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R.V. Zaytsev, M.V. Kirichenko[1], L.V. Zaytseva[2] , N.V. Veselova[1]
[1]National Technical University "Kharkiv Polytechnic Institute"
[2] National Aerospace University "Kharkov Aviation Institute"

INCREASING OF THE EFFECTIVENESS OF THE INDUSTRIAL SILICON PHOTO-ELECTRIC TRANSFORMERS FOR THE HYBRID PHOTO-POWER MODULE

Possibilities of increase in effectiveness over 20% for Chinese made silicon photo-electric transformers have been investigated. By the method of computer designing operation it is established that the lifetimes of nonequilibrium charge carriers realized in such photo-electric transformers which make 520 mcs do not limit a possibility of increasing their efficiency over 20%. It is shown that increase in density of a photo current up to 43.1 mA/cm^2 leads up to 20.1% to body height of efficiency, and decrease in density of the diode saturation current to 3.1·10^{-14} A/cm^2 - causes body height of efficiency to 20.4%. Simultaneous change of these of a diode characteristic leads to increase of efficiency up to 23.1%. In work physicotechnological approaches for increase in density of a photo current and decrease of density of the diode saturation current in ready photo-electric transformers are offered.

Keywords: *photo-electric transformers on the basis of crystal silicon, an efficiency, exit parameters, light diode characteristics.*

Р.В. Зайцев, М.В. Кириченко, Л.В. Зайцева, Н.В. Веселова

ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ПРОМИСЛОВИХ КРЕМНІЄВИХ ФОТОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ ДЛЯ ГІБРИДНОГО ФОТОЕНЕРГЕТИЧНОГО МОДУЛЯ

Досліджено можливості підвищення ефективності понад 20% для кремнієвих фотоелектричних перетворювачів китайського виробництва. Методом комп'ютерного моделювання встановлено, що реалізовані в таких фотоелектричних перетворювачів часи життя нерівноважних носіїв заряду, які складають 520 мкс, не обмежують можливість збільшення їх ККД понад 20%. Показано, що збільшення щільності фотоструму до 43.1 мА / см2 призводить до зростання ККД до 20.1%, а зниження щільності діодного струму насичення до 3.1 · 10-14 А / см2 - зумовлює зростання ККД до 20.4%. Одночасна зміна цих діодних характеристики призводить до збільшення ККД до 23.1%. У роботі пропонуються фізико-технологічні підходи для збільшення щільності фотоструму і зменшення щільності діодного струму насичення в готових фотоелектричних перетворювачів.

Ключові слова: *фотоелектричні перетворювачі на основі кристалічного кремнію, коефіцієнт корисної дії, вихідні параметри, світлові діодні характеристики.*

Р.В. Зайцев, М.В. Кириченко, Л.В. Зайцева, Н.В. Веселова

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ПРОМЫШЛЕННЫХ КРЕМНИЕВЫХ ФОТОЭЛЕКТРИЧЕСКИХ ПРЕОБРАЗОВАТЕЛЕЙ ДЛЯ ГИБРИДНОГО ФОТОЭНЕРГЕТИЧЕСКОГО МОДУЛЯ

Исследованы возможности увеличения эффективности свыше 20% для кремниевых фотоэлектрических преобразователей китайского производства. Методом компьютерного моделирования установлено, что реализованные в таких фотоэлектрических преобразователях времена жизни неравновесных носителей заряда, которые составляют 520 мкс, не ограничивают возможность увеличения их КПД свыше 20%. Показано, что увеличение плотности фототока до 43.1 мА/см^2 приводит к росту КПД до 20.1%, а снижение плотности диодного тока насыщения до 3.1·10^{-14} А/см^2 - обуславливает рост КПД до 20.4%. Одновременное изменение этих диодных характеристики приводит к увеличению КПД до 23.1%. В работе предлагаются физико-технологические подходы для увеличения плотности фототока и уменьшения плотности диодного тока насыщения в готовых фотоэлектрических преобразователях.

Ключевые слова: *фотоэлектрические преобразователи на основе кристаллического кремния, коэффициент полезного действия, выходные параметры, световые диодные характеристики.*

Introduction. The main problem of large-scale grand use of the most widespread PhET on the basis of crystal silicon is ensuring competitiveness of the electric power developed by such instrumental structures of electric power in comparison with traditional sources of the electric power [1]. It can be reached by a path of depreciation of value 1 Watt of peak power due to increase in coefficient of transformation (efficiency) of solar energy and decrease of prime cost of technology of their manufacture [1].

Now the western firms developed and realized design technology solutions of PhET on the basis of crystal silicon (CrS SI-PhET) with effectiveness more than 20% in the conditions of the industrial made [2-4]. Realization commercially in Russia of such CrS demands modernization of the domestic enterprises of an electronic profile which are engaged in the made release of PhET on the basis of crystal silicon due to purchase of the expensive science-capacions equipment which does not have domestic analogs.

Now, as a result of sharp increase in investments into made development, the leading Chinese firms reduced Si-PhET cost with efficiency at the level of 18% more than by 1.4 times, and in the next three years cost will be reduced by 1.3 times [5]. Thus, economically expediently, as initial instrument structures to use Si-PhET of the Chinese made. At the same time the urgent task should be considered the analysis of effectiveness of photo-electric transformation in such instrument structures for a research of a possibility of increase in efficiency of ready of the Chinese made PhET over 20%.

1. Technique of carrying out experiment

In the conditions of the industrial made when monitoring technological process by analytical processing light current-voltage characteristic CVCh is defined by exit parameters of Si-PhET: tension of a no-load operation (U_{no}), current density of a short-circuit (J_{shc}), filling factor light CVCh (FF) and efficiency (E). However these parameters represent the principal specifications of the device which do not have the one-to-one association with the photo-electric processes defining work of PhET. Therefore along with exit parameters it is necessary to analyze the light diode characteristics which are uniquely determinating the one-diode Si-PhET [6] model. Density of a photo current (J_{ph}), density of the diode saturation current (J_c), coefficient of ideality (A), shunting (R_{Sh}), and consistent (R) resistance, Si PhET calculated per acre belong to such diode characteristics. Communication of effectiveness of PhET with light diode characteristics is implicitly described by theoretical light CVCh by PhET [6]:

$$J_H = -J_{ph} + J_0 \left\{ \exp\left[\frac{e\left(U_L - J_L R\right)}{AkT} \right] - 1 \right\} + \frac{U_L - J_L R}{R_{sh}}, \quad (1)$$

where J_L – a current density, flowing past through loading; e - elementary charge; k - Boltzmann constant; T - temperature of a solar element; U_L - a voltage drop on loading.

By approximation of experimentally received values of I_L and U_L theoretical expression (1), it is possible to define exit parameters, light diode characteristics and efficiency of PhET. Analytical processing light CVCh the studied PhET was carried out by means of computer according to the developed program. According to the program analytical expression for light CVCh (1) will be transformed to expression:

$$J_L = A_0 - A_1 U_L - A_2 \exp\left(A_3 U_L + A_4 J_L\right), \quad (2)$$

where $A_0 = \frac{\left(J_c + J_0\right) R}{R_L + R}$, $A_1 = \frac{1}{R_l + R}$, $A_2 = \frac{J_0 R}{R_l + R}$, $A_3 = \frac{e}{AkT}$, $A_4 = \frac{eR_l}{AkT}$.

Using expression (2) and experimentally received values of J_L and U_L, way of a variation of the values stated above coefficients of A0, A1, A2, A3, A4, the program carries out the best approximation of the experimental datas of $I_L = I_L(U_L)$ of the curve described by the transformed theoretical expression (2). Usually at analytical processing root mean square deviation does not surpass 10^{-8} that corresponds to the relative accuracy in definition of exit parameters and light diode characteristics at the level of no more than 1%. After finding of the specified coefficients providing the best approximation exit parameters of PHET are defined: J_{shc}, U_{no}, FF, efficiency. Light diode characteristics of R_l, R_{Sh}, A and I0 are calculated on the found coefficients of A_0, A_1, A_2, A_3, A_4. Light CVCh PhET were measured by means of the laboratory stand at radiation of instrument structures by the sunlight simulator in ground conditions with a power of luminous flux of 100 MW/cm2. As the source imitating sunlight the 500 W halogen lamp connected to the stabilized electrical power unit was used.

Effectiveness of photo-electric processes – oscillations, diffusions, drift, division and collecting of the generated under the influence of light nonequilibrium charge carriers essentially depends on time of their life. Therefore when carrying out the analysis of effectiveness of Si-PhET we determined by method of a stress decay of a no-load operation a lifetime of nonequilibrium charge carriers in the studied instrument structures [7].

The research of spectral dependence of coefficient of quantum effectiveness Q(λ) allows to analyze integral effectiveness of photo-electric processes depending on incident radiant energy [7]. Therefore such researches also are necessary by optimization of ShC SI-PhET. Between current of a short-circuit of I_{chc} and the size Q(λ) there is the functional communication described at rather big shunting R_{Sh} resistance by a ratio [7]:

$$I_{chc} = e\int_0^{\lambda_{chc}} Q(\lambda)\cdot N(\lambda)\,d\lambda - I_d, \quad (3)$$

where λ - light wavelength; L_{chc} - a red photo current threshold; N(λ) - the speed of receipt of photons on PhET surface; I_d - the diode current of PhET.

In actual practice intensity of the sunlight arriving on a surface of SE is such that at observed value of consistent resistance of instrumental structure of $I_d << I_{chc}$; for this reason (3) will be transformed to a look:

$$I_{chc} = Q(\lambda) \cdot N(\lambda)\,. \tag{4}$$

The size N(λ) entering in (4) can be expressed through intensity of light I_l (λ) arriving on PhET surface:

$$Q(\lambda) = \frac{I_{chc}(\lambda) \cdot E(\lambda)}{eS \cdot I_l(\lambda)}\,. \tag{5}$$

When carrying out researches of spectral dependence of a photoresponse of Si PhET took place on an exit slit of a double monochromator and measurement of I_{chc} at the smoothly varying change of a wavelength of an incident radiation with the subsequent calculation of Q(λ) based on the ratio of (5) was taken. Intensity of I_l (λ) light is the characteristic of the used light source in quality which the filament lamp was used by 500 W.

2. Results and their discussion

2.1 The pilot studies of the industrial patterns of silicon photo-electric Chinese made transformers

For researches the most efficient productive Chinese made industrial patterns were chosen. CVCh 10 lights instrument structures were measured. Results demonstrate that the efficiency makes from 17.7% to 18.4%. For the analysis it was chosen light CVCh SI-PhET with the efficiency reference value – 18.1% (fig. 1, a curve 1). Analytical processing light CVCh allowed to define exit parameters and light diode characteristics of Si-PhET (see the table).

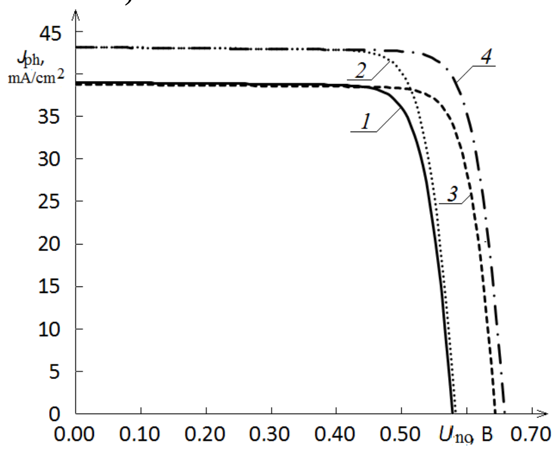


Fig. 1. **Light volt-ampere characteristics**

1 – initial, J_{ph} =39.0 mA/cm^2, J_c=5.4·10^{-13} A/cm^2, % Effeciency=18.1;
2 – theoretical CVCh at Jph =43.1 mA/cm^2, J_c=5.4·10^{-13} A/cm^2, % Effeciency=20.1;
3 – theoretical CVCh at Jph =39.0 mA/cm^2, J_c =3.1·10-14 A/cm^2, % Effeciency=20.4;
4 – theoretical CVCh at Jph =43.1 mA/cm^2, J_c =3.1·10-14 A/cm^2, % Effeciency=23.1.

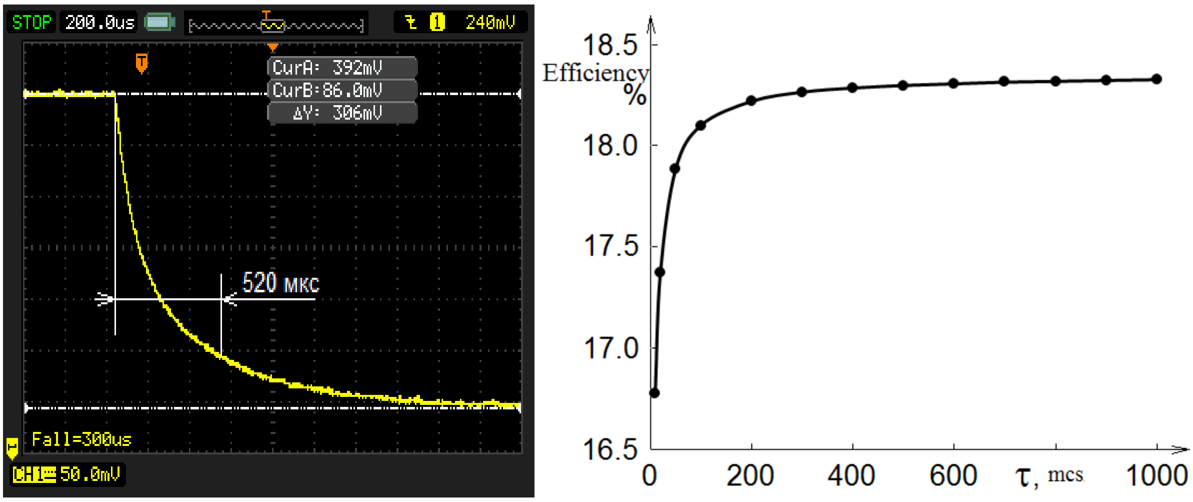
Table 1

The exit parameters and light diode characteristics of Si PhET received as a result of an experiment and model operation

Exit parameters and the light diode characteristics	The experimental patterns	Model operation of influence of J_c	Model operation of influence of Jph	Model operation of influence of Jph and J_c
J_{chc}, mA/cm^2	39.0	39.0	43.1	43.1
U_{shc}, мV	578	643	583	658
FF, rel. un.	0.80	0.82	0.80	0.82
η, %	18.1	20.4	20.1	23.1

J_{ph}, mA/cm^2	38.8	39.0	43.1	43.1
R_l, Om· cm^2	0.45	0.45	0.45	0.45
R_{sh},Om· cm^2	1013	1013	1013	1013
A, rel. un.	0.9	0.9	0.9	0.9
J_c, A/ cm^2	$5.4\cdot10^{-13}$	$3.1\cdot10^{-14}$	$5.4\cdot10^{-13}$	$3.1\cdot10^{-14}$

Researches of exit parameters and light diode characteristics were added with lifetime researches. On a stress decay of a no-load operation (see fig. 2, a) it was established that the lifetime of nonequilibrium charge carriers makes 520 microsec. Results of the research of spectral dependence of coefficient of quantum effectiveness (fig. 3, a curve 1) show that the spectral interval of a photosensitivity of Si-PhET makes 0.42-1.20 microns. The maximal Q(λ) value is observed in a spectral interval of 0.90 1.10 microns, and since 0.80 microns, Q(λ) considerably decreases.



a) b)

Fig. 2. **A research of a lifetime of nonequilibrium charge carriers in the industrial patterns of Si-PHET of the Chinese made(s) and model operation of time effect of life on their efficiency.**

2.2 Model operation of influence time of life of nonequilibrium charge carriers on effectiveness of the industrial patterns of silicon photo-electric of the Chinese made transformers

As efficiency value of the studied industrial patterns of the Chinese made conceded to effectiveness of the best industrial patterns of the European made which exceeds 20%, for searching of paths of increase in efficiency numerical model operation of parameters of the studied Si-PhET by means of computer was carried out. For model operation the PC1D 5.9 program developed at University of New South Wales (Australia) which is available in the free access was used. By means of this software the PhET electronic model was created. Such parameters of a basic silicon crystal of PhET as width of the forbidden region, the relative inductivity, characteristic concentration of charge carriers, value of mobility of electrons and holes, were a part of the software of PC1D 5.9. Besides at model operation such characteristics of the studied PHET were considered:

- level of a doping of a basic crystal of r-type which made $1.5\cdot10^{16}$ cm^3;
- thickness of a n+-layer is 0,1 microns, p + - a layer – 1.15 microns, the average level of their doping at erfc-distribution - 10^{20} cm^3 and 10^{18} cm^3, respectively;
- thickness of the clarifying covering from Si_3N_4 - 53 nanometers;
- height of a relief of chaotically textured frontal surface - 3 microns;
- recombination rates on the frontal and back surfaces of Sn=Sp = 10^3 m/s;
- the consistent and shunting resistance which were determined by analytical processing of the experimental light CVCh (see, the table).

Model operation of work of PhET was carried out for its temperature of 25 ° C in the mode of radiation AM1,5G at power illuminating intensity of the frontal surface 1000 W/sq.m. The lifetime of minority carriers of a charge which changed from 10 microsec to 1000 microsec was the varied parameter in this model.

The analysis of the obtained data (fig. 2, b) shows that since values of a lifetime of 300 microsec its further increase does not exert impact on efficiency. As for the studied industrial patterns of Si-PhET the experimental value of a lifetime made 520 microsec, it demonstrates that quality of a basic crystal is not the factor limiting efficiency of the studied Si-PhET at the level of 18%.

2.3 Model operation of influence of light diode characteristics on effectiveness of the industrial patterns of silicon photo-electric transformers of the Chinese made

Analyzing expression (1), it is possible to show that with body height of JF, RSh and with decrease of Jo, A, R effectiveness of PhET increases. However for identification of the physical mechanisms defining efficiency of PhET it is more useful to establish the quantitative connection between the effectiveness of tool-making structure and its light diode characteristics. It allows to define the dominating light diode characteristics which change at change of ShC SI-PhET causes change of its efficiency. As a result there is an opportunity to reduce significantly the volume of the subsequent pilot studies on establishment of physical regularities of influence of ShC on effectiveness of Si PhET. Therefore in work, using the developed computer program, model operation of influence of change of each of light diode characteristics of PHET on effectiveness was carried out. At the same time all light diode characteristics of PhET, except one, are fixed, and this light diode characteristic accepts value from the chosen interval. On a set of light diode characteristics, according to expression (1), the program counted theoretical light CVCh and defined efficiency. Then the following value of a light diode characteristic is got out of the chosen interval and the next theoretical light is calculated CVCh from which the efficiency is defined. As a result we receive theoretical dependence of efficiency on change in the chosen range of one diode characteristic at the fixed others. Similar model operation repeats for each light diode characteristic of PhET. Analyzing theoretical dependences of efficiency on change of light diode characteristics, we estimated the quantitative contribution of change of each of light diode characteristics to a possibility of achievement of efficiency over 20%.

Results of model operation show that increase in the shunting resistance and decrease in consistent resistance at the fixed other diode characteristics for Si-PHET with efficiency of 18.1% does not lead to essential increase in effectiveness (fig. 4 a, b). So increase of the shunting resistance from R_{Sh} = 1000 Ohms • cm^2 to R_{Sh} = 4000 Ohms • cm^2 causes growth of effectiveness by 0.1%. Decrease in consistent resistance from R = 0.45 Ohms • cm^2 to R = 0.1 Ohms • cm^2 leads to growth of efficiency by 0.5%.

Essential increase of effectiveness at the fixed other diode characteristics can be reached or due to body height of density of a photo current or due to decrease of density of the diode saturation current (fig. 4, c, d). So, body height of density of a photo current by 1.1 times, from J_{ph} = 39.0 mA/cm^2 to J_{ph} = 43.1 mA/cm^2 lead to body height of effectiveness up to 20.1% (see the table). And decrease in density of the diode saturation current from $J_c = 5.4 \cdot 10^{-13}$ A/cm^2 to $J_c = 3.1 \cdot 10^{-14}$ A/cm^2 allow to increase efficiency to 20.4% (see the table). Mathematical model operation showed that simultaneous body height of $J_c = 3.1 \cdot 10^{-14}$ A/cm^2 and J_{ph} = 43.1 mA/cm^2 leads to increase in efficiency up to 23,1% (see the table).

According to the experimental datas (see fig. 3) the short-wave limit of photosensitivity of the studied exemplars of Si-PHET makes 0.42 microns therefore in instrument structures an ultraviolet part of a range will not be transformed. Therefore body height of density of a photo current for the studied Si-PhET can be received when drawing on a surface of ready instrument structure of a luminescent coating. Such covering absorbs photons in an ultraviolet part of the solar spectrum and generates photons in an infrared part of the solar spectrum. The most optimum Si-PhET of the Chinese made for the industrial patterns is the luminescent coating put with an economic chemical method on the basis of quantum points of lead sulfide [8]. Such quantum points absorb light in the spectral range of 0.30-0.40 microns and generate photons with a length about 1:05 microns [8] that corresponds to area of the maximal experimental values of quantum effectiveness of Si-PHET investigated in work (fig. 3). According to the results of model operation presented in the work [8] use of such luminescent coating theoretically allows to increase an initial current density of a short-circuit more than at 1.1-1.2 time that, according to results of the researches conducted by us, it is enough for achievement of efficiency at the industrial patterns of Si-PhET of the Chinese made over 20%.

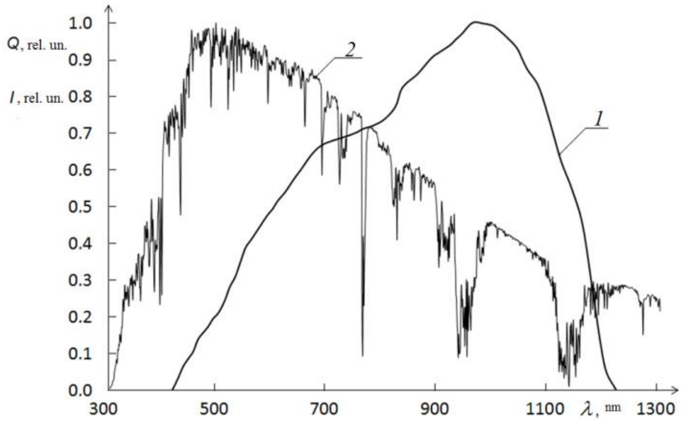


Fig. 3. **Spectral dependences of coefficient of quantum effectiveness of the Chinese made Si-PhET 1 – Q(λ) Si-PhET; 2 – solar spectrum of AM1.5G.**

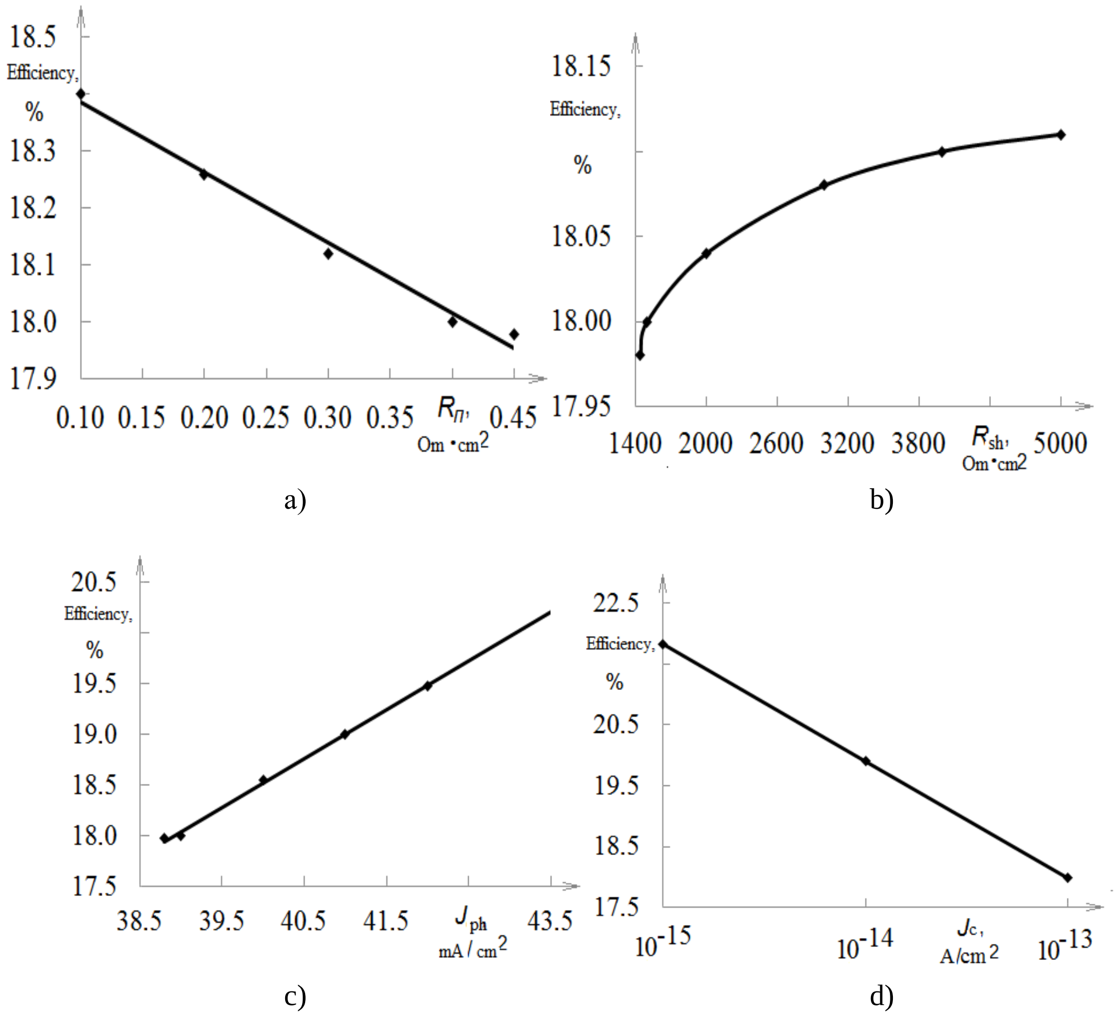


Fig. 4. **Model operation of influence of the consistent resistance (a) shunting resistance (b), density of a photo current (v) and density of the diode saturation current (g) on efficiency SI-PHET of the Chinese made**

For decrease of density of the diode saturation current it is possible to apply plazmonny coverings on a surface of Si-PhET or to carry out processing in a magnetic field. According to literary data (see, for example in [9]) plazmonny coverings allow to realize a new way of optimization of capture of photons by means of the metal nanoparticles applied on PHET surface. By exaltation of the surface the plasmon-polyariton of waves can be provided oscillation of nonequilibrium charge carriers only in p to area near a homojunction that will allow to reduce density of the diode saturation current. Magnetic processing of Si-PHET in the stationary field which according to literary data [10] influences electrically active internal defects and the defect complexes in a silicon plate, also theoretically allows to reduce density of the diode saturation current by reorganization of power structure of ensemble electrically active internal of dot defects in the field of a homojunction of instrument structure.

Conclusions. It was shown that the lifetimes of nonequilibrium charge carriers realized for the industrial patterns by Si-PhET of the Chinese made which make 520 microsec do not limit a possibility of increase in their efficiency over 20%. Reached the size of the consistent and shunting resistance of the industrial patterns of Si-PHET of the Chinese made which make 0.45 Ohms • cm^2 and 1000 Ohms • cm^2, respectively, do not need further optimization. It is shown that increase in density of a photo current from 39.0 mA/cm^2 to 43.1 mA/cm^2 in the industrial patterns of Si-PhET of the Chinese made without change of other diode characteristics leads up to 20.1% to body height of their effectiveness. For similar increase in density of a photo current on a surface of ready instrument structure it is necessary to form a luminescent coating the containing quantum points of lead sulfide. It is established that decrease in density of the diode saturation current from 5.4·10 13 A/cm^2 to 3.1·10-14 A/cm^2 in industrial patterns of Si-PhET of the Chinese made without changing of other diode characteristics leads up to 20.4% to body height of effectiveness. Possible physicotechnological approaches for decrease of density of the diode saturation current of ready PhET is drawing the plazmon of coverings or processing of instrument structures in a magnetic field. Simultaneous increasing of density of a photo current and density of the diode saturation current up to the values stated above allows to increase efficiency to 23.1%.

References.

1. Razykov T.M., Ferekides C.S., Morel D., Stefanakos E., Ullal H.S., Upadhyaya H.M. Solar photovoltaic electricity: Current status and future prospects // Solar Energy. 2011. V. 85. P. 1580–1608.
2. Rehman A., Lee S. H. Advancements in n-Type Base Crystalline Silicon Solar Cells and Their Emergence in the Photovoltaic Industry // Scientific World Journal. 2013. V. 2013. ID 470347. P.1-13
3. Binetti S., Acciarri M., Donne A. Le, Morgano M., Jestin Y. Key Success Factors and Future Perspective of Silicon-Based Solar Cells // International Journal of Photoenergy. 2013. V. 2013. ID 249502. P 1-6.
4. Saga T. Advances in crystalline silicon solar cell technology for industrial mass made // NPG Asia Materials. 2010. V. 2. P. 96–102
5. Bye G., Ceccaroli B. Solar grade silicon: Technology status and industrial trends // Solar Energy Materials & Solar Cells. 2014. V. 130. P. 634–646.
6. Möller H.J. Semiconductors for solar cells. Boston: Artech House, 1993.
7. Raushenbach H. S. Solar Cells Array Design. New York: Litton Uducation Publishing, 1980.
8. Shcherbatyuk, G. V.; Inman, R. H.; Wang, C.; Winston, R., Ghosh, S. Viability of Using Near Infrared PbS Quantum Dots as Active Materials in Luminescent Solar Concentrators. Appl. Phys. Lett. 2010. V. 96. P. 191901−191903.
9. Catchpole K.R., Polman A. Plasmonic solar cells // Optics Express. 2008. V. 16, № 26. P. 21793–21800.
10. Makar V. A., Vasilyev M. A., Steblenko L. P., Koplak O. V., Kurilyuk A.N., Kobza player YU.L., Naumenko of S. N. Provoked by action of a magnetic field changes of the impuritiest structure and microhardness of near-surface layers of crystals of silicon//Physics and technique of semiconductors. 2008. T. 42. Issue 9. C. 1061-1064.

Рецензенти:

Кудій Дмитро Анатолійович, в.о. декана ФТ факультету НТУ «ХПІ», к.т.н.;

Долбін Олександр Вітольдович, провідний науковий співробітник ФТІНТ НАН України ст.н.с., д. ф.-м.н.

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