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ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА. ТЕОРИЯ

IMPROVEMENT OF QUANTUM EFFICIENCY USING SURFACE TEXTURE OF SOLAR CELL IN THE FORM OF PYRAMID

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The work presented in this paper concerns a detailed study about the light transmission through textured surfaces in a surface made up of pyramids [1, 2]. We investigate to what extent and under what conditions we want to take advantage of ray incidence five times and more [3, 4]. It is found that these analyses can be used to determine the optimal surface texture, which provides the best light trapping for solar cells in terms of the total internal reflection occurring in the high-index medium at incidence angles larger than the nominal critical angle [5–11]. One of the main contributions of this paper is the analysis and quantification of the influence of the opening between the heads of the two closest pyramids in textured surface for solar cells and its application to the photovoltaic parameters, such as the quantum efficiency. In this model, we show that the material can have five and more successive incident ray absorptions instead of three currently, 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, an angle between the two neighbouring pyramids varies between 20 and 12° and an angle of incidence varies between 80 and 84°. For these values of the angle between the two neighbouring pyramids and incidence angle, the opening between the heads of the two closest pyramids varied respectively from 3.53 to 2.10 μm for a pyramid height of 10 μm. This leads to a substantial increase of the quantum efficiency, thus the photovoltaic efficiency.

Представленная работа посвящена детальному исследованию процесса прохождения света через поверхности, имеющие пирамидальную текстуру [1, 2]. Изучены условия, при которых возможно использование преимущества захвата падающих лучей с эффективностью, в пять и более раз большей по сравнению с уже имеющимися поверхностями [3, 4]. Показано, что полученные результаты можно использовать для определения оптимальной текстуры поверхности, которая обеспечивает наилучший захват света ячейками солнечных батарей при помощи механизма полного внутреннего отражения при углах наклона, больших номинального критического угла [5–11]. Одним из главных результатов статьи является анализ и численное описание влияния угла открытия между вершинами двух ближайших пирамид текстурированной поверхности ячеек солнечной батареи и его использование для определения фотогальванических параметров, таких как квантовая эффективность. В рассматриваемой модели показано, что предлагаемый материал имеет эффективность поглощения падающего излучения в пять и более раз выше, чем три уже существующие, где направление отраженного пучка изменялось путем изменения угла между двумя соседними пирамидами, угла падения, угла открытия между вершинами двух ближайших пирамид и их высоты. Таким образом, угол между двумя соседними пирамидами варьируется между 20 и 12°, а угол падения —

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между 80 и 84°. Для этих значений угол открытия между вершинами ближайших пирамид высотой 10 мкм находится в пределах от 3,53 до 2,10 мкм. Это приводит к существенному увеличению квантовой эффективности, а следовательно, и фотогальванической эффективности.

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INTRODUCTION

The quantum efficiency [12, 13] is the ratio of the number of carriers collected by the solar cell to the number of photons of a given energy incident on the solar cell. The quantum efficiency may be given either as a function of wavelength or as energy. If all photons of a certain wavelength are absorbed and the resulting minority carriers are collected, then the quantum efficiency at that particular wavelength is unity. The quantum efficiency for photons with energy below the band gap is zero.

The quantum efficiency for most solar cells is reduced due to recombination effects. The same mechanisms, which affect the collection probability, also affect the quantum efficiency. For example, front surface passivation affects carriers generated near the surface, and since blue light is absorbed very close to the surface, high front surface recombination will affect the "blue" portion of the quantum efficiency. Similarly, green light is absorbed in the bulk of a solar cell and a low diffusion length will affect the collection probability from the solar cell bulk and reduce the quantum efficiency in the "green" portion of the spectrum. The quantum efficiency can be viewed as the collection probability due to the generation profile of a single wavelength, integrated over the device thickness and normalized to the incident number of photons.

1. TEXTURED SURFACE IN THE FORM OF PYRAMID

This model is based on reflection and refraction laws of incident rays on the surfaces of two neighbouring pyramids [14].

Incoming light, I, strikes a surface with reflection r. The r varies from 0 to 1. The reflected light from the surface, rI, is reflected at the same angle at which the incoming light strikes the surface, and the transmitted light is $1 - r$.

In a textured surface (Fig. 1), rather than being lost, the reflected light can strike the surface again, thus reducing the reflection to r^2I, and the transmitted light is $1-r^2$.

Transmitted rays are the sum of two successive indexes: $[I(1 - r) + Ir(1 - r) = I(1 - r^2)]$.

A change of the aperture between the summits of the neighbouring pyramids will allow the Ir^2 rays to fall the second time on pyramid 1 and the Ir^3 rays to fall the third time on pyramid 2 and the Ir^4 rays to fall the fourth time and so on (Fig. 2). This mechanism will permit recuperating the third and fourth and fifth proportions of the incident rays $Ir^2(1 - r)$ and $Ir^3(1 - r)$ and $Ir^4(1 - r)$, that will participate into 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

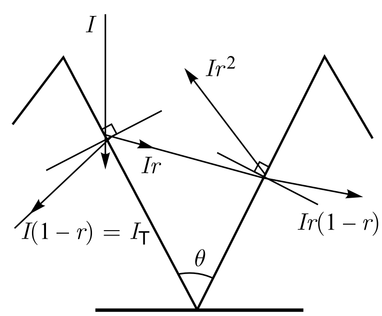

Fig. 1. Textured surface radius transmitted successively two times

$$[I(1 - r) + Ir(1 - r) + Ir^2(1 - r) + Ir^3(1 - r) + Ir^4(1 - r) = I(1 - r^5)]. \qquad (1)$$

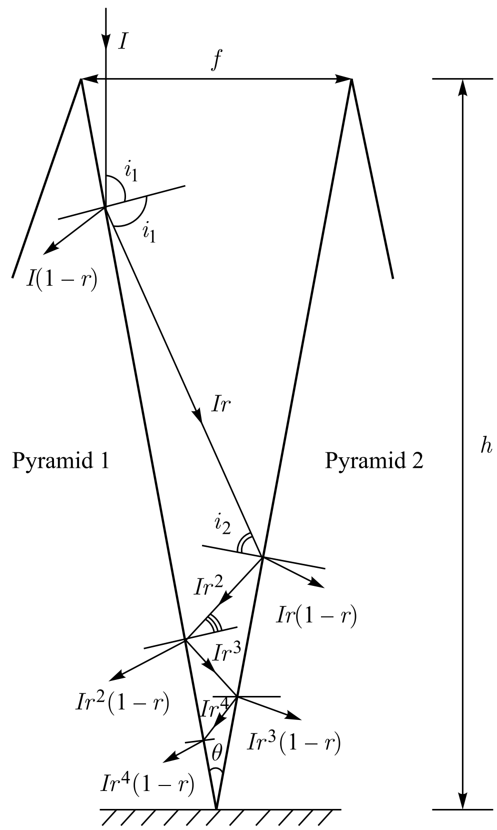

Fig. 2. Textured surface with five successive incidences. $\theta = 20°$; $i_1 = 80°$; $i_2 = 60°$; $i_3 = 40°$; $i_4 = 20°$; $h = 10$ μm; $f = 3.53$ μm

Transmitted rays are the sum of five successive indexes:

$$[I(1-r) + Ir(1-r) + Ir^2(1-r) + Ir^3(1-r) + Ir^4(1-r) = I(1-r^5)].$$

If i_1 represents the angle of the first projection on the surface of pyramid 1 and i_2 the angle of the second projection on the surface of pyramid 2 and i_3 the angle of the third projection on the surface of pyramid 1 and i_4 the angle of the fourth projection on the surface of pyramid 2,

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

$\theta = i_n - i_{n-1}$	f, μm	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8
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

then the angle between the two neighbouring pyramids is

$$\theta = i_n - i_{n-1}. \tag{2}$$

The opening between the heads of the two closest pyramids f is

$$f = 2h \tan\left(\frac{\theta}{2}\right). \tag{3}$$

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 in order to get height $h = 10$ μm are assembled in the Table.

2. QUANTUM EFFICIENCY

The quantum efficiency (or quantum yield) (QE) is the ratio of the number of carriers collected by the solar cell to the number of photons of a given energy incident on the solar cell. The quantum efficiency may be given either as a function of wavelength or as energy. If all photons of a certain wavelength are absorbed and the resulting minority carriers are collected, then the quantum efficiency at that particular wavelength is unity. The quantum efficiency for photons with energy below the band gap is zero.

Two types of the quantum efficiency of a solar cell are often considered:

The External Quantum Efficiency (EQE) is the ratio of the number of charge carriers collected by the solar cell to the number of photons of a given energy shining on the solar cell from outside (incident photons).

The Internal Quantum Efficiency (IQE) is the ratio of the number of charge carriers collected by the solar cell to the number of photons of a given energy shining on the solar cell from outside and absorbed by the cell.

The IQE is always larger than the EQE. A low IQE indicates that the active layer of the solar cell is unable to make good use of the photons.

The internal quantum efficiency is defined to have a quantity that depends less strongly on the optical design than the external quantum efficiency. The internal quantum efficiency is given by

$$Q_n = \frac{\alpha L}{1 + \alpha L}, \tag{4}$$

where α is the linear absorption coefficient of the simple relationship and L is the diffusion length.

For a textured plane the relation (4) becomes

$$Q_{nn} = \frac{\alpha_n L}{1 + \alpha_n L}, \tag{5}$$

$$\alpha_n = \frac{1}{d} \ln\left(\frac{1}{1 - r^n}\right), \tag{6}$$

where r is the reflection coefficient and d is the cell thickness.

In the case of normal plane, the internal quantum efficiency is

$$Q_{n1} = \frac{\alpha_1 L}{1 + \alpha_1 L}, \tag{7}$$

$$\alpha_1 = \frac{1}{d} \ln \left(\frac{1}{1 - r} \right). \tag{8}$$

For a textured plane the relation (5) becomes

$$Q_{n2} = \frac{\alpha_2 L}{1 + \alpha_2 L}, \tag{9}$$

$$\alpha_2 = \frac{1}{d} \ln \left(\frac{1}{1 - r^2} \right). \tag{10}$$

By applying the model that uses three successive incidences, the relation (5) becomes

$$Q_{n3} = \frac{\alpha_3 L}{1 + \alpha_3 L}, \tag{11}$$

$$\alpha_3 = \frac{1}{d} \ln \left(\frac{1}{1 - r^3} \right). \tag{12}$$

By applying the model that uses four successive incidences, the relation (5) becomes

$$Q_{n4} = \frac{\alpha_4 L}{1 + \alpha_4 L}, \tag{13}$$

$$\alpha_4 = \frac{1}{d} \ln \left(\frac{1}{1 - r^4} \right). \tag{14}$$

By applying the model that uses five successive incidences, the relation (5) becomes

$$Q_{n5} = \frac{\alpha_5 L}{1 + \alpha_5 L}, \tag{15}$$

$$\alpha_5 = \frac{1}{d} \ln \left(\frac{1}{1 - r^5} \right). \tag{16}$$

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

Figure 3 shows the different curves representing the internal quantum efficiency as a function of the reflection coefficient of a textured photovoltaic cell for d (the cell thickness $d = 100$ μm) and L (the diffusion length $L = 100$ μm).

This variation is compared in the same figure with the ideal case, with the case of the normal plane, and with that of the textured plane, in order to represent this relation for various values of the internal quantum efficiency, 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, then three, then twice, then once.

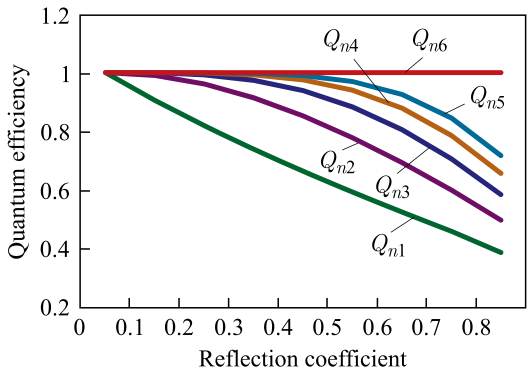

Fig. 3. Quantum efficiency vs. reflection coefficient ($d = L = 100$ μm): $Q_{n1} = \dfrac{\alpha_1 L}{1+\alpha_1 L}$, $Q_{n2} = \dfrac{\alpha_2 L}{1+\alpha_2 L}$, $Q_{n3} = \dfrac{\alpha_3 L}{1+\alpha_3 L}$, $Q_{n4} = \dfrac{\alpha_4 L}{1+\alpha_4 L}$, $Q_{n5} = \dfrac{\alpha_5 L}{1+\alpha_5 L}$, $Q_{n6} = 1$ (ideal case). $\alpha_1 = \dfrac{1}{d}\ln\left(\dfrac{1}{1-r}\right)$; $\alpha_2 = \dfrac{1}{d}\ln\left(\dfrac{1}{1-r^2}\right)$; $\alpha_3 = \dfrac{1}{d}\ln\left(\dfrac{1}{1-r^3}\right)$; $\alpha_4 = \dfrac{1}{d}\ln\left(\dfrac{1}{1-r^4}\right)$; $\alpha_5 = \dfrac{1}{d}\ln\left(\dfrac{1}{1-r^5}\right)$; α_6 — ideal case

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

CONCLUSION

A solar cell's quantum efficiency value indicates the amount of current that the cell will produce when irradiated by photons of a particular wavelength. If the cell's quantum efficiency is integrated over the whole solar electromagnetic spectrum, one can evaluate the amount of current that the cell will produce when exposed to sunlight.

This work is based on the use of successive reflections on the textured surface in the form of pyramid of solar cells, in order to improve the photovoltaic efficiency. For achieving this goal we used a model that can recuperate four reflections, 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 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 quantum efficiency. 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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