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POSSIBLE IMPROVEMENT OF SOLAR CELL EFFICIENCY

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In this work we present the development of a new solar cell prototype in order to improve photovoltaic efficiency. In this model we show that the material can have three successive incident ray absorptions instead of two currently, by varying the incidence angle, the aperture between the summits of two neighbouring pyramids and their height. This study concerns in particular the photovoltaic parameters such as the spectral response. This model was checked for angles varying between 54 and 60° and for pyramid heights between 5 and 10 μm. For these values of incidence angle, the apertures between the summits of two neighbouring pyramids varied respectively from 14.54 to 11.54 μm for a pyramid height of 10 μm.

В работе представлена разработка нового прототипа солнечной батареи с улучшенной фотогальванической эффективностью. Для данной модели показано, что рассматриваемый материал может иметь три последовательных ступени поглощения начального излучения, в отличие от двух ступеней для имеющихся моделей, за счет изменения начального угла, апертуры между вершинами двух соседних пирамид и их высот. Исследуются, главным образом, фотогальванические параметры, а именно спектральный отклик. Модель была проверена для углов, изменяющихся в пределах от 54 до 60°, и для высот, изменяющихся в интервале 5–10 мкм. Для рассмотренных значений начального угла апертуры между вершинами двух соседних пирамид менялись от 14,54 до 11,54 мкм при заданной высоте пирамиды 10 мкм.

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INTRODUCTION

Photovoltaic materials [1–4] are distinguished by an index of refraction greater than 3 and a high reflection coefficient in the visible spectrum. The reflection can be more reduced by covering the cell surface with an antireflective layer in order to bring the percentage of the reflected rays to a reasonable value. In effect, a normal plane of silicon can reflect up to 35% of the received rays [5]. This rate can be reduced to 10% if the plane is covered with an antireflective layer and hence making the penetrating rays rate reach 90%. With the prototype presented in this model three reflections can be minimized to less than 10%, leading to the improvement of the spectral response, the absorption coefficient, the generation rate and the photovoltaic efficiency.

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1. DEVELOPMENT OF THE SUGGESTED MODEL

In this model, the textured surface is obtained by an anisotropic chemical attack on semiconductor material. The pyramids obtained by this mechanism present regular orientations having a height comprised between 5 and 10 μm.

The model suggested in this work allows the material to have three successive absorptions of the incident rayon, by varying the incident angle i, the aperture between the pyramids f and their height h.

This model is based on reflection and refraction laws of incident rays on the surfaces of two neighbouring pyramids. By considering N the number of rays that are incident on the surface of pyramid I and the reflection coefficient r, 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. 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 (Fig. 1). This mechanism will permit one to recuperate a third proportion of the incident rays $Nr^2(1-r)$, that will participate in the improvement of the photovoltaic properties such as the spectral response, the absorption coefficient and the generation rate. The total amount of the absorbed rays in the sum of the three successive incidences is given by $N(1-r^3)$.

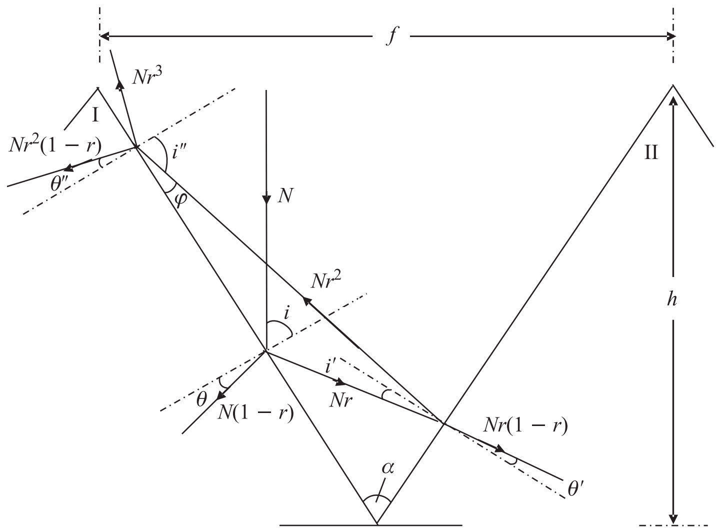

Fig. 1. Textured surface with three successive reflections (suggested model)

Let φ be the angle between the incident ray Nr^2 and the face of pyramid I, and α — the angle between the two neighbouring pyramids:

$$\alpha = i + i'. \tag{1}$$

The sum of triangle angles is π, thus

$$\varphi = \left(5i - \frac{3\pi}{2}\right). \tag{2}$$

And as $\varphi > 0$, then

$$i > \left(\frac{3\pi}{10} = 54^\circ\right). \tag{3}$$

If i represents the angle of the first projection on the surface of pyramid I, and i' — the angle of the second projection on the surface of the second pyramid, then

$$i' = \pi - 3i. \tag{4}$$

In the case of crystalline silicon and for wave length $\lambda = 590$ nm; the application of Snell's law between the surfaces of pyramids I and II permits one to obtain the refraction angles θ, θ', θ''. The angles correspond respectively to the incidence angles i, i' and i'' (Table 1).

Table 1. **Incidence and refraction angles**

i, °	54	55	56	57	58	59	60
i', °	18	15	12	9	6	3	0
i'', °	90	85	80	75	70	65	60
θ, °	11.76	11.91	12.06	12.20	12.34	12.47	12.61
θ', °	4.46	3.74	3.00	2.26	1.51	0.76	0
θ'', °	14.59	14.53	14.36	14.08	13.69	13.20	12.60
φ, °	0	5	10	15	20	25	30
α, °	72	70	68	66	64	62	60

Table 2. **Distance (f, μm) between the summits of two neighbouring pyramids**

h, μm	i, °						
	54	55	56	57	58	59	60
5	7.27	7.00	6.75	6.49	6.25	6.00	5.77
6	8.72	8.40	8.10	7.79	7.50	7.20	6.92
7	10.18	9.80	9.45	9.09	8.75	8.40	8.08
8	11.63	11.20	10.80	10.38	10.00	9.60	9.23
9	13.09	12.60	12.15	11.68	11.25	10.80	10.39
10	14.54	14.00	13.50	12.98	12.50	12.00	11.54

The aperture f between the summits of the two neighbouring pyramids is given by the relation:

$$f = 2h\tan\left(\frac{\pi}{2} - i\right). \tag{5}$$

The calculated values of f for different heights h and different incidence angles i are assembled in Table 2.

2. SPECTRAL RESPONSE

The spectral response is an essential parameter in the characterization of solar cells; for a silicon normal plane this parameter is given by the relation:

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

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

For a textured plane, relation (6) becomes

$$R_s = \frac{J_{\mathrm{ph}}}{qN(1 - r^2)}, \tag{7}$$

where $N(1 - r^2)$ represents the absorbed rays. By applying the model that uses three successive incidences, relation (7) becomes

$$R_s = \frac{J_{\mathrm{ph}}}{qN(1 - r^3)}, \tag{8}$$

where $N(1 - r^3)$ represents the absorbed rays.

If we write $x = J_{\mathrm{ph}}/qN$, we get

$$R_s = \frac{x}{(1 - r^3)}. \tag{9}$$

In the case of this model the variation of the spectral response as a function of the reflection coefficient r is shown in Fig. 2.

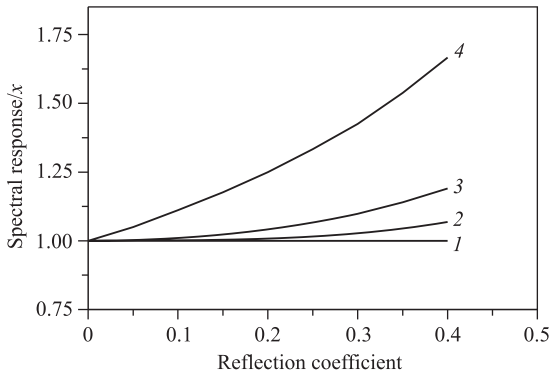

Fig. 2. Spectral response vs. reflection coefficient: *1* — ideal case; *2* — suggested model; *3* — textured surface; *4* — normal surface

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. The results show that spectral response of the suggested model approaches more and more the ideal case.

3. ANTIREFLECTIVE LAYER

If we cover the surface of the cell with an antireflective layer 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 to improve photopile performance. Figure 3 sums up what has been mentioned above for the various wavelengths located in the visible spectrum.

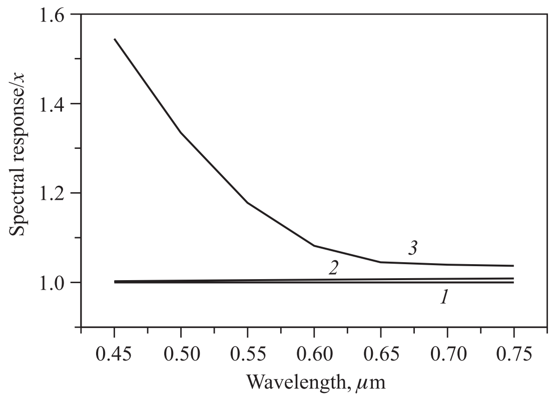

Fig. 3. Spectral response vs. wavelength: *1* — ideal case; *2* — with an antireflective layer ($d = 0.12$ μm); *3* — without an antireflective layer

CONCLUSION

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 the second reflection instead of one currently, by varying the incidence angle, and the aperture between the neighbouring pyramids. This model permits the solar incident rays to have three successive absorptions by the material. The calculations of incidence angles on the pyramids surfaces and the aperture f between the neighbouring 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 absorption coefficient and the generation rate. 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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