Axicons for power conversion efficiency enhancement in solar cells for the visible spectrum

V V Podlipnov[1,2] , A P Porfirev[1,2], S N Khonina[1,2]

[1] Samara National Research University, Moskovskoe shosse 34, Samara, 443086, Russia
[2]Image Processing Systems Institute of RAS, Molodogvardeyskaya 151, Samara, 443001, Russia

Abstract. We investigate the possibility of using diffractive microaxicons with different periods for power conversion efficiency enhancement in solar cells. The microaxicons were manufactured by using electron beam lithography. The parameters of the manufactured microaxicons were measured using scanning electron microscopy (SEM). For imitation of solar light, we utilised a tunable laser (the used wavelength range is from 400 nm to 800 nm). Experimentally measured dependence of solar cell efficiency for the case of a combination of a solar cell and microaxicons of various types demonstrates a power conversion efficiency enhancement in the case of using such structures.

1. Introduction

The primary goal of manufacturing solar cells (SC) is to enhance their energy efficiency. The problems of increasing the conversion efficiency of solar light into electricity could be conditionally divided into two classes: the problems associated with an increase in the efficiency of conversion of the incident light into electricity (quantum efficiency), and the problems associated with an increase in the rate of optical energy reaching the absorber semiconductor (optical efficiency).

In order to enhance quantum efficiency, reliability and durability, and to compete in the market of photovoltaics, the scientists extend the research area of photovoltaic materials from crystalline silicon to polycrystalline and amorphous silicon, as well as one- and multi-junction SC based on thin film of CdS, CdTe, GaAs, InP, GaInAsP, and more complex compositions of Cu(In, Ga) Se2-KCC. It allowed using new types of substrates, such as organic, polyimide films for flexible solar cells [1]. Another promising direction in the area of photovoltaics is to create a photovoltaic SC in which the photo-generating carriers are the organic and polymeric materials with various impurities [2-3] and organo-metallic perovskite materials [4]. Such approaches allow you to vary the properties of the material in a wide range and to increase solar cell efficiency. The last mentioned materials are particularly interesting. Solar cells on the basis of their demonstrated unprecedented progress and increase of conversion efficiency to 21%.

However, the world-record efficiency of 46% belongs to the solar cell based on inorganic materials, developed at the Fraunhofer Institute for Solar Energy Systems ISE. This result could not have been achieved without the use of methods to increase optical efficiency. In this solar cell, multiple active junctions were used. Each of them converts light of a specific spectral range into electricity with the greatest efficiency. The light is the first incident through the lens, focusing it on a very small element [5].

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Basic principles of the methods for improving optical efficiency are described in [6]. Problems associated with the use of additional optical elements, mirrors, and refractive or diffractive secondary optics to concentrate the light and to direct the light to the solar cell with high efficiency are of great interest. The solution to these problems allows reducing the cost of electricity generation through the use of solar cells of a significantly smaller area [7]. To increase the efficiency, texturing of the solar cell surfaces is widely used [8]. Structures based on diffraction gratings [9], luminescent structures based on quantum dots [10], randomly arranged textures that increase the diffuse scattering of light [11], plasmonic structures on the surface [12], photonic crystal structures [13], pyramidal surface structures [14], the structure in the form of nanocones [15], and silicon nanowires [16] are used to increase the capture of light and reduce reflection by texturing.

Thus, it can be concluded that current manufacturing elements with structures based on diffraction gratings, which may be created using, for example, inexpensive nanoimprinted lithography [17] and further plasma-chemical etching, are an inexpensive and appropriate approach for industrial production of solar cells. This technology is well combined with the technologies of microelectronic production and manufacturing of the classic silicon solar cells. Diffraction gratings may be used for texturing the front-side of the solar element [18], forming the back-side of the solar element [19], and for their combination in a single solar cell [20]. This allows you to maximise the light trapping and power conversion efficiency. However, the choice of the most effective types of diffractive gratings is an actual problem. To date, the results of the use of one-dimensional arrays, two-dimensional arrays, and solar cells with two filling-factor gratings [21] have been described in many works. Despite this, the use of diffraction and Fresnel diffraction axicon lenses as light-trapping structures has been investigated poorly. In most papers, their use is limited to use as secondary optics thin-film elements, namely a light concentrator [22]. In this paper, we demonstrate investigation of axicon applications to improve the efficiency of silicon solar cells.

2. The principle of a diffractive axicon

As is known, axicons are widely used for generating ring light distribution in a far-field region and for generating axial intensity distribution in a near-field region (see figure 1). Thus, they can be used for concentrating energy on the optical axis. However, if the period of the diffraction axicon is close to the wavelength of the illuminating radiation, most of the energy is scattered in the near field of the optical element at high diffraction orders [23, 24].

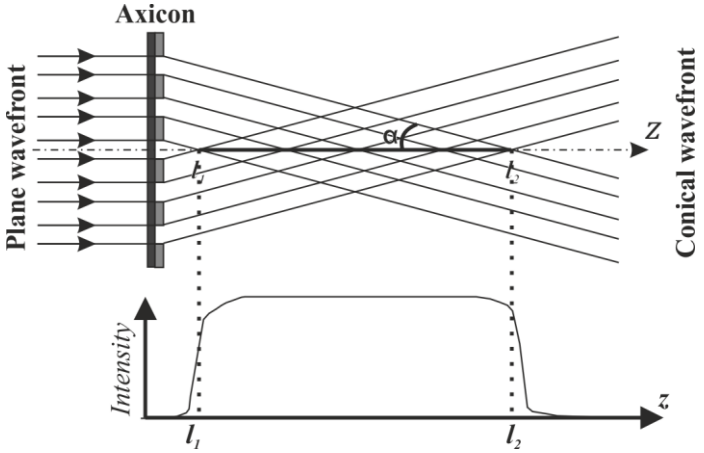


Figure 1. The principle of a diffractive axicon.

Let us consider a linearly polarized field in x-direction when flat beam bounded in circle of radius R illuminates the diffraction axicon:

$$\tau(r) = \exp\left(ik\alpha_0 r\right), \tag{1}$$

where α_0 is an axicon parameter that determines its numerical aperture.

Then the spectral distribution of the x-component will be obtained as

$$P_x(\sigma)=\int_0^R \exp\left(ik\alpha_0 r\right) J_0(kr\sigma)\, r\,\mathrm{d}r\ . \tag{2}$$

Then the field at distance z from the axicon takes form [25-27]:

$$\mathbf{E}(\rho,\theta,z)=k^2\int_{\sigma_1}^{\sigma_2}\begin{bmatrix} t_{TE}(\sigma)B_0^{SS}(k\sigma\rho,\theta)+t_{TM}(\sigma)\sqrt{1-\sigma^2}\,B_0^{CC}(k\sigma\rho,\theta) \\ B_0^{SC}(k\sigma\rho,\theta)\left(t_{TM}(\sigma)\sqrt{1-\sigma^2}-t_{TE}(\sigma)\right) \\ -t_{TM}(\sigma)\sigma B_0^{C}(k\sigma\rho,\theta)\end{bmatrix} P_x(\sigma)\exp\left[ikz\sqrt{1-\sigma^2}\right]\sigma\,\mathrm{d}\sigma, \tag{3}$$

where $B_0^{C}(k\sigma\rho,\theta)=iJ_1(k\sigma\rho)\cos\theta$, $B_0^{CC}(k\sigma\rho,\theta)=0.5\left[J_0(k\sigma\rho)-J_2(k\sigma\rho)\cos 2\theta\right]$, $B_0^{SS}(k\sigma\rho,\theta)=0.5\left[J_0(k\sigma\rho)+J_2(k\sigma\rho)\cos 2\theta\right]$, $B_0^{SC}(k\sigma\rho,\theta)=-0.5J_2(k\sigma\rho)\sin 2\theta$.

Now the x- and z-components of the electric field make the main contribution to the intensity near by the optical axis (z-axis):

$$E_x(\rho,\theta,z)=\frac{k^2}{2}\int_{\sigma_1}^{\sigma_2}\left[J_0(k\sigma\rho)\left(t_{TE}(\sigma)+t_{TM}(\sigma)\sqrt{1-\sigma^2}\right)+J_2(k\sigma\rho)\cos 2\theta\left(t_{TE}(\sigma)-t_{TM}(\sigma)\sqrt{1-\sigma^2}\right)\right]\times$$
$$\times P_x(\sigma)\exp\left[ikz\sqrt{1-\sigma^2}\right]\sigma\,\mathrm{d}\sigma, \tag{4a}$$

$$E_z(\rho,\theta,z)=ik^2\int_{\sigma_1}^{\sigma_2}J_1(k\sigma\rho)t_{TM}(\sigma)P_x(\sigma)\exp\left[ikz\sqrt{1-\sigma^2}\right]\cos\theta\sigma^2\,\mathrm{d}\sigma. \tag{4b}$$

The value of the equation (2) in neighborhood of $\sigma=\sigma_0$ is significantly higher than the values in other regions, so the integrals of equations (4a) and (4b) can be approximated as their integrands. The electric field x-component reaches its maximum intensity value at $\rho=0$ and z-component at $\rho=1.84\lambda/(2\pi\alpha_0)$. The ratio of the maximum values of the longitudinal and transverse components in the interval $\rho_\lambda\in[0,\lambda]$ along the polarization direction $\theta=0$ is then

$$\eta_\lambda=\frac{\left|E_z^{\max}(\rho_\lambda,0,z)\right|^2}{\left|E_x^{\max}(\rho_\lambda,0,z)\right|^2}\approx\frac{\left(1.16\cdot\alpha_0 t_{TM}\left(\alpha_0\right)\right)^2}{\left|\left[\left(t_{TE}\left(\alpha_0\right)+t_{TM}\left(\alpha_0\right)\sqrt{1-\alpha_0^{\,2}}\right)\right]\right|^2}\,.. \tag{5}$$

If we denote $\zeta(\alpha_0)=t_{TE}(\sigma)/t_{TM}(\sigma)$ we obtain

$$\eta_\lambda\approx\frac{1.34\alpha_0^2}{\left(\varsigma\left(\alpha_0\right)+\sqrt{1-\alpha_0^{\,2}}\right)^2}\underset{\alpha_0\to 1}{=}\frac{1.34}{\varsigma^2\left(1\right)}.. \tag{6}$$

In addition, if we denote the refractive index of the axicon by n_1 and the refractive index of the environment by n_2, assume that $n_1>n_2$, and write $\gamma=\sqrt{1-\alpha_0^2}$, then for the real values of $\gamma>n_2/n_1$ we obtain

$$\varsigma\left(\alpha_0\right)=\frac{2n_1n_2-\gamma\left(n_1^2+n_2^2\right)}{n_1^2+n_2^2-2\gamma n_1n_2}\,. \tag{7}$$

If $\alpha_0=1$ and $\gamma=0$ we get

$$\varsigma(1)=\frac{2n_1n_2}{n_1^2+n_2^2}. \tag{8}$$

As a result, equation (6) will increase by a decrement of equation (8), i. e. with an increment of the relative refractive index $n=n_1/n_2$. If $n_1=1.5$ and If $n_2=1$, then $\zeta(1)\approx0.857$ and the maximum of equation (6) is $\eta_{max}(n=1.5)\approx1.83$.

3. Experimental measurements

In this article, we propose using a combination of solar cells and an array of microaxicons. Such a structure is shown in figure 2. An array of microaxicons is placed on the front-side of the solar cells. In this case, each of the microaxicons concentrates energy on a specific area of the solar cell. Thus, the microaxicon array formed a high-energy density region on the surface of the solar cell. It can be used to enhance the absorption of light energy in the upper layer of n-type silicon. In addition, each of the microaxicons refracts light rays normally incidental on the surface of each of the microaxicons. This leads to the fact that the refracted light beams propagate at an angle normal of the surface of the solar cell; thus, the probability of light trapping increases. As a result, light absorption efficiency must be increased. This must lead to an increase in the efficiency of conversion of light energy into electricity.

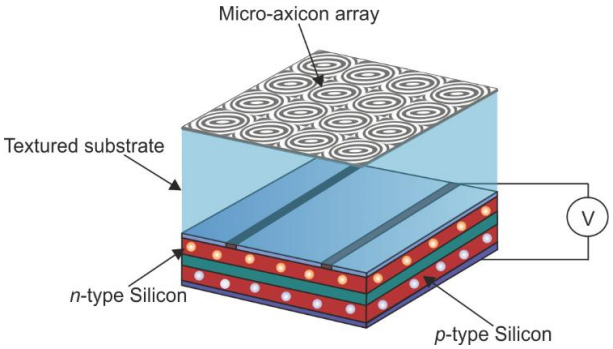


Figure 2. The scheme of a combination of a solar cell and a microaxicon array for enhancement of the light absorption efficiency.

For experimental investigation of the above-discussed combination of solar cells and microaxicons of different types, we use the scheme shown in figure 3. In the experiments, we used a tunable laser (EKSPLA NT200). This allowed us to change the laser wavelength of the generated laser radiation in the range from 400 to 800 nm. The output laser beam is directed by means of a mirror to a structure composed of a photocell and an axicon. We used three different microaxicons with periods of 645 nm, 1000 nm and 1500 nm. These micro-electronic lithography axicons were manufactured with a scanning electron microscope, Carl Zeiss Supra 25, and a Xenos XeDraw 2 high-speed writer. Images of the manufactured axicon are shown in figure 4.

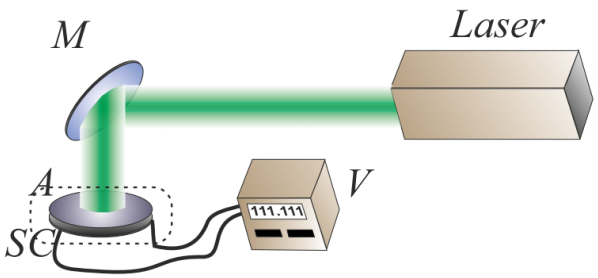


Figure 3. Experimental optical setup: *Laser* is a tunable EKSPLA NT200, *M* is a mirror, *A* is an axicon, *SC* is a solar cell, *V* is a multimeter.

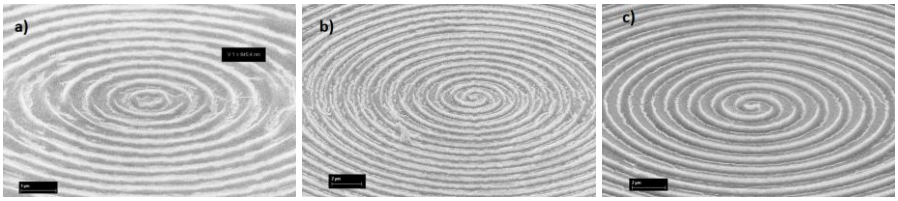


Figure 4. SEM images of microaxicons with periods of 645 nm (a), 1000 nm (b) and 1500 nm (c).

Figure 5 shows the experimentally measured dependence of the voltage on the wavelength. From this graph it is seen that for each of the three cases, using a combination of solar cells with different types of microaxicons in the wavelength range of 450 to 700 volts causes a distinct increase compared with the case of using only one solar cell without axicons. In the case of the combination of solar cells and axicons with a period of 645 nm, we achieved the maximum voltage increase — a relative increase compared to the combination of a solar cell and a quartz substrate was about 7% (the peak corresponds to a wavelength of 650 nm). This effect can be explained by the fact that the axicons with a large period should work efficiently for radiation with larger wavelengths in comparison with the wavelengths in the visible spectrum.

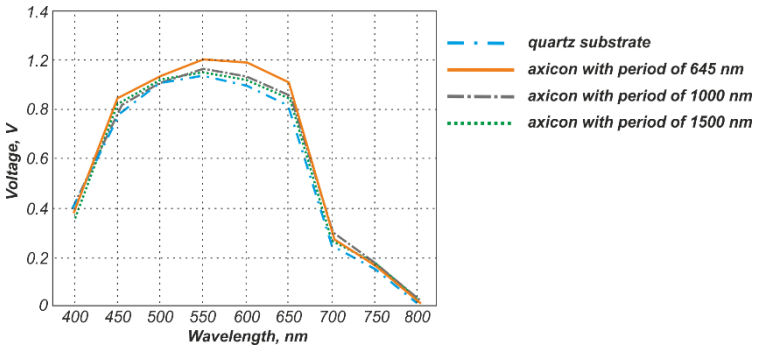


Figure 5. The dependence of the voltage on the wavelength.

4. Conclusion

We have investigated the possibility of using diffractive microaxicons with different periods for power conversion efficiency enhancement in solar cell. In the case of the combination of solar cells and axicons with a period of 645 nm, we achieved the maximum voltage increase — a relative increase compared to the combination of a solar cell and a quartz substrate was about 7% (the peak corresponds to a wavelength of 650 nm).

Acknowledgments

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