SILICON MULTIJUNCTION PLANAR PV CELLS

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ABSTRUCT

The research of silicon planar multijunction PV cells is addressed. While being of multijunction and high voltage type, the standard shape of planar converters could be maintained for such solar cells. Introduction of multijunction high voltage PV cells into traditionally shaped planar PV systems and modules results in benefits from lesser losses at higher nominal voltage and better performance.

Structurally these solar cells represent multilayer composition of elements of the structure – single photoelectric converters traversed by light going through consequent semiconductor layers. The theoretical framework and boundary parameters of photoelectric and power characteristics of monochromatic and solar radiation high voltage PV cells are presented together with optimal thicknesses and number of single photo converters deposited onto the base photo converters, including spectral response, current-voltage characteristics and efficiency.

The calculations, charts and design solutions are also provided.

1. DESIGN

The photovoltaic (PV) cell comprises a base photo converter (PC), layers deposited upon it, antireflective coating and metal contacts. The deposited layers form planar n^+-p-p^+ (p^+-n-n^+; n-p-p^+; p-n-n^+) diode structures or n-p structures referred to as single PCs, connected in series in the direction of incoming radiation flax. The thickness of diode structure is in reverse portion to the maximal value of semiconductor light absorption coefficient in the direction of incident radiation (1-4).

The thickness of single PC is in reverse portion to photon absorption coefficient and decreases smoothly with the number of single PC and rises with the charge carriers collection coefficient in the 1st (base) PC. The base area thickness does not exceed the diffusion length of minor charge carriers. The thicknesses of p, n and n^+ layers are in the range 10nm to 10μ while that of p^+ layers is in the range 10nm to 1000nm.

Fig. 1 shows the structure of planar multijunction PV cell with heavily doped p^+ layers.

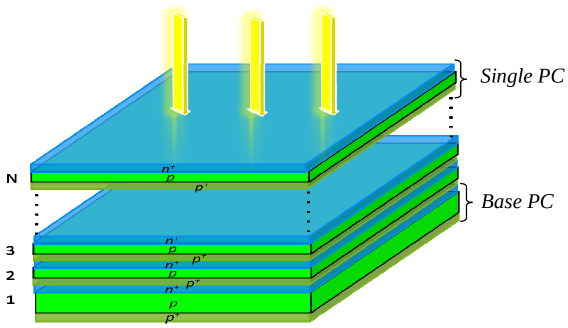


Fig. 1: Planar multijunction PV cell structure.

Two procedures of multilayer structure preparation (one by epitaxy and the other using consequential spattering of layers) and two methods connecting the single PCs (one using the electric breakdown and the other by forming tunnel junctions) have been investigated. The base PC that can be fabricated using conventional technologies provides the mechanical integrity of the entire structure.

Thin heavily doped p^+ layers are grown less than 1μ of thickness with the active dopant density exceeding 10^{18} sm^{-3}. They form the short-circuiting tunnel p^+-n(n^+) junctions providing ohmic contacts owing to the quantum-mechanical tunneling of charge carriers through the potential barrier existing on the p^+-n^+ junction.

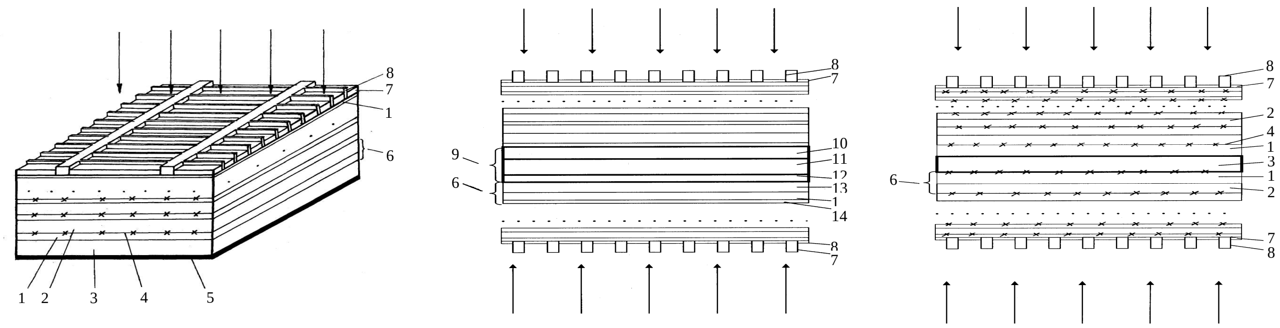
The number of layers is defined by particular technology equipment facilities, as well as by the specifics of layer fabrication procedure depending on the application area of PV cells with the required number of layers in particular PV modules designs.

Generally, the layer thickness increases with the distance from operating surfaces which makes it possible to obtain PV cells having identically high output parameters for much wider layers identity tolerance range.

An additional efficiency is achieved owing to the antireflection coating located also on the side planes and the operating surface area including, at least, one more generator plane.

As a variant, the above series of single PCs can be formed on the both sides of bifacial PC wafer. In such structures, the generation function in each single PC is the sum of generation functions related to the radiation flaxes incident upon both the front and the back wafer surfaces. Thus the resulting generation function appears to be more isotropic making the areas remote from p-n junction exposed to the incident light. For the effective operation of such structures the requirements for layers' thickness are very strict. It means that the layers of greater thickness can be made without shading the back surface.

Fig. 2 show different design options of the proposed planar multijunction PV cells.



a) b) c)

Fig. 2: Variants of planar multijunction PV cells design: a) unifacial PV cell, b) bifacial PV cell on the basis of n^+-p-p^+ diffusion base cell and thin p^+ layers, c) bifacial PV cell with contacts made by electric breakdown.
1 – p layer, 2 – n layers, 3 – semiconductor substrate without diode structure, 4 – electrically broken reverse-biased p-n junctions, 5 – back surface contact, 6 – single PCs, 7 – antireflective coating, 8 – contact grid, 9 – base PC, 10 – diffusion n^+ layer,11– substrate base area, 12 – diffusion p^+ layer,13 – n^+ layer, 14 – p^+ layers.

The PV cell operates as follows. The electromagnetic radiation falling upon both frontal and back surfaces of photoelectric converter enters the single PCs through the antireflection coating. Low (≤ 10μ) layers thickness and, accordingly, that of single PCs makes them transparent for light. Each single PC receives the radiation passed through the all president semiconductor layers. Phonon absorption occurs followed by creating of electron-hole pares and appearance of excess charge carriers. The electron-hole pares get broken in the electric field producing photocurrents and photo-EMF in the structures and between metallic contacts of an external circuit. Thus the voltage increases and the resulting PV cell voltage value equals to the sum of all single PCs voltages.

2. CHARACTERISTICS

The maximal output power value for a photoelectric cell can be only achieved in the case that the photoelectric currents of all single PCs of the structure are in match with each other.

For the series connection, the currents of all single PCs shall be equal to each other. To avoid circuit mismatch losses in a multijunction photoelectric converter each single PC shall operate in the optimal point of its current-voltage characteristics under illumination. Since the optimal value of PV cell operating current is near to that of photoelectric current the condition of maximal power generation in the structure is actually reduced to the requirement of equality of photocurrents for all single PCs included in the PV cells' structure. To fulfill this requirement the determining of the corresponding base layers' thickness values for each single PC is necessary.

The presented concept allows to set one even more generic problem, that of structure and design optimization of the proposed PV cells. Since the intensity of light entering each single PC and the base PC decreases with the number *N* of single PCs in a series due to radiation absorption in upper layers the photocurrent generated in the structure also decreases with *N*. At the same time, the total voltage of the structure increases with the number of single PCs. It means that, generally, the output power changes non-monotonously with the increasing *N* and attains its maximum value for a certain *N* value. It is clear that the optimal values of single PCs thickness and those of their number, as well as the value of generated power depend on the incident light spectral composition, diffusion and recombination characteristics of each semiconductor layer.

Having got passed a single PC the flax of photons with frequency ω decreases so that in an infinitely thin layer of thickness *dx* the intensity of radiation decreases proportionally to the layer thickness:

$$d\Phi = -\alpha(\omega)\,\Phi dx,$$

where Φ is the photon flax and α is absorption coefficient. We integrate to obtain the following expression that shows that the photon flax decreases exponentially in the depth of PV cell:

$$\Phi = \Phi_0 \exp(-\alpha x),$$

where Φ_0 is the photon flax on the front surface (x=0).

The relative photon flax distribution on thickness of the PV cell $\Phi(x)$ presented in Fig. 3 illustrates the principle of determining the optimal values of the single PCs' base area thickness.

The presented theoretical research made it possible to evaluate the operation of photoelectric converter and its parameters for both monochromatic and solar illumination with the tunnel effect either taken into consideration or not (5).

One of the major problems is the estimation of all possible opportunities provided with the application of the proposed PV cells in terms of optimized PV cells designs and idealized, theoretically proved upper limit parameter values of semiconductor structures. Particularly it corresponds to the conditions for which both volume and surface recombination of charge carriers in epitaxial layers deposited upon the base PC can be neglected. The possibility of implementing such conditions is based on the assumption that the optimal layer thickness values may, a priori, appear to be lower than those of the diffusion lengths for charge carriers in the corresponding layers while the recombination can be principally avoided with the help of existing technological methods.

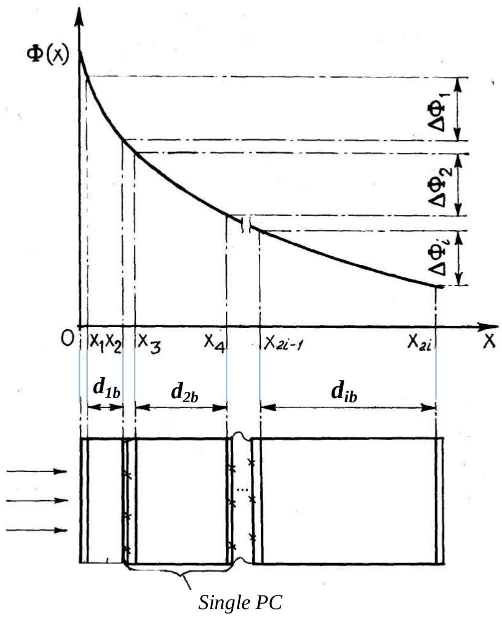


Fig. 3: Relative photon flax distribution on thickness of the PV cell.

From the practical point of view, solar spectrum conversion is of most interest. However this spectrum is of a rather complex nature. Moreover, as far as terrestrial conditions are concerned, it is essentially dependent on the season and weather situation. Therefore the calculations are usually made for a black body spectrum at temperature T_c that, in general, adequately approximates the solar radiation distribution on frequencies ω:

$$\frac{d\Phi}{d\omega} = \frac{\Phi_c \cdot \omega^2}{e^{\frac{\hbar\omega}{kT_c}} - 1}$$

where $\hbar$ is Planck constant and k is Boltzman constant. The constant Φ_c can be easily linked to the experimentally determined parameter W, which is the flux density of solar energy:

$$\frac{d\Phi}{d\omega} = W \cdot \frac{15}{\pi^4} \cdot \frac{\hbar^3}{(kT_c)^4} \cdot \frac{\omega^2}{e^{\frac{\hbar\omega}{kT_c}} - 1}$$

To ensure the equality of total photocurrents the thickness of single PCs' base layers shall comply with the condition of equality of all spectral components of photocurrents integrated over the incident radiation spectrum.

The photocurrents equality conditions for the entire PV cell circuit are:

$$\left.\begin{aligned}
&\int_0^\infty \frac{d\Phi}{d\omega}\cdot e^{-\alpha\sum_{k=i+2}^{N} d_k}\cdot(1-e^{-\alpha d_{i+1}})\cdot d\omega = \\
&\qquad = \int_0^\infty \frac{d\Phi}{d\omega}\cdot e^{-\alpha\sum_{k=i+1}^{N} d_k}\cdot(1-e^{-\alpha d_i})\cdot d\omega; \quad i=2,3,\dots,N-1 \\
&\int_0^\infty \frac{d\Phi}{d\omega}\cdot e^{-\alpha\sum_{k=i+1}^{N} d_k}\cdot(1-e^{-\alpha d_i})\cdot d\omega = \\
&\qquad = \int_0^\infty \frac{d\Phi}{d\omega}\cdot e^{-\alpha\sum_{k=2}^{N} d_k}\cdot Q(\omega)\cdot d\omega; \qquad i=2,3,\dots,N
\end{aligned}\right\}$$

The photon absorption coefficient $\alpha(\omega)$ and, accordingly, the collecting coefficient of generated charge carriers $Q(\omega)$, have a threshold at $\omega = \omega_0 = E_g/\hbar$, where E_g is the width of the forbidden band of the semiconductor. The dependencies $d\Phi/d\omega$, $\alpha(\omega)$ and $Q(\omega)$ are of a rather complex nature, therefore the integrals in system were determined by numerical methods.

The thickness d_i of the *i*-th single PC is the sum of thicknesses of the doped layer, base layer and p^+ layer:

$$d_i = d_{i_d} + d_{i_b} + d_{i_{p^+}} \ .$$

The spectral collection coefficient of such single *PC* is:

$$Q_i = Q_{i_d} + Q_{i_b} + Q_{i_{p^+}} \quad ,$$

where $Q_{i_d}, Q_{i_b}, Q_{i_{p^+}}$ are the spectral collection coefficients of the doped layer, base area and heavily doped layer, respectively, for the *i*-th single PC. Each of the above spectral coefficients can be expressed with the help of one general function $Q(\alpha, d, L, S, D)$ of absorption coefficient α, layer thickness d, minor charge carriers diffusion L, surface recombination ratio on the surface opposite to the n^+-p (or p-p^+) junction S and minor charge carriers diffusion coefficient D.

Taking into account absorption of radiation in upper layers, the spectral collection coefficient decreases in relation to the intensity of the incident flax and can be estimated as:

$$\Phi_i = e^{-\alpha\sum_{k=i+1}^{N} d_k} Q_i \ .$$

The thicknesses of PCs' base layers d_{ib} are determined from the system comprising N - 1 non-linear equations:

$$\int_0^\infty d\lambda S(\lambda)\Phi_i(\lambda) = \int_0^\infty d\lambda S(\lambda)\Phi_1(\lambda) \qquad i = 2,3,\dots, N\,,$$

where $S(\lambda)$ is the spectral density of incident radiation.

These equations describe the structure in terms of most stringent requirements: the output power of PV cell shall be as high as possible which means the equality of the spectral photocurrents integrated over the whole incident radiation spectra. Computer-assisted optimization of the fabrication process based on this equation system makes it possible to achieve the best correspondence of the PV cell output parameters to those obtained by calculations and the best controllability of fabrication process. Since the PV cell comprises a number of structures connected in series the only condition that has to be complied with to implement this effect is that the lowest photocurrent value for all structures shall be not less than the minimum permissible photocurrent value for the photoelectric cell as a whole.

As an example, the PV cell consisting of two (N = 2) single PCs having a non-photoactive, infinitely thin p^+ layer. Computations are made for the depth axis in the assumption that: the doped layers of structures are identical in terms of their electro-physical characteristics and thickness and p^+ layer provides a metal-type transient contact between the p and n layers.

The spectrum of absolutely black body having the temperature of 6000 K (extraterrestrial solar radiation) was used to approximate the incident light. Integration over wavelength was performed in the range of 0.4μ to 1.1μ. (There is no data available on absorption coefficient for silicon in lower wavelength range). Thus it was assumed that the charge carriers' collection coefficient for incident radiation with wavelengths < 0.4μ equals to zero. The input data for semiconductor layers parameters and the computation results are presented in Table 1 and Table 2, respectively.

<u>TABLE 1: THE INPUT DATA FOR SEMICONDUCTOR LAYERS PARAMETERS</u>

N/ layer	L [μ]	S [cm/s]	D [cm^2/s]	d [μ]	Doping level [1/ cm^3]
1/ base	300	10^6	25	500	10^{16}
1/ doped	1	10^6	1	1.0	10^{19}
2/ base	300	0 - 10^6	25	**?**	10^{16}
2/ doped	1	10^6	1	1.0	10^{19}

TABLE 2: RESULTS OF PHOTOELECTRIC GENERATOR PARAMETERS CALCULATIONS FOR VARYING S_{2b}

Parameter / S_{2b} [cm/s]		0	10	10^2	10^3	10^4	10^5	10^6
Photo current	j_1 [mA/cm^2]	17.044	17.044	17.041	17.018	16.799	15.603	14.703
	j_2 [mA/cm^2]	17.044	17.044	17.041	17.018	16.799	15.603	14.703
	j^* [mA/cm^2]	34.374	34.374	34.374	34.374	34.374	34.374	34.374
Reverse current	j_{01} [mA/cm^2]	$2.851\cdot10^{-9}$	$2.851\cdot10^{-9}$	$2.851\cdot10^{-9}$	$2.851\cdot10^{-9}$	$2.851\cdot10^{-9}$	$2.851\cdot10^{-9}$	$2.851\cdot10^{-9}$
	j_{02} [mA/cm^2]	$6.716\cdot10^{-11}$	$9.855\cdot10^{-11}$	$3.808\cdot10^{-10}$	$3.170\cdot10^{-9}$	$2.796\cdot10^{-8}$	$1.226\cdot10^{-7}$	$1.623\cdot10^{-7}$
η_1 [%]		12.137	12.137	12.137	12.137	12.137	12.137	12.137
η_{1+2} [%]		12.737	12.622	12.216	11.5677	10.772	9.564	8.910 %.
U_{oc}* [mB]		580.324	580.324	580.324	580.324	580.324	580.324	580.324
U_{oc1} [mB]		562.786	562.786	562.782	562.748	562.423	560.578	559.092
U_{oc2} [mB]		656.494	646.906	613.113	560.099	505.343	466.544	458.044
U_{oc1+2} [mB]		1219.281	1209.691	1175.895	1122.848	1067.767	1027.122	1017.136
d_2 [μ]		2.999	2.999	3.000	3.013	3.139	3.905	4.588

*of lower cell in the independent operation mode

The full voltage U generated by the structure is the sum of voltages generated by all single PCs. The current-voltage characteristic of the multijunction PV cell for both monochromatic and solar radiation can be written in form:

$$U = \frac{AkT}{q}\sum_{i=1}^{N} ln\left(\left(\frac{q\Phi\cdot Q}{1+(N-1)\cdot Q} - j\right)\Big/ j_{0i} + 1\right)$$

where j_{0i} is the density of dark reverse current of the i-th PC (which for identical technological PC formation conditions does not practically depend on its number: $j_{0i} = j_0$), A is the characteristic curvature parameter. The open circuit voltage monotonously increases with the growth of PC number N in the system (for low values of N it grows approximately linearly), slightly depending on j_0 and Q. In the asymptotical limit (for N·Q>> 1) it is getting still weaker than the linear dependence on N that is uniform for any value of Q.

Thus the ultimate current-voltage characteristic of multijunction PV cell having the semiconductor structure optimized for a certain wavelength of monochromatic radiation or for solar radiation has a similar generic form.

Fig. 4 shows the dependence of open circuit voltage for silicon PV cell on N for a number of values of tunnel layer thickness δ for $\alpha = 0.125\mu^{-1}$, Q = 0.8, light intensity equal to that of solar radiation ($q\Phi$ = 45 mA/cm^2) and other parameters corresponding to recombination mechanism currents (A = 2; $J_0 = 10^{-7}$ A/cm^2).

The generated power at the optimal operation point of current-voltage characteristics of multijunction PV cell changes non-monotonously with the number of elements N. It increases for small N values then passes a maximum and, in the asymptotical limit, poorly (logarithmically) falls for all Q values.

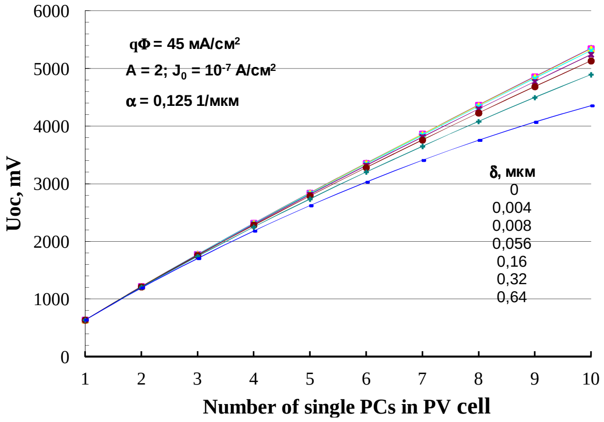
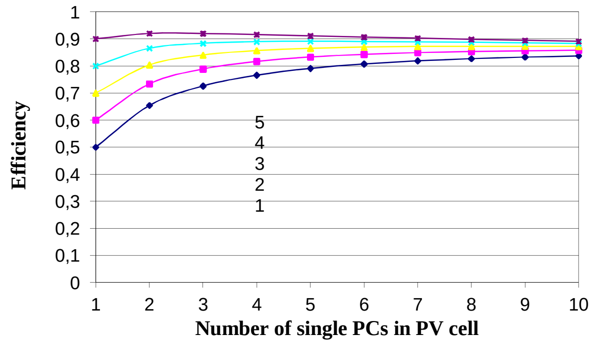


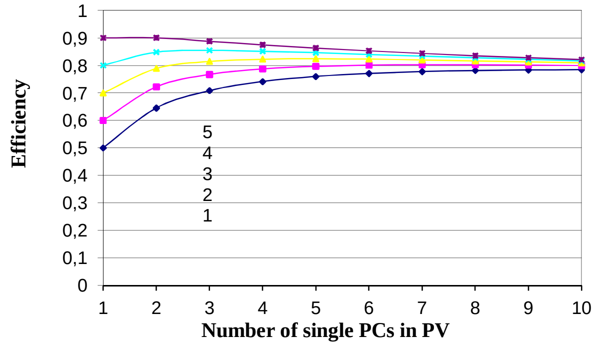
Fig.4: Open circuit voltage of silicon multijunction planar PV cell.

These planar multijunction PV cells not only provide the multiple voltage gain but also the perspective of achieving the efficiency values exceeding those of the base PC, particularly in the range of low charge carriers collection coefficient values in it.

The relative efficiency of silicon planar multijunction PV cell, i.e. the relation of output power P of PV cell to the maximum output power P_{1m} of separate base PC (corresponding to the conditions N = 1, Q = 1), is shown in Fig. 5 for exoatmospheric solar radiation conditions (W = 0.136 W/cm^2, $\Phi = 3.08\times10^{17}$/cm$^2\cdot$s) for various Q values and for two values of reverse saturation current: one for $j_0 = 10^{-11}$ A/cm^2 (for diffusion current mechanism: A = 1) and the other for $j_0 = 10^{-7}$ A/cm^2 (for the recombination current mechanism: A = 2).



a)



b)

Fig. 5: Top limit of relative efficiency for silicon multijunction planar PV cell.
a) A = 1, $j_0 = 10^{-11}$ A/cm^2.Q =: 0.5 (1); 0.6 (2); 0.7 (3); 0.8 (4); 0.9 (5); b) A = 2, $j_0 = 10^{-7}$ A/cm^2. Q =: 0.5 (1); 0.6 (2); 0.7 (3); 0.8 (4); 0.9(5).

It is seen that for Q> 0.5 the efficiency reaches its maximum in the range of N = 4 to 7 that drifts towards smaller N with the increase of Q.

The absolute maximum efficiency value of separate base PC under solar radiation is equal to $\eta_{1m} = P_{1m}/W$. For A = 1 and $j_0 = 10^{-11}$ A/cm^2 we obtain $\eta_{1m} = 0.173$. For A = 2 and $j_0 = 10^{-7}$ A/cm^2 the calculated efficiency value is $\eta_{1m} = 0.190$. The absolute maximum efficiency (η = P/W) of multijunction PV cell for Q ≥ 0.7 has the following values: $\eta \geq 0.151$ for A = 1 and $j_0 = 10^{-11}$ A/cm^2; $\eta \geq 0.157$ for A = 2 $j_0 = 10^{-7}$ A/cm^2.

These PV cells structures are operational under tough conditions of concentrated electromagnetic radiation at high temperatures providing the potential for additional radiation conversion efficiency enhancement.

3. DESIGNS WITH PLANAR MULTIJUNCTION PV CELLS

Photoelectric devices and system element on the basis of multijunction planar PV cells have the following advantages: 1) substantial reduction of the effect of non-homogeneous radiation distribution (possibility of parallel connection of PV cells in modules), 2) using less complicated electronic power conversion devices in a solar system accompanied by the reduction of power losses in them (owing to much higher output voltage: 48VDC to 50VDC for a single-piece PV module and 220VDC to 240VDC for an entire system).

Fig. 6a presents the diagram of 12VDC, 24VDC and 48VDC module with parallel PV cells connection and Fig. 6b shows schematically the photoelectric system.

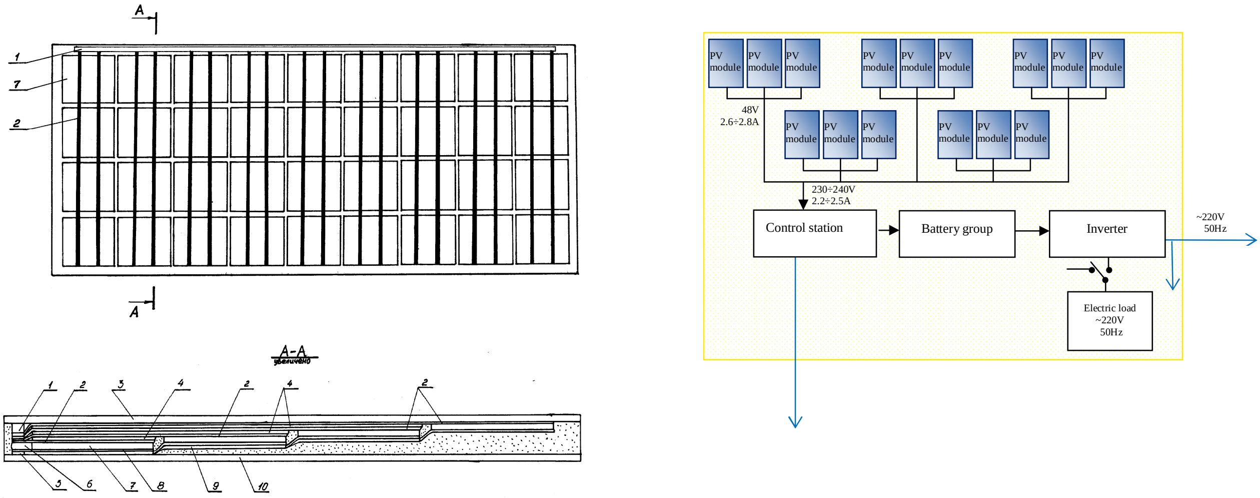
4. CONCLUSIONS

The proposed PV cells are of planar-high-voltage type. They provide the option of combining the advantages of these two structures insuring much higher efficiency of electromagnetic radiation conversion and output voltage. Planar technology is of the most developed and it makes it possible to manufacture high-voltage PV cells, planar PV cells designed to convert effectively concentrated radiation into electricity.

The photocurrent of multijunction PV cell decreases exponentially with the number of single PC (for asymptotic limit). The upper limit values of output voltage, power and efficiency change non-monotonously with the increasing number of single PC, reach their maximum and then fall for its asymptotic growth.

The thickness of tunnel layers in the structure is the most critical quantity determining the efficiency of planar multijunction PV cell. Therefore the optimization of existent structures for recommended output voltage values is essential.

The optimal values of single PCs deposited on the base PC decrease with their number. For silicon structures they are in the range from one to several microns. Therefore it is technologically easy to manufacture such PV cells.



a) b)

Fig. 6: Designs with multijunction planar PV cells: a) PV module with parallel PV cells connection; b) Diagram of system. 1 – upper connection bar, 2 – upper connection strips, 3 – upper glass, 4, 9 – dielectric film, 5 – lover connection bar; 6 – spacer , 7 – PV cells, 8 – lover connection strips, lover glass.

6. REFERENCES

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