, neither the economic viability of the procedure nor its applicability in a production setting have been extensively studied. The use of lasers in solar cell operations has been effectively brought to industry in the past, and laser technology is constantly evolving. It would be beneficial for solar cells if this technique could be executed affordably; we have shown that lasers can texture silicon solar cells. Overall, it can be concluded that reflectance on silicon surfaces can be reduced by simple and low-cost techniques. Laser texturing techniques also can be used in industrial applications for massive production.

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