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The effects of different parameters of pyramidal textured silicon surface on the optical reflectance

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ABSTRACT

The effects of different light trapping structure, as formed on the surface of silicon solar cells to increase the light trapping efficiency, are different on the optical reflectance and absorptance. The aim of this paper is to study the effects of the incident angle and pyramidal textured surface formed mechanically on the light trapping efficiency. The base angle size can be controlled mechanically to break through the limitation of crystal structure, and a fillet on the included angle between neighboring pyramidal structures was obtained unavoidable. A numerical algorithm was developed to calculate the weighted reflectance of different structure in this work. Every light transmission process was tracked and the weighted reflectance was calculated numerically. Then the light trapping efficiency of the pyramid texture with different parameters was obtained and analyzed. The weighted reflectance in changed conditions was calculated respectively. By analyzing the values, the optimized parameters of the pyramid texture were proposed, and the best incident angle was obtained.

1. Introduction

Reducing the cost of solar cells and improving the photoelectric conversion efficiency have attracted great attention in recent years. Forming a textured surface using suitable texturing methods was demonstrated as an effective means of increasing the light trapping efficiency (Razykov et al., 2011) and has become an essential aspect of solar cell technologies.

Silicon is the dominant material for fabricating solar cells nowadays (Swanson, 2006) because of its abundant content in earth's crust, high photoelectric conversion efficiency and low ecological impact (Bruton, 2002). The main preparation methods of the light trapping structure on the surface of silicon solar cells are wet etching techniques (Kim et al., 2008; Kumar et al., 2015; Vallejo et al., 2007), mechanical texturization (Spiegel et al., 2002), laser treatment (Dobrzański et al., 2008), reactive ion etching (RIE) (Chen et al., 2015; Ruby et al., 2002; Winderbaum et al., 1997), mask technique (Green, 2003) and electrochemical corrosion (Kim et al., 2004), etc. These methods have played a positive role in reducing the reflection of light and improving the utilization rate of light. Currently, wet etching is actually a good compromise between cost and efficiency to fabricate the light trapping structure on the surface of silicon solar cells (El-Amin, 2015; Papet et al., 2006). It is now well established that porous silicon and texturization are a promising candidates for reducing surface reflectance (Mohamed et al., 2013). Owing to the isotropy of polycrystalline silicon, the morphology of porous silicon can be etched on the surface of polycrystalline silicon solar cells by acid etching (Kim et al., 2008). As for monocrystalline silicon solar cells, pyramidal textured surface can be formed due to the anisotropy of material (Baker-Finch and Mcintosh, 2013) by alkaline etching (Moreno et al., 2014). The reflectance showed dependence on the base angle, with larger base angle size resulting in reduced reflectance (Hua et al., 2010). However, the limitation of crystal structure makes the largest base angle of the pyramid is 54.74° (Magnin et al., 2014), some experimental studies believe that the angle is closer to 50–52° (Baker-Finch and Mcintosh, 2013; Yang et al., 2013). The mechanical manufacturing process can break through the limitation, to obtain larger base angle, but we found very few studies researched mechanical method deeply. A fillet on the included angle between neighboring pyramidal structures was obtained unavoidable, which was also a considered aspect.

The pyramidal textured silicon surface fabricated by the mechanical manufacturing process was tightly and regularly. And the processing parameters can be arbitrarily controlled in the process, which makes it easier to obtain a lower reflectance. The lowest reflectance of the pyramidal textured surface formed by

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alkaline etching is about 10.50% (Lv et al., 2011; Rosa et al., 2011). Our work here showed that 5% or even lower reflectance can be obtained mechanically with reasonable processing parameters. To obtain an optimized structure parameters and incident angle, a numerical algorithm was designed using ray-tracing simulation (Byun et al., 2011; Magnin et al., 2014; Yagi et al., 2006) as a theoretic basis.

In this paper, the mechanism of light trapping was studied in principle. An algorithm was developed using MATLAB, which can calculate the weighted reflectance of any light trapping structure with equation-expressed cross-section curves. The optimized structure parameters and the best incident angle were obtained by analyzing the calculated values. A novel method was provided for the subsequent fabrication of pyramidal textured surface by mechanical way, which can maximize the photoelectric conversion efficiency of silicon solar cells, and reduce the production cost.

2. Pyramidal textured surface models and calculated methods

2.1. Pyramidal textured surface models

Normal pyramidal textured surface morphology was depicted in Fig. 1. The reflectance does not depend upon the height of pyramid, theoretically. In the perspective of geometric-optical, the size-independent behavior of the reflectance was illustrated by a simple two-dimensional mathematical model schematically in Fig. 2, which was a profile. The main areas which play the role of light trapping efficiency is the orange (second reflection) and green (third reflection) areas. The ratio of the orange area to the green area does not change with different model sizes, which mean that the reflectance will not change. This principle applies equally to the three-dimensional pyramid structure. The principle is still the same even the shape of pyramid was changed. The ratios of different reflection areas may change with different shape of pyramid, but not sizes, the proportion of lights which enters each area accounting for the total area does not change. Therefore, the height of the structure was defined as a unit length. The reflectance of the whole wafer was not affected by the change of the parameters in the subsequent stage.

Although the structure size has little effect on the reflectance, a smaller, denser structure is expected (right one showed in Fig. 3) in the actual preparation process of the light trapping structure. On the one hand, the transmission distance in light trapping structure was reduced, which reduced the loss of light, improved the absorption rate; on the other hand, less materials were removed during the production process, which improved the production efficiency, enhanced the strength of the substrates.

The response sensitivity of photovoltaic cells to the lights with different wavelength was not coincident. The solar radiation wavelength which can produce photovoltaic effect were generally ranging from 0.4 μm to 1.2 μm (Llopis and Tobías, 2005). Therefore, the texture which can be considered as a smooth plane which cannot produce a light trapping efficiency with size smaller than 0.4 μm, made all effective wavelengths larger than it, mirror reflection occurred; on the other hand, diffuse reflection occurred when the texture size is larger than 1.2 μm. For this reason, the height of the structure should be larger than the maximum effective wavelength 1.2 μm.

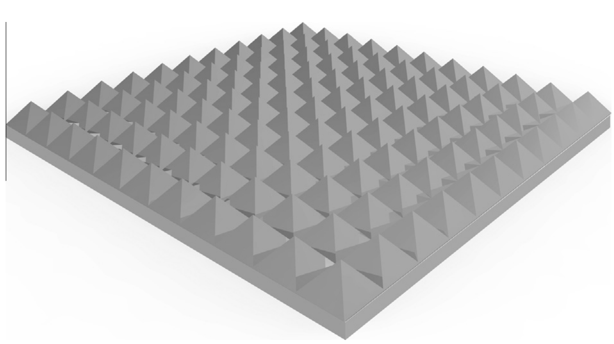

Fig. 1. Normal pyramidal textured surface morphology.

Schematics of cross-sectional views for ideal model with no fillet on the included angle and the model with a fillet on the included angle were shown in Fig. 4(a) and (b), respectively. The second model was proposed considering that there exists a fillet on the included angle between neighboring pyramidal structures fabricated by mechanical way. As mentioned above, the height of the structure was set to a unit length in the algorithm. Each size and angle of the structure were shown in Fig. 4.

2.2. Calculated methods

A thin beam of light entered into the light trapping area and escaped after reflecting several times. The trajectory of incident light and the cross-section curves of the light trapping structure were expressed by equations. The ratio of the reflected light intensity to the incident light intensity was defined as primary reflectance R. The ratio of the reflected light intensity after t times of reflections to the incident light intensity was defined as exitance β:

$$\beta = R^t \tag{1}$$

As depicted in Fig. 5, n thin beams of light were obtained in the width direction (AC) on average when a beam of parallel light was projected onto the light trapping structure. It was assumed that n is large enough, the reflection times of the jth beam of light was noted for t_j, and the exitance was $\beta_j = R^{t_j}$. The ratio of the total reflected light intensity to the total incident light intensity was defined as the weighted reflectance γ, which can be expressed by the following equation:

$$\gamma = \frac{1}{n}\sum_{j=1}^{n}\beta_j = \frac{1}{n}\sum_{j=1}^{n}R^{t_j} \tag{2}$$

Note the number of beams of light whose reflection times t_j is i for n_i ($0 \leqslant n_i \leqslant n$), hence the equation (2) can be rewritten as:

$$\gamma = \frac{1}{n}\sum_{j=1}^{n}R^{t_j} = \sum_{i=1}^{\infty}\zeta_i R^i \tag{3}$$

where ζ_i is the proportion of lights whose reflection times is i accounts for the total lights. It can be conformed to the following equation:

$$\sum_{i=1}^{\infty}\zeta_i = 1, \quad \zeta_i = \frac{n_i}{n}, \quad i = 1, 2, \ldots \tag{4}$$

The reflectance R of common silicon wafer is about 33.33% (Nositschka et al., 2003). The exitance $\beta_{19} = R^{19} = 8.6 \times 10^{-10}$ with $i = 19$. Because of $\zeta_i < 1$, the calculations can be ignored when $i > 19$, in which case, the weighted reflectance γ:

$$\gamma = \sum_{i=1}^{19}\zeta_i R^i \tag{5}$$

In order to calculate the weighted reflectance, tracked each of thin beam of light according to the reflection law. A program was designed to calculate the reflection times of every thin beam of light, and the weighted reflectance was calculated according to the reflection times. The calculation process was performed using MATLAB. The flow chart for the numerical algorithm was shown