ABSTRACT

Currently, in the photovoltaic industry, wet chemical etching technologies are used for saw damage removal and surface texturing. Alternative to wet chemical etching is plasma etching. However, as for example, the linear microwave plasma technique, developed by Roth&Rau, has not been implemented in the photovoltaic industry for etching, because of the very low etch rate (<1 μm/min) and the high cost of ownership related to the etching process. In this study, different front surface textured crystalline silicon wafers obtained by means of the linear microwave plasma technique and the expanding thermal plasma technique are investigated in terms of weighted reflection by using reflectometry (250–1200 nm) to study the optical properties of the textures in detail. In addition, atomic force microscopy is used to measure the surface topography to determine statistical roughness parameters, as presented in this paper. Effective light trapping can be obtained by multiple reflections as well as by a graded layer, which leads to a diffuse front surface, or a combination of both. A graded layer can be described as a smooth transition with increasing refractive index from air to silicon with typical thickness of (200 ± 50) nm. We have found that the average plane tilt angle correlates to the measured weighted reflection. Moreover, we can determine from the aspect ratio whether the light trapping is effective by multiple reflections. From the roughness exponent, which is a measure for the micro roughness, we can determine whether the light trapping is effective by a graded layer. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS

texture; light trapping; reflection; plasma etching; silicon; surface topography

1. INTRODUCTION

In 2002, crystalline silicon (c-Si) solar cells were industrially manufactured from wafers with wafer thickness of more than 300 μm, while now a wafer thickness of less than 200 μm is common. Reducing the wafer thickness is a trend, which has already been recognized in the industrial manufacturing of c-Si solar cells for saving costs of the photovoltaic (PV) system [1]. Thinner wafers lead to less bulk recombination, which can lead in potential to higher solar cell efficiencies. Thinner Si substrates lead to an increasing importance of effective light trapping by front and rear side texturing. Especially, the trapping of near bandgap photons, which have an electron energy only slightly smaller than 1.1 eV becomes more important for thinner wafers. The absorption length of infrared light with wavelength of 1000 nm is relatively long (~200 μm) in comparison with blue light, which has an absorption length smaller than 1 μm. Appropriate front and rear side textures scatter the light into different directions, which will lead to optical path length enhancement, and increases the optical thickness of the wafers [2,3]. It has been investigated by Yablonovitch that in the limit of zero absorption, a bare silicon wafer with a perfectly transmitting top surface and a perfectly reflecting back surface, the path length of normally incident light rays is increased by factor
4 \cdot (n_{Si}/n_{Air})^2 (\approx 50) \) compared with the case that the back surface is perfectly transmitting [4,5], Note that besides the increasing importance of light trapping in the case of thinner Si substrates, there is also an increasing importance to passivate the c-Si surfaces, because of the increasing surface-to-volume ratio. As for example, the passivated emitter and rear cell (PERC)-type solar cell concept strongly benefits from a well adapted and optimized surface morphology of the front and rear surface. The rear side of a passivated emitter and rear cell-type solar cell based on p-type silicon can be passivated with a thin-film surface passivation, as for example, Al2O3 based on plasma-assisted atomic layer deposition (ALD). Relatively low surface recombination velocities (\( \leq 13 \text{ cm/s} \)) have been obtained for ALD AL2O3 and can, therefore, be used to reach a high solar cell efficiency [6,7].

Starting from an as cut c-Si wafer, the first manufacturing step to produce solar cells is the removal of the saw damage on both sides of the wafer, while in most cases this also includes the creation of the front side texture. The thickness of the saw damage is typically several micrometers. Front side texturing leads to an improved light trapping compared with a polished wafer [4,8,9]. Currently, in the PV industry, wet chemistry is used for saw damage removal and texturing. On mono c-Si material with crystal direction (100), potassium hydroxide isopropanol (KOH/IPA) results in anisotropic etching and leads to a pyramidal texture with an effective light trapping [10–12]. On multicrystalline Si (mc-Si) material, KOH/IPA does not lead to a texture with an effective light trapping, caused by the different crystal orientations. Texturing of mc-Si material is done using acidic isotropic solutions, as for example, with a solution that consists of HF and HNO3. However, acidic texturing of mc-Si material is not as effective for the light trapping as KOH/IPA on mono c-Si material [13,14].

Alternative method to wet chemical etching is plasma-based etching. Plasma etching results in a smaller consumption of de-ionized water for the etch- and subsequent rinsing steps. Plasma etching is independent of crystal orientation of the wafer material and, therefore, suitable for wafers with different crystal orientations like mc-Si materials. Plasma texturing leads on mc-Si material to a texture with an improved light trapping compared with wet chemical acidic or alkaline (KOH) etching coating at a high deposition rate of \( \approx 5 \text{ nm} \text{s}^{-1} \) [20]. The DEP system has been developed by OTB solar (Eindhoven, the Netherlands), which is now part of Roth&Rau. Note that the ETP technique has been used for etching of silicon wafers by Beulens et al., who achieved etch rates larger than \( 15 \mu\text{m/min} \) in a setup for single wafer treatment [21]. The deposition rate of the LMP system developed by Roth&Rau for deposition of a-SiNx:H anti-reflection coating is \( 1–2 \text{ nm} \text{s}^{-1} \) [22]. For the study described in this paper, the ETP technique and the LMP technique have both been used for texturing of silicon wafers.

As known from literature, efficient light trapping is obtained for two typical textures and depends on the wavelength: a texture which leads to multiple reflections and a texture with a graded layer, which results in a diffuse front surface. For texture feature sizes larger than the wavelength of the incident light, multiple reflections of the incident light towards the wafer surface occur in the case of a high aspect ratio, as illustrated in Figure 1 [4,9,23].

For feature sizes smaller than the wavelength of the light, efficient light trapping can be obtained in the case of sufficient micro roughness. In this case, the light does not see the details of the texture. The textured surface with micro roughness can be described as a graded layer, by means of an effective medium. The density of the graded layer increases smoothly from 0% representing the density of air to 100% representing the density of silicon, which corresponds to an increase of the refractive index of air to the refractive index of silicon, respectively [9]. A textured surface with micro roughness is presented in Figure 2(a) and is described schematically by a graded layer in Figure 2(b). A texture that consists of a needle-like structure on a scale smaller than the wavelength of the light could be also described by a graded layer. Such “black silicon” called structure leads to complete suppression of
Light trapping and surface topography of plasma textured c-Si wafers

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Figure 1. Schematic overview of a pyramidal texture with $\Delta b$ as lateral distance from top of the peak to top of the neighbors peak and $\Delta h$ the vertical distance from bottom to top of the peak on the front side of the c-Si wafer. A light ray (1) hits the front side of the pyramid. The light ray (1) moves from the air to the air-silicon interface and is partly transmitted into the silicon wafer (light ray (2)) and partly reflected (light ray (3)). The angle between light ray (1) and (3) is the plane tilt angle $\theta_{\text{plane tilt}}$. The reflected light ray (3) has a second chance to be coupled in silicon: it hits again the pyramidal texture and is partly coupled into silicon (light ray (4)) and partly reflected (light ray (5)). The second hit of the reflected light ray to the texture is an advantage of the textured surface in comparison with a polished surface. The figure has been redrawn from a figure presented by Hylton et al. [23].

Figure 2. Schematic overview of light ray (1a) that hits the textured silicon surface with micro roughness on the scale smaller than the wavelength of the light. On the air-silicon interface, the light ray is partly transmitted into silicon (light ray (2a)) and partly reflected light ray (3a) (a). The textured surface with micro roughness can be presented schematically as a graded layer by means of an effective medium between air and silicon material. The light ray (1b) hits the air-effective medium interface and is partly transmitted into the effective medium light ray (2b) and partly reflected back into air (light ray (3b)). The refractive index of the effective medium increases smoothly from air to silicon and the light ray (2b) is partly transmitted into silicon (light ray (4b)). The effective medium leads to an increased light trapping compared with a silicon surface without effective medium (b).

2. APPROACH

In this study, starting on mono c-Si as cut material (Czochralski, p-type, crystal orientation (100), resistivity $3–6\,\Omega\,\text{cm}$, thickness $330\,\mu\text{m}$) different textures have been created using the LMP technique and the ETP technique in a SF$_6$/O$_2$ plasma chemistry. The plasma textured surfaces are compared with the KOH/IPA process, which is used in solar cell manufacturing. The surface topography of these textures has been measured by atomic force microscopy (AFM), and from these height data, statistical roughness parameters have been determined. The reflection of the textured surfaces has been measured using an integrating sphere setup with wavelength range of 250–1200 nm. From the measured reflection ($R$) as function of the wavelength ($\lambda$) for a textured silicon wafer, the weighted reflection ($R_w$) is determined. Note that for determination of the weighted reflection, also the radiation spectrum of the sun (AM 1.5 global) (=S) as well as the internal quantum efficiency (IQE) of a high efficiency mono c-Si solar cell is taken into account for the wavelength range from the minimum wavelength of the solar
spectrum ($\lambda_{\text{min}} = 250 \text{ nm}$) to the wavelength of the photons corresponding to the bandgap energy of silicon ($\lambda_{\text{Si bandgap}} = 1200 \text{ nm}$). The following equation is used to determine the weighted reflection [29]:

$$R_w = \frac{\int_{\lambda_{\text{min}}}^{\lambda_{\text{Si bandgap}}} S(\lambda) \cdot \text{IQE}(\lambda) \cdot R(\lambda) \cdot \frac{q}{h} \frac{c}{hc} d\lambda}{\int_{\lambda_{\text{min}}}^{\lambda_{\text{Si bandgap}}} S(\lambda) \cdot \text{IQE}(\lambda) \cdot \frac{q}{h} \frac{c}{hc} d\lambda}$$

(1)

In equation (1), $q$, $h$, and $c$ present the elementary charge, Planck’s constant, and the speed of the light in vacuum, respectively.

In this work, we show a statistical roughness parameter, which is directly related to the weighted reflection. Moreover, we show a method based on the statistical roughness parameters of a textured surface to determine whether the efficient light trapping is caused by multiple reflections or by a graded layer, which leads to diffuse reflection, or by a combination of multiple reflections and a graded layer.

### 3. EXPERIMENTAL SETUP AND METHODS

As mentioned in the last section, surface texturing on silicon wafers has been created using the ETP and LMP techniques. The LMP technique, developed by Roth & Rau and installed at Fraunhofer ISE, consists of two continuous-microwave generators with a linear copper antenna inside, applied in an industrial semi-inline setup. The microwave generators have a microwave frequency of 2.45 GHz. The copper antenna is surrounded by a quartz tube for protection of the processing gasses. Microwave power is supplied from both sides into the linear antenna and plasma is generated around the quartz tube [16,17,22,30,31].

The ETP technique, used for this study, is installed at Eindhoven University of Technology. The plasma source is a DC current, cascaded arc. In the plasma source a non-depositing and non-etching gas Ar is injected and the ionization degree is typically about 10% at a relatively high pressure in the order of 0.4 bar. The pressure of the plasma in the reactor chamber is typically 0.2 mbar. Caused by the relatively large pressure difference between the source and the reactor, the ETP technique is an ultimately remote plasma technique and the plasma is accelerated leading to a supersonic expansion. The plasma chemistry in the reactor chamber is completely separated from the plasma generation in the source. The created reactive species in the arc dissociate downstream precursor gasses, as for example, SF$_5$/O$_2$, used for etching of the silicon wafer. The silicon wafer is placed on a sample holder directly connected to a chuck. The temperature of the silicon wafer can be controlled by a heating element and a liquid nitrogen flow in the chuck. Note that this setup is suited for single wafer treatment [21,32].

For the LMP technique, the wafer is positioned in the afterglow zone, and for the ETP technique, the wafer is positioned downstream in which the plasma is basically also an afterglow. In these afterglow zones, the electron temperatures are relatively low (especially for the ETP technique), which leads to relatively low ion energies (Table I) [17,21,31,32]. This implies that etching by these plasmas is dominated by chemical rather than by ionic processes. In both plasmas, the etching takes place predominantly by F radicals. In the LMP technique, these F radicals are mainly created by electron-impact collisions (by electrons in the tail of the energy distribution) as presented by [17]:

$$\text{e}^- + \text{SF}_6 \rightarrow \text{e}^- + \text{SF}_5 + \text{F}$$

(2)

where SF$_5$ and F are radicals.

In a similar way, O$_2$ molecules are dissociated as is presented by the following reaction [17]:

$$\text{e}^- + \text{O}_2 \rightarrow \text{e}^- + \text{O} + \text{O}$$

(3)

According to Beulens et al., the production of radicals in the ETP technique is dominated by charge exchange reactions. This reaction is presented by [21]:

$$\text{Ar}^+ + \text{SF}_6 \rightarrow \text{Ar} + \text{SF}_5^+ + \text{F}$$

(4)

where F is a radical. Subsequently, this reaction is followed by dissociative recombination with electrons resulting, for example, in SF$_4$ and F radicals [21]:

$$\text{SF}_5^+ + \text{e}^- \rightarrow \text{SF}_4 + \text{F}$$

(5)

Note that similar as for SF$_6$, also O$_2$ undergoes charge exchange reactions [33]:

$$\text{Ar}^+ + \text{O}_2 \rightarrow \text{O}_2^+ + \text{Ar}$$

(6)

which is followed by [33]:

$$\text{O}_2^+ + \text{e}^- \rightarrow \text{O} + \text{O}$$

(7)

Table I. Settings and parameters are presented for the linear microwave plasma technique in the “afterglow” zone near to the substrate and for the expanding thermal plasma technique at substrate level.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LMP [17,31]</th>
<th>ETP [21,32]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (plasma on) (mbar)</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Gas flow SF$_6$ (sccm)</td>
<td>320</td>
<td>362</td>
</tr>
<tr>
<td>Gas flow O$_2$ (sccm)</td>
<td>80</td>
<td>48</td>
</tr>
<tr>
<td>Electron density (m$^{-3}$)</td>
<td>$10^{10}$--$10^{17}$</td>
<td>$10^{16}$--$10^{17}$</td>
</tr>
<tr>
<td>Electron temperature (eV)</td>
<td>1–2</td>
<td>0.25–0.35</td>
</tr>
<tr>
<td>Ion energy (eV)</td>
<td>&lt;10</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>

LMP, linear microwave plasma; ETP, expanding thermal plasma.
In reaction (7), O is a radical. Consequently, on the basis of reaction mechanisms in both the LMP and ETP technique, it is expected that the surface chemical processes are governed by F and O radicals. Details about the physical explanation of the creation of a texture by using the LMP technique in a SF$_6$/O$_2$ plasma chemistry can be found elsewhere [15–17].
The textured surfaces have been analyzed by means of reflectometry (Varian Carry 501ii, 250—1200nm), which consists of an integrating sphere setup to investigate the front surface reflection reduction. Before measuring the reflection of the plasma textured wafers, adsorbate layers, as for example SiO$_2$, explained in detail in Ref. [16] and [17], have been removed using a wet chemical HNO$_3$ and successively a HF clean. Atomic Force Microscopy (AFM) (Veeco, Dimension 3100, Tapping mode) has been used to analyze the surface topography of the textured surfaces. The scan area of the textured surface is 25 μm × 25 μm consisting of 512 × 512 height data points.

4. RESULTS

Using AFM, the surface plot image and the height profile along the horizontal axis of the wafers etched by the different wet and dry etching processes are presented in Table II. Note that the etch depth for these wafers, which is determined by measuring the mass of the wafer before and after etching, is more than 9.0 μm. This etch depth is sufficient for complete removal of the saw damage. Clear differences in the surface morphology can be observed from visual inspection of the surface topography and height profiles. The LMP process results in a texture with small features, which are locally rough where the vertical peak to peak difference is similar to the as cut wafer. The ETP process leads to a texture consisting of wide crater structures. The ETP-created structures are relatively locally smooth. The vertical peak to peak difference of the ETP textured wafer is more similar to the as cut wafer. A pyramidal structure is created by applying the KOH/IPA process. The pyramidal structures have the largest peak to peak difference compared with other structures. The local smoothness of the pyramidal structures is very similar to the as cut wafer.

The height profile of the structures is presented by $(h(r))$. It is assumed that $h(r)$ is a properly defined mathematical entity, which describes the surface height of a rough surface with respect to a polished reference surface. Using first-order statistics, the 1D height distribution probability density function (HDPDF), also called $p(h)$ of the wafers etched by the LMP process, etched by the ETP process, etched by KOH/IPA and of the as cut wafer are presented in Figure 3.

The variation of heights is expressed by the root mean square (RMS) roughness and is also measure for the full width at half maximum of the HDPDF. The RMS roughness $(w)$ is expressed in micrometer and determined by [34]

$$w = \sqrt{\frac{1}{N} \sum_i (h_i - h_{avg})^2}$$  

In (8), $N$ is the total number of height data points, $h_i$ is the height for point $i$, and $h_{avg}$ is the average height based on all measured height data points. A texture with a relatively large RMS roughness leads to a large chance for multiple reflections of the incident light to the textured surface, which can result in an improved light trapping compared with a polished wafer. Note that a relatively large RMS roughness corresponds to a relatively large $\Delta h$, as presented in Figure 1, which is the vertical distance from bottom to top of the peak on the front side of the c-Si wafer. The RMS roughness of the KOH/IPA textured wafer is determined to be $(1.4 ± 0.1) μm$, which is more than two times larger than the RMS roughness of the as cut wafer $(0.59 ± 0.05) μm$ and, therefore, the HDPDF of the KOH/IPA textured surface is wider compared with the as cut wafer. The RMS roughness of the LMP textured surface is determined to be $(0.66 ± 0.02) μm$ and more similar to the as cut wafer. The RMS roughness of the ETP process is determined to be $(0.4 ± 0.1) μm$, which is marginally smaller than the as cut wafer.

The average distance between hills and valleys of a textured surface is expressed by the lateral correlation length. Similar to a large RMS roughness, a small lateral correlation length leads also to a large chance of multiple reflections of the incident light to the textured surface and, therefore, to an improved light trapping compared with a polished wafer. Note that a small lateral correlation length corresponds to a relatively large $\Delta x$, as presented in Figure 1, which is the lateral distance from top of the peak to top of the neighbors peak. To determine the lateral correlation length, we need second-order statistics to calculate the connection between random variables at different positions $r(x_1,y_1)$ and $r(x_2,y_2)$. For a homogeneously textured surface, it is valid that $p(h_1)$ is equal to $p(h_2)$, and the normalized autocorrelation function $R(\rho)$ of the height data $h(r)$ is presented by [34]:

$$R(\rho) = \frac{1}{w^2} \sum \sum h_1 \cdot h_2 \cdot p(h_1, h_2; \rho) \cdot Δh_1 \cdot Δh_2$$  

where $p(h_1, h_2; \rho)$ is the joint distribution probability density function (JDPDF) and is related to the HDPDF as well as to
the correlation of heights between two separated positions. Equation (9) describes the correlation between heights \(h_1\) and \(h_2\) at distance \(\rho\). Note that the HDPDF together with the JDPDF gives a complete and unique description of the textured surface height \(h(r)\). In the case that the distance between \(h_1\) and \(h_2\) goes to zero, the autocorrelation function equals 1, which is the maximum. In the case that the distance between \(h_1\) and \(h_2\) goes to infinity, the autocorrelation function goes to zero and the heights are uncorrelated. The lateral correlation length can be determined from the autocorrelation function and is defined as the length where the autocorrelation function equals 1/e [34]. The autocorrelation function of the KOH/IPA etched wafer, of the LMP etched wafer, of the ETP etched wafer and of the as cut wafer are presented in Figure 4. The autocorrelation functions of all the wafers have an exponential decay with an oscillating behavior, which presents the regular structure as the pyramids in the case of the KOH/IPA textured wafer, the regular structure of the LMP textured surface as well as the regular structure of the ETP textured surface. Starting from the as cut wafer with lateral correlation length of \((3.0 \pm 0.3)\ \mu m\), the KOH/IPA process creates a texture with a marginally smaller lateral correlation length of \((2.6 \pm 0.1)\ \mu m\). The lateral correlation length of the LMP textured surface is determined to be \((2.4 \pm 0.1)\ \mu m\), which is also marginally smaller than the lateral correlation length of the as cut wafer. Whereas the ETP process leads to a big crater structure with a larger lateral correlation \((3.3 \pm 0.5)\ \mu m\) and more similar to the as cut wafer.

From the RMS roughness \((w)\) and the lateral correlation length \((\xi)\), it makes sense to introduce an “aspect ratio” (AR) defined as:

\[
AR = \frac{w}{\xi}
\]

A high aspect ratio leads to a high chance for multiple reflections of the incident light and can lead to an improved light trapping compared with a polished wafer. The wafer with the largest aspect ratio is the KOH/IPA etched wafer and determined to be \((0.53 \pm 0.07)\). The LMP process results also in a larger aspect ratio of \((0.28 \pm 0.01)\) compared with the as cut wafer, which has an aspect ratio of \((0.20 \pm 0.03)\). The aspect ratio of the ETP etched wafer is determined to be \((0.13 \pm 0.02)\), which will clearly lead to less multiple reflections compared with the as cut wafer.

It should be noted that a meaningful RMS roughness can be described only on scales much larger than the lateral correlation length. The roughness on scales smaller than the lateral correlation length, called the micro roughness, is described by the roughness exponent \((\alpha)\). The micro roughness might also have strong effect on the reflection. The roughness exponent equals to the slope of the linear increasing part of the log-log-plot of the RMS roughness as function of the scan length \((L)\) of the AFM for scan lengths much smaller than the lateral correlation length [35]:

\[
w(L) \sim L^\alpha \quad L \ll \xi
\]

\[
w(L) \sim w \quad L \gg \xi
\]

The roughness exponent is between 0, which corresponds to a surface with “the maximum” of micro roughness, and 1, which corresponds to a texture that is locally smooth. The RMS roughness as function of the scan length of the LMP etched wafer, the ETP etched wafer, the KOH/IPA etched wafer and the as cut wafer is presented in Figure 5. The pyramidal structures are locally very smooth, which corresponds to a relatively high roughness.

![Figure 4. Autocorrelation function determined for the height data obtained from atomic force microscopy for the wafer etched by the linear microwave plasma (LMP) process, by the expanding thermal plasma (ETP) process, by potassium hydroxide isopropanol (KOH/IPA) and the as cut wafer.](image)

![Figure 5. Log-log plot of the root mean square roughness determined as function of the length of the scan area, which represents a square of the linear microwave plasma (LMP) etched wafer, the expanding thermal plasma (ETP) etched wafer, the potassium hydroxide isopropanol (KOH/IPA) etched wafer and the as cut wafer. The RMS roughness determined at different lengths of scan areas \((w(L)\)\) is normalized with RMS roughness of the total scan area \((w)\).](image)
The reflection as function of the wavelength for the wafer etched by the different processes is presented in Figure 6. Applying the KOH/IPA process and the LMP process leads to a decrease in reflection as function of the wavelength compared with the as cut wafer, apart from the infrared part of the LMP textured wafer. Whereas, applying the ETP process leads to an increase of the reflection as function of the wavelength and the ETP process, under the conditions used, is, therefore, not efficient for effective light trapping. Similar to the reflection as function of the wavelength, the weighted reflection ($R_w$), which is also presented in Table III, of the wafer etched by the ETP process is increased to $(31.9 ± 0.1)\%$ in comparison with the as cut wafer $(27.2 ± 0.1)\%$. The KOH/IPA and LMP processes lead to a lower weighted reflection of $(11.2 ± 0.1)\%$ and $(8.8 ± 0.1)\%$, respectively.

As presented, the ETP technique, under the conditions used, leads to surface smoothing and, therefore, it seems to be a good technique for removal of the saw damage. Drawback of the ETP technique, under the conditions used, is that the etched wafer has a reflection, which is even higher than the as cut wafer. However, it has been shown that the LMP technique leads to an efficient light trapping and for this reason it might be promising to combine the ETP technique, for removal of the saw damage, and the LMP technique, to create a texture with efficient light trapping. The surface scan and related height profile of the ETP + LMP textured wafer are presented in Table IV. From visual inspection of the ETP + LMP etched wafer, it is shown that the LMP technique leads to an increase of the micro roughness in comparison with the ETP etched wafer, which has already been presented in Tables II and III. This result is quantified by the roughness exponent of $(0.6 ± 0.1)$ for the ETP + LMP etched wafer, which is very similar to the roughness exponent of the LMP textured wafer of $(0.66 ± 0.02)$ and smaller compared with the roughness exponent of the ETP etched wafer $(0.89 ± 0.02)$ (Table III). Other statistical roughness parameters of the ETP + LMP etched wafer are very similar to the ETP etched wafer. The reflection as function of the wavelength of the ETP + LMP etched wafer is shown in Figure 7. Starting from the reflection of the ETP etched wafer, the LMP post-treatment leads to a reflection, which is more similar to the LMP etched wafer. The micro roughness of the ETP + LMP textured wafer leads to a complete suppression of the reflection in a broad spectral range in comparison with the ETP textured wafer. The weighted reflection of the ETP + LMP textured wafer is determined to be $(9.8 ± 0.1)\%$ [8]. The complete suppression of the reflection in a broad spectral range by nanoscale texturing, which leads to a graded layer of silicon surfaces by application of the LMP
technique, results in black silicon and has also been found in, for example Ref. [27]. Note that in Ref. [27], another texturing technique has been used as the LMP technique. Moreover, the LMP textured wafer and the ETP + LMP textured wafer appear also as black silicon, because of the sufficient micro roughness, which results also in suppression of the reflection in the range of 250–1000 nm. Furthermore, Rentsch et al. have produced complete solar cells based on plasma texturing using the LMP technique in a SF$_6$/O$_2$ plasma chemistry [15,17]. The ETP + LMP etched wafer has the potential to achieve a higher solar cell efficiency compared with the LMP textured wafer, because of the smaller aspect ratio of the ETP + LMP textured wafer. Note that the achieved solar cell efficiency of plasma textured surfaces might also strongly depend on the passivation technique, which will be used. It might be that ALD techniques lead to better passivation properties compared with plasma-enhanced chemical vapor deposition techniques.

By using the Rayleigh criterion, as described in detail by Beckmann and Spizzichino in Ref. [36], it can be proven that all textured wafers discussed in this paper are “rough”. In the case of a rough surface, the light reflects diffusely and, therefore, scatters in different directions. Moreover, in the case of a rough surface also the refracted light scatters in different directions into the silicon material in comparison with a flat surface. Specular and diffuse reflections are shown schematically in Figure 8. Note that the only possibility for the derivation of an equation for the reflection as function of the statistical roughness parameters can be done under very specific assumptions.

**Table IV.** Atomic force microscope scan is presented of the wafer etched by the ETP + LMP process. The three dimensional image and the height profile are presented.

<table>
<thead>
<tr>
<th>3D-AFM image</th>
<th>2D-AFM height profile</th>
</tr>
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<tbody>
<tr>
<td>ETP + LMP</td>
<td></td>
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</table>

AFM, atomic force microscopy; LMP, linear microwave plasma; ETP, expanding thermal plasma.

**Figure 7.** Reflection as function of the wavelength for the wafers etched by the linear microwave plasma (LMP) process, expanding thermal plasma (ETP) process, ETP + LMP process, potassium hydroxide isopropanol (KOH/IPA) process and the as cut wafer [8].

**Figure 8.** Specular reflection for a perfectly smooth surface (a) and diffuse reflection for a “rough” surface (b). Figure 8a and 8b have been redrawn from Figures presented in Ref. [36].
of the rough surface and of the incident light, which has been done by Beckmann and Spizzichino [36]. One assumption is that there is complete reflection of the incident light. However, it is clear that the textured silicon wafers presented in this paper also transmit light into the wafer and, therefore, the weighted reflection cannot be related directly by an equation to the statistical roughness parameters, which have been introduced in this section [36].

To further investigate the textured surface, the measured height data of the AFM are divided in triangles as presented in Figure 9(a and b). Note that the lateral distance of the successive measured height data points, which is equal to \(25 \mu m \times 511 = \approx 49 \text{ nm}\). We have determined the tilt angles of the triangular planes \(\theta_{\text{plane tilt}}\). From the tilt angles of the triangular planes, the plane tilt angle distribution function (PTADF) and the average plane tilt angle \(\theta_{\text{plane tilt, avg}}\) are both determined. The PTADF and the average plane tilt angle determined for the lateral size of the triangles of 49 nm provide insight in the micro roughness and/or the aspect ratio of the texture. The incident light does not see the details of the texture on the lateral scale of 49 nm and, therefore, it is assumed that the micro roughness on the scale smaller than the wavelength of the light has no impact on the scatter angle of the reflected light. In addition, it is assumed that the light with wavelength \(\lambda\) between 250 and 1200 nm will be reflected specularly by a triangle with lateral size, which is in the order of the wavelength \(\lambda\). To get insight in the reflection angle of the incident light, we have determined the average plane tilt angle as function of the lateral size of the triangular planes up to 1200 nm, which corresponds to the length of the wavelength of the near bandgap photons. Note that a relatively large plane tilt angle leads to possibilities for multiple reflections, as presented in Figure 1. One example is that the light with wavelength 250 nm will be reflected specularly by the triangle \(h_{11}-h_{16}-h_{61}\) (Figure 9(a and b)).

It is assumed that the scatter angle of the reflected light with wavelength 250 nm is determined by the slope of the triangle \(h_{11}-h_{16}-h_{61}\). Note that the lateral distance between \(h_{11}\) and \(h_{16}\) of the triangle \(h_{11}-h_{16}-h_{61}\) is determined to be 245 nm and is in the order of the wavelength of 250 nm. Moreover, it is assumed that the created micro roughness by the height points in between the triangle \(h_{11}-h_{16}-h_{61}\) will have no impact on the scatter angle of the incident light with wavelength of 250 nm.

For investigation of the light trapping, we have determined the PTADF for the lateral size of the triangles of 49 nm. The PTADF for the created textures employing the different etching techniques is presented in Figure 10 [8]. The PTADF of the ETP etched wafer is shifted to
Light trapping and surface topography of plasma textured c-Si wafers

F. M. M. Souren, J. Rentsch and M. C. M. van de Sanden

...smaller plane tilt angles compared with the as cut wafer. Whereas the PTADF of the wafer etched by the KOH/IPA process and the PTADF of the wafer etched by the LMP process show that these structures have larger plane tilt angles compared with the as cut wafer. The short post-treatment of the ETP etched wafer by the LMP technique, which is presented by the ETP + LMP etched wafer, leads to a shift of the PTADF to even larger plane tilt angles compared with the as cut wafer.

From the tilt angles of the angular planes, the average plane tilt angle (\(\theta_{\text{plane tilt, avg}}\)) has been determined. The weighted reflection has been plotted as function of the average plane tilt angle in Figure 11. The average plane tilt angle of the KOH/IPA etched wafer is determined to be (23 ± 2)° and is smaller compared with the average plane tilt angle of the as cut wafer, which is determined to be (53 ± 2)°. Note that for the ETP etched wafers, the weighted reflection is larger than the weighted reflection of the as cut wafer. The curve has a so called “tipping point”, which shows a huge decrease in the weighted reflection in comparison with the as cut wafer, where the average plane tilt angle is only marginally larger than the average plane tilt angle of the as cut wafer. The average plane tilt angle of the textured wafer, which presents the tipping point, is determined to be (61 ± 3)°, has been created by applying the LMP technique at an etch depth of (1.6 ± 0.3) μm, and is called “LMP weak texture”. It is presented in Figure 11 that the textured wafers with an average plane tilt angle larger than the average plane tilt angle of the “tipping point” have a huge decrease in weighted reflection compared with the as cut wafer. These wafers have an effective light trapping and have been etched by the KOH/IPA process, by the LMP process at different etch depths, and by the ETP + LMP process, respectively. It is presented in Table III that the average plane tilt angle of the KOH/IPA and of the LMP etched wafer is determined to be (94 ± 4)° and (93 ± 3)°, respectively. The post-treatment of the ETP etched wafer by the LMP process, presented as ETP + LMP, leads to an average plane tilt angle of (69 ± 11)°. From Figure 11, one can conclude that the average plane tilt angle correlates to the weighted reflection.

The principles of light trapping for the textures with an effective light trapping by multiple reflections, by a diffuse front surface or a combination of both will be discussed. The micro roughness of the KOH/IPA etched wafer is very similar to the micro roughness of the as cut wafer, which means that the KOH/IPA etched wafer has no additional graded layer. The KOH/IPA etched wafer has a relatively large aspect ratio of (0.53 ± 0.07) compared with the aspect ratio of the as cut wafer (0.20 ± 0.03). As a consequence of the higher aspect ratio of the KOH/IPA etched wafer compared with the as cut wafer and the very similar micro roughness, the effective light trapping of the KOH/IPA etched wafer is explained by multiple reflections.

As discussed in this section, it is assumed that light with wavelength \(\lambda\) will be reflected specularly by a triangle with lateral size in the order of the wavelength \(\lambda\). The average plane tilt angle as function of the lateral size of the triangular grids leads to physical insight of the reflection angles of the light corresponding to the wavelengths and is presented in Figure 12. For the KOH/IPA etched wafer, the large aspect ratio corresponds also to a large average plane tilt angle as function of the increasing length of the lateral size of the triangular grids as presented in Figure 12 and explains the multiple reflections that lead to efficient light trapping.

The ETP textured wafer has a relatively high weighted reflection ((31.9 ± 0.1)%) compared with the as cut wafer.
has been determined from the measured height pro-

The thickness of the as cut wafer, the small micro roughness and the small aspect ratio of the ETP etched wafer correspond also to the small average plane tilt angle as a function of the lateral size of the triangular grids as presented in Figure 12.

The efficient light trapping of the ETP + LMP etched wafer can be explained by a graded layer, because of more micro roughness of the ETP + LMP textured wafer compared with the as cut wafer. The thickness of the graded layer has been estimated on (200 ± 50) nm, which has been determined from the measured height profile. Additional multiple reflections do not occur for the ETP + LMP textured wafer, because of the very similar aspect ratio (0.17 ± 0.04) compared with the as cut wafer (0.20 ± 0.03). For small lateral size of the triangular grids, the average plane tilt angle of the ETP + LMP textured wafer is even larger than the as cut wafer, because of more micro roughness of the ETP + LMP textured wafer. With increasing lateral size of the triangular grids the large average plane tilt angle converges to the average plane tilt angle of the ETP textured wafer as presented in Figure 12. This can be explained by the fact that the ETP + LMP textured wafer is very similar to the ETP textured wafer with both a very similar aspect ratio, but the ETP + LMP textured wafer has additional micro roughness, which is not measured with increasing lateral size of the triangular grids and results in a very similar average plane tilt angle.

The efficient light trapping of the LMP textured wafer can be explained by a combination of multiple reflections of the incident light towards the wafer surface and a graded layer. Multiple reflections can be explained by the higher aspect ratio of the LMP textured wafer (0.28 ± 0.01) compared with the as cut wafer (0.20 ± 0.03). The LMP textured surface contains also a graded layer, because of the higher micro roughness compared with the as cut wafer. The thickness of the graded layer of the LMP textured wafer is determined to be (200 ± 50) nm. For small lateral sizes of the triangular grids, the average plane tilt angle of the LMP textured wafer is similar to the average plane tilt angle of the KOH/IPA etched wafer. The average plane tilt angle for the LMP textured wafer decreases more with increasing lateral size of the triangular grids compared with the KOH/IPA textured wafer. This can be explained by the fact that with increasing grid size the micro roughness of the LMP textured wafer is excluded and the aspect ratio of the LMP textured wafer is smaller compared with the KOH/IPA textured wafer. The average plane tilt angle of the LMP textured wafer is larger than the as cut wafer with increasing grid size, which corresponds to the larger aspect ratio of the LMP textured wafer compared with the as cut wafer and explains the additional multiple reflections for the LMP textured wafer.

The light trapping of the “LMP weak texture” is efficient, which can be explained in a similar way as the efficient light trapping of the ETP + LMP textured wafer. The “LMP weak texture” has more micro roughness compared with the as cut wafer and, therefore, the “LMP weak texture” has an additional graded layer compared with the as cut wafer. The aspect ratio of the “LMP weak texture” is determined to be (0.19 ± 0.03), which is very similar as the aspect ratio of the as cut wafer (0.20 ± 0.03) and means that the effect of multiple reflections is very similar for the “LMP weak texture” and the as cut wafer. The roughness exponent of the “LMP weak texture” is determined to be (0.74 ± 0.02), which is only marginally smaller than the roughness exponent of the as cut wafer (0.78 ± 0.02). The higher micro roughness of the “LMP weak texture” leads to a larger average plane tilt angle compared with the as cut wafer for small lateral size of the triangular grids and with increasing lateral size of the triangular grids, the average plane tilt angle of the “LMP weak texture” decreases to a level that is similar to the as cut wafer.

Deposition of the a-SiNₓ:H anti-reflection coating with thickness of (67 ± 5) nm on the front side of the ETP etched wafer, which is abbreviated as ETP + a-SiNₓ:H system, results in an improved light trapping compared with the ETP etched wafer as presented in Figure 13. Note that the a-SiNₓ:H anti-reflection coating has been deposited using the LMP technique. The reflection as a function of the wavelength for the ETP + a-SiNₓ:H system has a minimum at 5.3 × 10² nm, and the weighted reflection is determined to be (9.7 ± 0.1)%. As mentioned before, the ETP + LMP etched wafer has a graded layer which results in effective light trapping in a broad wavelength range of 250–1000 nm and the ETP + a-SiNₓ:H system has a
minimum of the reflection at one specific wavelength, because the a-SiN$_2$H has one typical refractive index as function of the thickness of the a-SiN$_2$H. The ETP + LMP etched wafer has a lower reflection for wavelengths smaller than $4.2 \times 10^2$ nm as well as for wavelengths between $7.3 \times 10^2$ nm and $11.4 \times 10^3$ nm compared with the ETP + a-SiN$_2$H system as is shown in Figure 13. For the dielectric passivation system of the wafer etched by the ETP + LMP process, which is abbreviated as ETP + LMP + a-SiN$_2$H system, also a broad spectrum of wavelengths from 250 nm up to 1000 nm is trapped effectively and leads to a lower reflection as function of the wavelength compared with the ETP + a-SiN$_2$H system and the ETP + LMP etched wafer, which is also presented in Figure 13. The thickness of the a-SiN$_2$H for the ETP + LMP passivation system is determined to be $(84 \pm 5)$ nm. The reflection of the ETP + LMP + a-SiN$_2$H system is lower than 1% between $5.2 \times 10^2$ nm and $8.2 \times 10^2$ nm, and the weighted reflection is determined to be $(1.3 \pm 0.1)%$ and shows that the light trapping is excellent compared with the other optical systems shown in Figure 13. Note that the thickness of the a-SiN$_2$H deposited on the different textured wafers as presented in Figure 13 has not been optimized to minimize the reflection. However, the results in Figure 13 show clearly that a-SiN$_2$H leads to a minimum of the reflection at one specific wavelength and that a graded layer as obtained for the ETP + LMP textured wafer leads to broad range of wavelengths, which are trapped effectively. Deposition of the a-SiN$_2$H anti-reflection coating results for the LMP textured wafer and for the KOH/IPA etched wafer also in very efficient light trapping with weighted reflection $<2%$.

5. CONCLUSION

A complete description of the textured surface $h(r)$, measured by AFM, can be obtained using the HDPDF, based on first-order statistics and the JPDF, based on second-order statistics. In this paper, we found a clear relation between the average plane tilt angle and the weighted reflection. Using this relation, we are able to determine whether a texture leads to an efficient light trapping based on the average plane tilt angle of the textured wafer with respect to the tipping point of the weighted reflection as function of the average plane tilt angle.

It has already been presented in literature that effective light trapping can be obtained by multiple reflections or by a graded layer, which results in a diffuse reflection or a combination of both effects. We have determined that multiple reflections occur in the case of a sufficient high aspect ratio compared with the as cut wafer. Effective light trapping caused by a graded layer occurs in the case of a higher micro roughness compared with the as cut wafer. The pyramidal structure of the KOH/IPA textured wafer has a high aspect ratio and the effective light trapping is explained by multiple reflections. The LMP textured wafer has an effective light trapping, which can be explained by a combination of multiple reflections and a graded layer. The increase in multiple reflections of the LMP textured wafer compared with the as cut wafer can be explained by an increase in aspect ratio and the graded layer of the LMP textured wafer can be explained by the increase in micro roughness compared with the as cut wafer. Application of the ETP technique, under the conditions used, leads to a smaller aspect ratio and even less micro roughness compared with the as cut wafer and explains the higher reflection of the ETP etched wafer compared with the as cut wafer. A short post-treatment of the ETP etched wafer by the LMP technique results in the ETP + LMP etched wafer, which has an efficient light trapping in a broad wavelength range of 250–1000 nm, explained by a graded layer and corresponds to an increase in micro roughness. a-SiN$_2$H with thickness of $(67 \pm 5)$ nm, deposited on the ETP etched wafer, has one refractive index and, therefore, a minimum in the reflection at one specific wavelength of $5.3 \times 10^2$ nm. The ETP + LMP + a-SiN$_2$H system has also an effective light trapping in a broad spectral range of 250–1000 nm with weighted reflection of $(1.3 \pm 0.1)%$ and even a lower reflection compared with the ETP + LMP etched wafer.

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Light trapping and surface topography of plasma textured c-Si wafers

365


