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МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

THE INFLUENCE OF THE OPENING BETWEEN THE HEADS OF THE TWO CLOSEST PYRAMIDS IN TEXTURED SURFACE FOR SOLAR CELLS AND ITS APPLICATION ON THE SPECTRAL RESPONSE

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This study is concerned with the development of a new solar cell prototype in order to improve photovoltaic efficiency. In this model we show that the material can have five and more successive incident-ray absorptions instead of three current, where we changed the direction of the reflected ray, by varying the angle between the two neighbouring pyramids, the incidence angle, the opening between the heads of the two closest pyramids and their height. Thus, with an angle between the two neighbouring pyramids varying between 24 and 12° and an angle of incidence varying between 78 and 84°, the opening between the heads of the two closest pyramids varied respectively from 4.25 to 2.10 μm for a pyramid height of 10 μm. This leads to a substantial increase of the spectral response and the photovoltaic efficiency.

Статья посвящена разработке прототипа новой солнечной батареи с улучшенной фотоэлектрической эффективностью. Показано, что используемый для прототипа материал может достичь пяти и более успешных поглощений падающего луча вместо трех, достигнутых в настоящее время, за счет изменения направления отраженного луча варьированием угла между двумя соседними пирамидами, угла падения, расстояния между вершинами двух ближайших пирамид и их высоты. А именно, угол между двумя соседними пирамидами меняется в диапазоне от 24 до 12°, а угол падения — в диапазоне от 78 до 84°. Для этих значений углов расстояние между вершинами двух ближайших пирамид меняется от 4,25 до 2,10 мкм для пирамиды высотой 10 мкм. Это приводит к значительному возрастанию спектрального отклика и фотоэлектрической эффективности.

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INTRODUCTION

Renewable resources are clean or green energy sources that give much lower environmental impact than conventional energy sources. Renewable resources are attractive because they are replenished naturally — which means that they will never run out. Solar cells use the sun, a free and inexhaustible source of fuel, to produce emission-free electricity. The crystalline

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silicon is the most important material in the photovoltaics today. According to predictions, it will remain an important and dominant material in photovoltaics over the next years, owing to its well recognized properties and its established production technology [1, 2]. Crystalline silicon solar cells operate by absorbing light and using the discrete energy from the received photons to pump electrons to their excited state. The excited electrons migrate through the material's layers and produce an electrical current [3, 4]. Silicon is an important alternative. High-efficiency silicon solar cells need a textured front surface to reduce reflectance since optical losses due to reflectance of incident solar radiation are one of the most important factors limiting their efficiency. Texturing of monocrystalline silicon is usually done by etching in alkaline solutions [5–9]. There are three different kinds of texturization techniques for multicrystalline silicon solar cells which are currently under investigation for implementation in a production line:

1) Acid texturization [10, 11];
2) Reactive ion etching [12];
3) Mechanical texturization [13, 14].

1. TEXTURED SURFACE IN THE FORM OF PYRAMID

Surface texturing can be accomplished in a number of ways. A single crystalline substrate can be textured by etching along the faces of the crystal planes. The crystalline structure of silicon results in a surface made up of pyramids if the surface is appropriately aligned with respect to the internal atoms. One such pyramid is illustrated in Fig. 1. An electron microscope photograph of a textured silicon surface is shown below. This type of texturing is called «random pyramid» texture, and is commonly used in industry for single crystalline wafers [15].

For multicrystalline wafers, only a small fraction of the surface will have the required orientation of $\langle 111 \rangle$ and consequently these techniques are less effective on multicrystalline wafers. However, multicrystalline wafers can be textured using a photolithographic technique [16] as well as mechanically sculpting the front surface using dicing saws [17] or lasers [18] to cut the surface into an appropriate shape [19].

Another type of surface texturing used is known as «inverted pyramid» texturing [20, 21]. Using this texturing scheme, the pyramids are etched down into the silicon surface rather than etched pointing upwards from the surface. A photograph of such a textured surface is shown below.

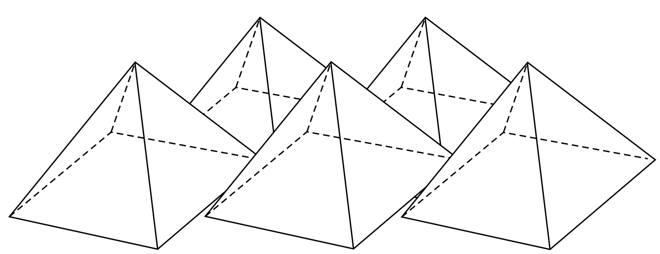

Fig. 1. A square based pyramid which forms the surface of an appropriately textured crystalline silicon solar cell

2. DEVELOPMENT OF SUGGESTED MODEL

The model suggested in this work allows the material to have four and more successive absorptions of the incident rayon, by varying the incident angle i_1, the opening between the heads of the two closest pyramids f, the angle between the two neighbouring pyramids and their height h ($h = 10\ \mu$m).

This model is based on reflection and refraction laws of incident rays on the surfaces of two neighbouring pyramids [22]. By considering N the number of rays that are incident on the surface of pyramid I and r the reflection coefficient, the proportion of the absorbed rays by the material is given by $N(1-r)$, whereas that of the reflected rays is Nr. These tatters fall on the surface of pyramid II where they are absorbed with $Nr(1-r)$ proportion, while Nr^2 proportion is reflected [23]. A change of the aperture between the summits of the neighbouring pyramids will allow the Nr^2 rays to fall a second time on pyramid I and the Nr^3 rays to fall a third time on pyramid II and the Nr^4 rays to fall a fourth time and so on (Fig. 2). This mechanism will permit one to recuperate a third and fourth and fifth proportion of the incident rays $Nr^2(1-r)$ and $Nr^3(1-r)$ and $Nr^4(1-r)$, that will participate to the improvement of the photovoltaic properties such as the spectral response. The total amount of the absorbed rays in the sum of the five successive incidences is given by

$$N(1-r) + Nr(1-r) + Nr^2(1-r) + Nr^3(1-r) + Nr^4(1-r) = N(1-r^5). \quad (1)$$

If i_1 represents the angle of the first projection on the surface of pyramid I, i_2 the angle of the second projection on the surface of the second pyramid, i_3 the angle of the third projection on the surface of pyramid I, and i_4 the angle of the fourth projection on the surface of pyramid II, then the angle between the two neighbouring pyramids

$$\alpha = i_4 - i_3 = i_3 - i_2 = i_2 - i_1 = i_n - i_{n-1}. \quad (2)$$

The opening between the heads of the two closest pyramids is

$$f = 2h \operatorname{tag}\left(\frac{\alpha}{2}\right). \quad (3)$$

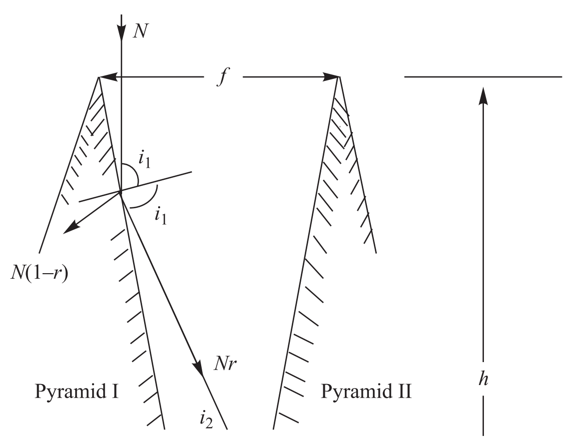

Fig. 2. Textured surface with five successive incidences (suggested model) $\alpha = 22^\circ$; $i_1 = 79^\circ$; $i_2 = 57^\circ$; $i_3 = 35^\circ$; $i_4 = 13^\circ$; $h = 10\ \mu$m; $f = 3.89\ \mu$m

Incidence angles and the angle between the two neighbouring pyramids and the opening between the heads of the two closest pyramids

$\alpha = i_n - i_{n-1}$	f, μm	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8
30	5.36	75	45	15					
28	4.99	76	48	20					
26	4.62	77	51	25					
24	4.25	78	54	30	6				
22	3.89	79	57	35	13				
20	3.53	80	60	40	20	00			
18	3.17	81	63	45	27	9			
16	2.81	82	66	50	34	18	2		
14	2.46	83	69	55	41	27	13		
12	2.10	84	27	60	48	36	24	12	00

The calculated values of f for different angle between the two neighbouring pyramids α and the opening between the heads of the two closest pyramids f and different incidence angles i_n in order to the height $h = 10$ μm are assembled in table.

3. SPECTRAL RESPONSE

The spectral response is conceptually similar to the quantum efficiency. The quantum efficiency gives the number of electrons output by the solar cell compared to the number of photons incident on the device, while the spectral response is the ratio of the current generated by the solar cell to the power incident on the solar cell.

The ideal spectral response is limited at long wavelengths by the inability of the semiconductor to absorb photons with energies below the band gap. This limit is the same as that encountered in quantum efficiency curves. However, unlike the square shape of QE curves, the spectral response decreases at small photon wavelengths. At these wavelengths, each photon has a large energy, and hence the ratio of photons to power is reduced. Any energy above the band gap energy is not utilized by the solar cell and instead goes to heating the solar cell. The inability to fully utilize the incident energy at high energies, and the inability to absorb low energies of light represents a significant power loss in solar cells consisting of a single $p{-}n$ junction.

Spectral response is important since it is the spectral response that is measured from a solar cell, and from this the quantum efficiency is calculated. The quantum efficiency can be determined from the spectral response by replacing the power of the light at a particular wavelength with the photon flux for that wavelength.

The spectral response is higher in the visible and infrared regions. It is given by

$$R_s = \frac{J_{\text{ph}}}{qN(1-r)}, \tag{4}$$

where $N(1-r)$ represents the proposition of absorbed rays.

For a textured plane the relation (4) becomes

$$R_s = \frac{J_{\mathrm{ph}}}{qN(1-r^2)}, \tag{5}$$

where $N(1-r^2)$ represents the absorbed rays. By applying the model that uses three successive incidences, the relation (5) becomes

$$R_s = \frac{J_{\mathrm{ph}}}{qN(1-r^3)}, \tag{6}$$

where $N(1-r^3)$ represents the absorbed rays. By applying the model that uses five successive incidences, the relation (6) becomes

$$R_s = \frac{J_{\mathrm{ph}}}{qN(1-r^5)} \tag{7}$$

where $N(1-r^5)$ represents the absorbed rays. We fix $x = J_{\mathrm{ph}}/qN$ and, as we started on the basis of r as reflection coefficient, we will get

$$R_s = \frac{X}{(1-r^5)}. \tag{8}$$

In the case of this model the variation of the spectral response as a function of the reflection coefficient r is shown in Fig. 3.

This variation is compared in the same figure with the ideal case, with the case of normal plane and with that of the textured plane in order to represent this relation for various values of the spectral response as a function of the reflection coefficient r shown in Fig. 3 which shows well enough that we are getting nearer to the ideal values in case we want to take advantage of ray incidence five times, then four times, then three, then twice, then once.

Based on these results, we will get good results especially for the treated plane surface, where reflection coefficient r is near zero and consequently the spectral response increases almost to the ideal values, which helps contribute to a significant improvement of the photovoltaic efficiency.

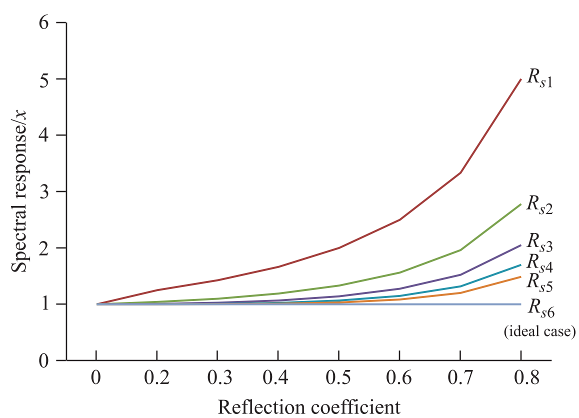

Fig. 3. Spectral responce vs reflection coefficient $R_{s1} = x/1-r$, $R_{s2} = x/1-r^2$, $R_{s3} = x/1-r^3$, $R_{s4} = x/1-r^4$, $R_{s5} = x/1-r^5$, $R_{s6} = x$ (ideal case)

CONCLUSIONS

This study is based on the use of successive reflections on the surface of textured planes of solar cells, in order to improve the photovoltaic efficiency. For achieving this goal, we developed a model that can recuperate three and four reflections instead of two current, by varying the incidence angle, the angle between the two neighbouring pyramids and the aperture between the neighbouring pyramids. This model permits the solar incident rays to have four and five successive absorptions by the material.

The calculations of incidence angles on the pyramids surfaces and the opening between the heads of the two closest pyramids were carried out for different pyramid heights. The application of the suggested model shows a significant improvement of the photovoltaic parameters such as the spectral response. The representative curves of these parameters in the case of this model approach those representing the ideal case. In conclusion, we can say that this model can contribute to a significant improvement of the photovoltaic efficiency and can be applied to other photovoltaic materials.

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