

ESTIMATION OF SOLAR CELL PARAMETERS IN VIEW OF SOLAR RADIATION SPECTRAL STRUCTURE

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The approach based on the account of photon energies and their density in sunlight flows looks to be promising for investigation of solar cell and estimation of their parameters. In this case, theoretical and experimental researches of physical processes and the phenomena occurring in the photo-electric converter could be based on the analysis of interaction between the material of photocells and flows of photons, amount and energy of which are determined by position in the given site of spectrum. In its turn, it allows estimating limiting (theoretical) values of solar cell efficiency coefficient and its dependence on degree of concentration of solar irradiation in the context of photon density increase in a light stream.

The use of the information on amount and energy of photons in each site of spectrum and specificity of interaction of photons of the given type with the solar cell material (silicon) makes it possible to identify expected integral characteristics of a solar cell more correctly.

To the best of our knowledge, the studies in which processes in solar elements are considered in the context of the above mentioned factors, especially concerning the given photon position in the solar irradiation spectrum, acting in a working zone and the mechanism of their interaction with solar cell component (in particular, directly in the p-n junction area, in the base, doped layer, and on contacts) are not described widely.

For this kind of investigations, the amount of photons and their energies for each line of spectrum could be found by the special calculations from the spectral structure of the standard solar radiation of 1000 W/m^2 suggested and accepted by the International Electrotechnical Committee [1].

In the present work, the standard table of the solar radiation spectral structure was supplemented with calculated values of photon energy of respective wavelengths, such as spectral photon density of a standard solar radiation as a derivative of energy spectral density and photon energy, and also the density of photon flows in each wavelength sub-diapason of the considered table. Photon energy was represented both in joule and in electron-volt equivalent, which is very convenient for different kinds of future investigations. The tables obtained require a lot of space. Therefore, they are not included in the paper in their original form and are represented as graphs.

Figure 1 depicts the graph of the energy density distribution for the above mentioned standard solar radiation versus wavelength. Figure 2 illustrates the results of calculation for spectral photon density distribution of the solar radiation flow of 1000 W/m^2 .

Comparative consideration of Fig. 1 and Fig. 2 shows that the spectral photon density slightly varies from the energy density distribution in a wavelengths band from 0.5 up to 1 micron and its maximum shifts in the area of higher wavelengths in comparison with the maximum of energy density.

Unlike the mechanism of interaction of the high energy quantum of the electromagnetic irradiation with electron (the Compton effect), when the photon energy could be transmitted to an electron partly, at the photo effect photon is absorbed completely. A part of the photon energy is consumed for breaking the chemical link of valence electron in semiconductor (for silicon $E_{cl} = 1.1 \text{ eV}$), and the remaining part of energy disperses in the volume and is consumed for increasing electron kinetic energy. Even photons with highest energy (part of spectrum with wavelength $\sim 0.3 \mu\text{m}$) are not capable of forming more than one electron-hole pair.

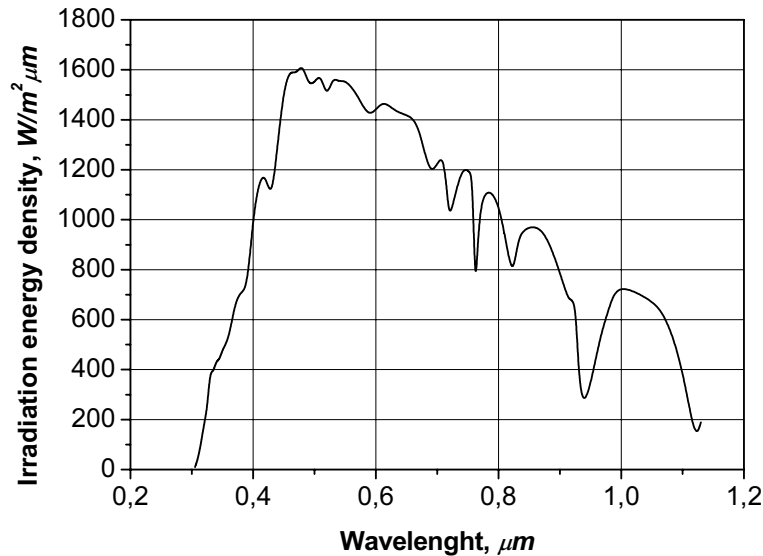


Fig. 1. Energy density of solar irradiation versus wavelength.

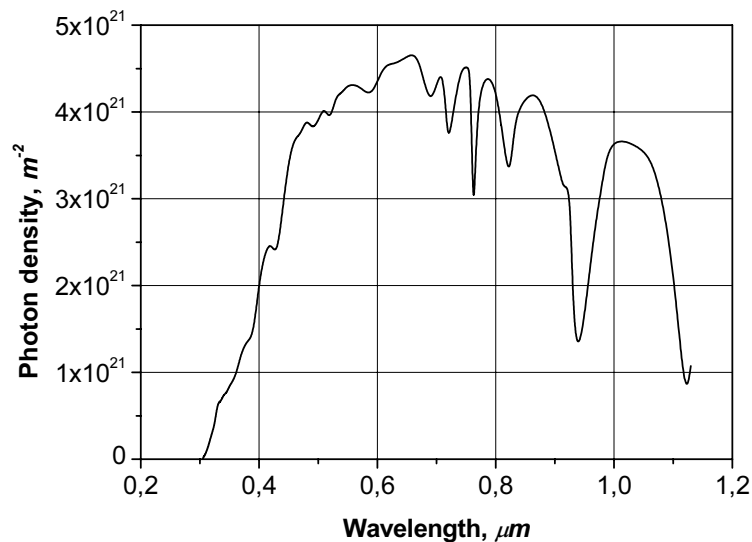


Fig. 2. Photon density for different wavelengths of standard solar radiation.

We can conclude from the above statement that one photon absorbed in silicon can create only one electron-hole pair. Therefore, the conclusion follows that the most efficient photon for effective operation of silicon solar cell will be a photon with the energy value close to the band gap width. At absorption, a photon with higher energy surplus of the photon energy will be transformed to heat and will not participate in electricity generation.

From the earlier mentioned standard solar spectrum of the radiation, one can calculate the total density of photon flow capable of forming an electron-hole pair. By integrating photon flows in each step $\Delta\lambda$ on the whole spectrum from maximum values until the energy corresponding to the band gap width of the semiconductor (1.1 eV for Si), we can obtain the value for photon flow Σn_j , which is estimated as follows

$$\Sigma n_j = 2.7247 \cdot 10^{21} m^{-2} s^{-1}. \quad (1)$$

At total absorption of the solar radiation flow and full separation of generated current carriers the maximum value of the short circuit current (I_{sc}) could be expressed as follows

$$I_{sc} = \Sigma n_j e = 4.35 A/dm^2, \quad (2)$$

where Σn_j is the amount of the photons incident on the surface of 1 dm^2 in sec.

The analysis of factors which makes it impossible to obtain these values in actual practice is the subject of an independent research.

The diagram of the spectral dependence of a silicon layer thickness, in which the radiation flow of the given wavelength diminishes in e times, was constructed according to [2], in which the dependence of solar radiation absorption in silicon versus wavelength was discussed.

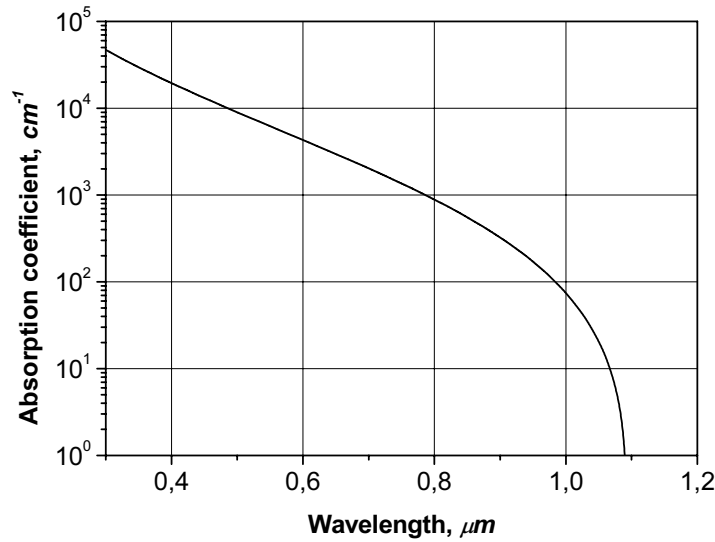


Fig. 3. Solar irradiation absorption coefficient α in silicon versus wavelength.

The amount of absorbed photons in a silicon layer will be defined by the layer thickness and absorption coefficient corresponding to wavelengths of the standard spectrum of solar radiation.

Figure 3 shows the coefficient of the solar light absorption in silicon versus wavelength in the range under study [2].

It follows from analysis of the above values that the absorption coefficient in silicon with wavelength increasing falls and becomes lower ($\alpha = 10 \mu m^{-1}$). In the range of wavelengths $\sim 1 \mu m$, silicon becomes more transparent for a long-wave photon. However, for wavelengths of $\sim 0.3 \mu m$, the absorption coefficient is sufficiently high ($\alpha = 10^4 \mu m^{-1}$) and practically explains high absorbing ability of heavily doped layer of the solar cell in this spectrum range.

The analytical expression for absorption coefficient in silicon, according to [2], looks as follows

$$\alpha = 0.526367 - 1.14425 \lambda^{-1} + 0.585368 \lambda^{-2} + 0.039958 \lambda^{-3}, \quad (3)$$

where λ is the wavelength (μm).

Figure 4 depicts the parameter inverse to absorption coefficient versus wavelength.

Physically, this parameter shows at which thickness of silicon layer the light flow of the given wavelength weakens in e times (certain resemblance with diffusion length in semiconductors). Analysis of this curve shows that for the left part of the standard solar spectrum, i.e., for photon with wavelength $\lambda \sim 0.3 \mu\text{m}$, this value is estimated as $0.2 \mu\text{m}$, but for wavelengths of $\sim 1 \mu\text{m}$, this value is 100 microns.

This result makes it possible to estimate the transmission factor for light flows of different wavelengths and silicon layers of different thicknesses. The graphs illustrating results of these calculations show that transmission of the irradiation through silicon layers increases with increasing wavelength and approaches 1 at a wavelength of $\sim 1 \mu\text{m}$. The transmission factor also increases as the layer thickness decreases. Theoretical estimations show that, at the thickness of silicon layer equal to zero, the dependence is transformed in vertical direct line, which is in a good agreement with requirements on optimum operation of silicon photoelectric converters stated in [3].

These results provide an opportunity to apply the method of nondestructive control of the dead layer thickness in already fabricated wafers after diffusion, i.e., during technologic process of solar cell fabrication in the future. For this objective, it is intended to use results of short circuit current measurements under laser irradiation.

The graph for integrated dependence of the predicted value of the solar cell photocurrent on the thickness of highly doped ("dead") layer was plotted on the basis of the analysis of spectral dependence of the solar radiation transmission through silicon layers of different thickness (Fig. 5).

It is shown that the measurement of I_{sc} for given wavelengths may be used in the process of solar cell manufacturing for the estimation of diffusion layer thickness and for operative updating of technological process.

As it is clear from above figure, the maximum value of the short circuit current density of the real solar cell will not exceed 4.35 A/dm^2 even at zero thickness of the dead layer.

The standard method for determination of solar cell efficiency coefficient consists in measurement of U-I characteristic and searching for

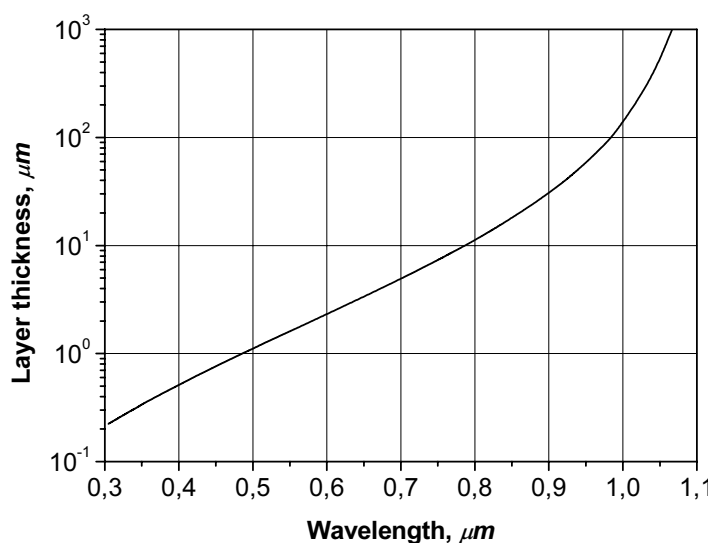


Fig. 4. Layer thickness at which the density of light flow decreases in e times versus wavelength (calculation).

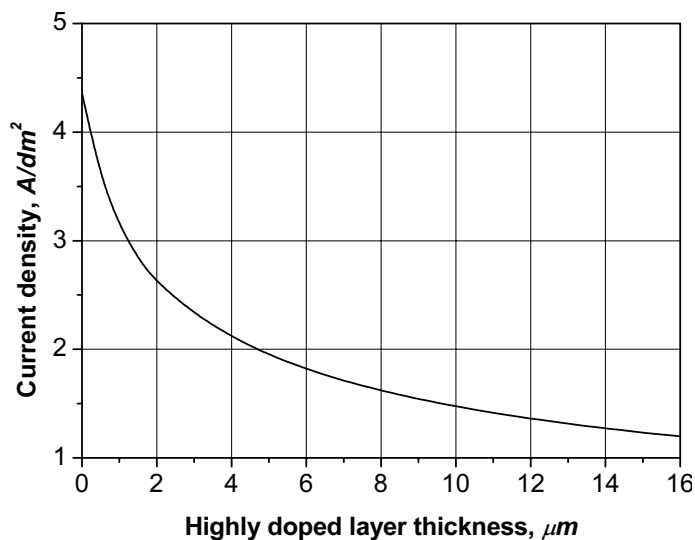


Fig. 5. Short circuit current density versus doped layer thickness at 1000 W/m^2 and AM 1.5 (calculation).

values of the voltage and current corresponding to the maximum electrical power. For these methods, the most important features of solar cells, such as values of the short circuit current and voltages of the open circuit, are hardly used at all. Here, a shot is made at the use of the above mentioned parameters plus fill-factor FF, important parameters of solar cells as well, in practical aims.

Taking into account that, at the highly concentrated illumination, U_{os} of silicon solar cell tends to the value of 1.1 V (the band gap width) [4], U_{os} at standard illumination can be estimated as 0.7 V.

In a general form, the efficiency of a solar cell is described by the expression

$$\eta = \frac{I_{sc} U_{os} FF}{R_c S}, \quad (4)$$

where FF is the fill-factor, R_c is the specific power of the solar radiation flow at the standard spectrum (W/m^2), and S is the area of the cell. Then, in view of the maximum value of I_{sc} of $4.35 A/dm^2$ and the value of U_{os} determined above and equal to 0.7 V and taking into consideration FF values of 0.8, it is possible to find that the maximum of the planar silicon solar cell efficiency will make up the value of $\sim 24.4\%$.

References

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