THE PLANAR HIGH-VOLTAGE SOLAR CELL ON THE BASIS OF THE HOMOGENEOUS SEMICONDUCTOR

Yuri D.Arbuzov, Vladimir M.Evdokimov, Dmitry S.Strebkov, Olga V.Shepovalova

The All-Russian Research Institute for Electrification of Agriculture (GNU VIESH), Moscow, (Russia)

1. Introduction

Usual homogeneous semiconductor photoconverters (PC), including one p-n junction (Lidorenko et al. 1988, Arbuzov and Evdokimov 2008), generate the voltage, determined by the height of the potential barrier of junction. For technologically the most used photoelectric materials, silicon and gallium arsenide, at illumination with intensity of the order one solar voltage achieve 0,6-0,9 V. At the same time for the operation of the typical electronic equipment the voltage considerably exceeding these values (up to ten times) that is carried out due to commutation separate PC in the battery are required. However it leads to inevitable ohmic and commutation losses of power, therefore the problem of creation effective PC with voltage increased even in some times is actual.

In the given work the new type offered by authors homogeneous planar PC on the basis of multijunction semiconductor structure n^+-p-p^+-n^+-p-p^+-…-n^+-p-p^+ (Strebkov et al. 2008, Arbuzov et al. 2007, Arbuzov et al. 2008) which principally allows to increase values of the output voltage is considered. At the present time the similar structure can be created by methods liquid or gas epitaxy by creating the subsequent layers on base PC. Base PC can be created by usual way and will provide mechanical hardness of all structure. As p^+ and n+ layers are heavily doped between them ohmic contact due to quantum mechanical tunneling of charge carriers through a potential barrier on p^+-n^+ junction is provided. Such structure shown on fig.1, represents homogeneous high-voltage PC, consisting of consistently connected PC, illuminated by light which has been consistently pass through the previous semiconductor layers.

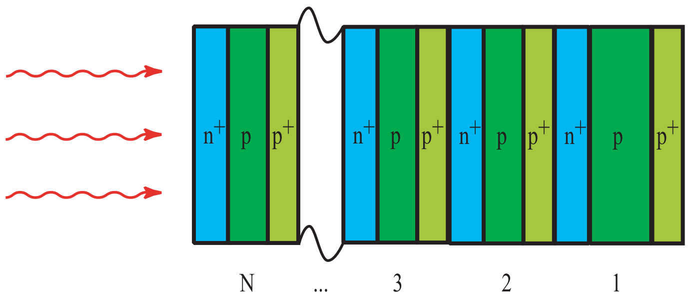

Fig. 1. Structure of the homogeneous high-voltage photoconverter. Figures designate PC number .

In the series-connected elements currents are identical, and for avoidance of circuit losses in cascade PC each element at illumination should be in an optimum point of current-voltage characteristics. As value of PC optimum operating current is close to a photocurrent the condition of generation of the maximal power in structure is actually reduced to the requirement of equality of photocurrents of all entering in structure PC. For realization of this it is necessary to determine corresponding values of thickness of separate PC base layers .

Besides the stated statement allows to formulate and the more general problem of structure optimization and a design offered homogeneous cascade PC. As illumination of everyone separate PC and base PC decreases with growth of their quantity in a circuit because of absorption of light in more top layers, the photocurrent generated in structure also decreases with growth of the separate PC quantity. At the same time the full voltage generated in structure, representing the sum of the voltages generated in separate PC, with growth of their quantity will increase. It is meant, that output power, generally, will depend non monotonously on quantity PC in cascade N, achieving the maximal size at some value N. It is natural, that optimum values of separate PC thickness and their full quantity, as well as value of the maximal generated power, will depend on a spectrum of falling radiation, diffusion and recombination parameters of each semiconductor layer.

2. Limiting photo-electric characteristics of high-voltage homogeneous photoconverters.

One of the primary goals is definition of the maximal opportunities of the offered new type homogeneous high-voltage PC with use of the optimized designs cascade PC and idealized, theoretically limiting values of semiconductor structures parameters. In particular, it corresponds to conditions of neglect volume and surface recombination of charge carriers in epitaxial layers deposited on base PC. The opportunity of realization of such conditions is based that optimum values of thickness of layers a priori can appear small in comparison with the diffusion lengths of charge carriers in them, and surface recombination can be essentially eliminated by existing technological methods.

The problem is solved for conversion of the monochromatic radiation, giving function of generation of charge carriers on depth x from a illuminated surface of a kind:

$$\Phi(x) = \Phi \cdot e^{-\alpha x}, \qquad \text{(eq. 1)}$$

Where Φ - density of a stream of falling photons, α - coefficient of absorption of the radiation, depending on wave length λ and the nature of the semiconductor.

The density of photocurrent $J_{\Phi i}$ generated in i-th PC, with the account of light absorption in the previous layers, is equal:

$$J_{\Phi i} = q \cdot \Phi \cdot e^{-\alpha \sum_{k=i+1}^{N} d_k} Q_i; \quad i = 1, 2, ..., N, \qquad \text{(eq. 2)}$$

where q - an electron charge, d_k - thickness of k-th PC, $Q_{i.}$ - spectral coefficient of charge carriers collection to p-n junction in i-th PC. According to idealized model we accept, that the coefficient of carriers collection in i-PC is equal to the share of radiation absorbed in these PC, i.e.

$$Q_i = 1 - e^{-\alpha d_i}; \quad i = 2, 3, ..., N, \qquad \text{(eq. 3)}$$

and the coefficient of carriers collection in base 1-st PC is accepted fixed: $Q_1 = Q$.

Proceeding from this, conditions of equality of photocurrents in a consecutive circuit of the cascade present as:

$$1 - e^{-\alpha d_{i+1}} = e^{-\alpha d_{i+1}} \left(1 - e^{-\alpha d_i}\right); \quad i = 2, 3, ..., N, \qquad \text{(eq. 4)}$$

$$1 - e^{-\alpha d_i} = e^{-\alpha \sum_{k=2}^{i} d_k} Q; \quad i = 2, 3, ..., N. \qquad \text{(eq. 5)}$$

The decision of these equations gives following value:

$$d_i = \frac{1}{\alpha} \cdot \ln\left[\frac{1 + (i-1) \cdot Q}{1 + (i-2) \cdot Q}\right]; \quad i = 2, 3, ..., N. \qquad \text{(eq. 6)}$$

PC thickness changes as inverse proportion to coefficient of photons absorption, slowly falls with PC number increase and grows with increase in coefficient of charge carriers collection in base 1-st PC.

From here we receive value of a photocurrent in series circuit of N elements:

$$J_{\Phi} = J_{\Phi i} = q\Phi \cdot (1 - e^{-\alpha d_N}) = q\Phi \cdot \frac{Q}{1 + (N-1)Q}; \quad i = 1, 2, ..., N \qquad \text{(eq. 7)}$$

Apparently, the photocurrent falls with growth N (at N×Q>> 1 - in inverse proportion) and gradually becomes independent from Q, coming nearer to value $J_{\Phi} = q\Phi/N$.

3. Prospects of achievement of high-voltage in cascade photoconverters.

The total voltage U generated in structure, represents the sum of the voltages generated in separate PC. Thus, extremely achievable the current voltage characteristic of ideal cascade PC looks like:

$$U = \frac{AkT}{q} \sum_{i=1}^{N} \ln\left(\left[\frac{q\Phi \cdot Q}{1 + (N-1) \cdot Q} - J \right] \Big/ J_{0i} + 1 \right), \qquad \text{(eq. 8)}$$

where kT - thermal energy, J_{0i} - density of the dark reverse current in i-th PC, A - parameter of the characteristic curvature. As thickness of i-th PC enough slowly depends on its number, and all PC are created on uniform technology value J_{0i} practically appears identical to all PC and the current voltage characteristic becomes:

$$U = N \frac{AkT}{q} \cdot \ln\left(\left[\left(\frac{q\Phi \cdot Q}{1 + (N-1) \cdot Q} - J \right) \right] \Big/ J_0 + 1 \right), \qquad \text{(eq. 9)}$$

with an open circuit voltage

$$U_{oc} = N \frac{AkT}{q} \cdot \ln\left(\frac{q\Phi \cdot Q}{1 + (N-1) \cdot Q} \Big/ J_0 + 1 \right). \qquad \text{(eq. 10)}$$

Dependence of the open circuit voltage of ideal cascade PC from N in relation to a voltage of base PC (N = 1) open circuit U_{oc1} for various values of charge carriers collection coefficient in base Q is presented on fig. 2.

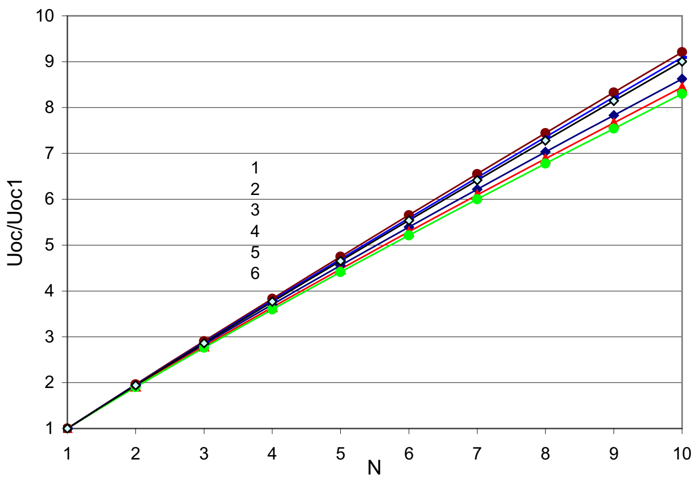

Fig. 2. Open Circuit voltage of cascade PC.
Curves 1 - 3: A = 1, $J_0 = 10^{-11}$ A/cm^2, Q =: 0,5 (1); 0,7 (2); 0,9 (3).
Curves 4 - 6: A = 2, $J_0 = 10^{-7}$ A/cm^2, Q =: 0,5 (4); 0,7 (5); 0,9 (6)

With growth of PC quantity N in system the relative open circuit voltage monotonously grows approximately directly proportional and slowly depends on value of the dark reverse current and coefficient of charge carriers collection in base PC. In the asymptotic limit at N×Q>> 1 the open circuit voltage of cascade PC gets weak distinct from linear dependence:

$$U_{oc} = N\frac{AkT}{q}\cdot \ln\left(\frac{q\Phi}{N\cdot J_0}+1\right);\quad N\cdot Q >> 1 \qquad \text{(eq.11)}$$

Thus, in offered new type cascade homogeneous PC there is a basic opportunity of achievement of voltage, it is more than ten times exceeding voltage in usual planar PC.

4. Prospects of efficiency increase of cascade photoconverters.

Generated power of ideal cascade PC in an operating point of current voltage characteristics (9) is equal (Arbuzov and Evdokimov 2008):

$$P = m\cdot J_{\Phi}\cdot U_{oc} = m\frac{q\Phi\cdot Q\cdot N}{1+(N-1)\cdot Q}\cdot\frac{AkT}{q}\cdot\ln\left(\frac{q\Phi\cdot Q}{1+(N-1)\cdot Q}\Big/J_0+1\right), \qquad \text{(eq. 12)}$$

Where m - filling coefficient of the characteristic which at enough large value of an open circuit voltage can be presented by asymptotic dependence:

$$m = 1-\frac{AkT}{qU_{oc}}\cdot\left(\ln\frac{qU_{oc}}{AkT}+1\right);\quad \frac{qU_{oc}}{AkT} >> 1 \qquad \text{(eq. 13)}$$

With growth of number N the filling coefficient converge to one because of corresponding growth of an open circuit voltage, and cascade PC power, generally, changes non monotonously. At small number PC (N = 2 - 3) power sharply enough grows with increase N, passes then a maximum and in asymptotic limit very slowly falls according to expression:

$$P = AkT\cdot\Phi\cdot\ln\left(\frac{q\Phi}{N\cdot J_0}+1\right);\quad N\cdot Q >> 1, \qquad \text{(eq. 14)}$$

The relative efficiency ideal cascade PC, i.e. the relation of power of the cascade to the maximal power of base PC (corresponding condition N = 1, Q = 1), in neglecting weak dependence of factor m from N, is presented on fig. 3 and 4 for various values Q and for two values of a dark reverse current: $J_0 = 10^{-11}$ A/cm^2 (at diffusion mechanism of a current A = 1) and $J_0 = 10^{-7}$ A/cm^2 (at recombination mechanism of a current A = 2).

With growth of number N efficiency of cascade PC, as well as its power, changes non monotonously, increasing at small N, passing flat enough maximum in the region of N = 2 - 7 and at N×Q>> 1 falling according to expression for power (eq. 14) at any values Q. Thus the maximal efficiency achieves the values making more 0,8 from limiting efficiency base PC. For various mechanisms of the dark reverse current in PC character of this dependence is qualitatively kept.

Thus, offered cascade homogeneous PC, created on the basis of usual planar PC, alongside with repeated increase of a voltage have prospect of achievement of the efficiency considerably exceeding efficiency of the base PC, especially at low values of charge carriers collection coefficient in it.

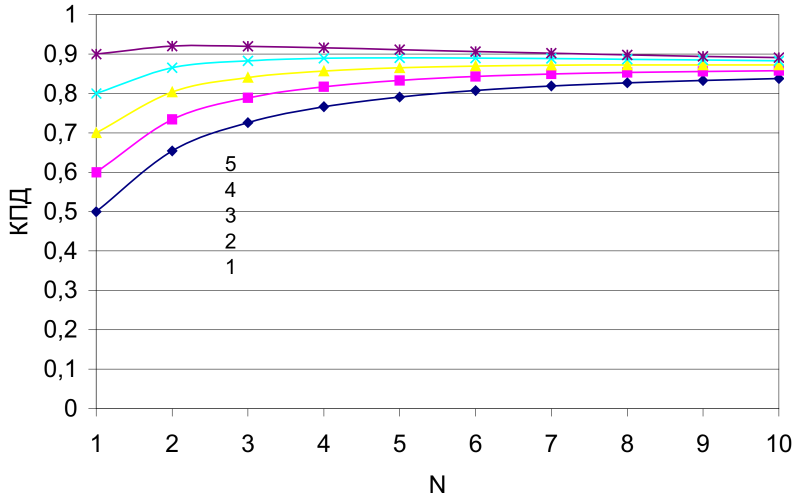

Fig. 3. Relative efficiency cascade PC. A = 1, $J_0 = 10^{-11}$ A/cm^2.
Q = 0,5 (1); 0,6 (2); 0,7 (3); 0,8 (4); 0,9 (5).

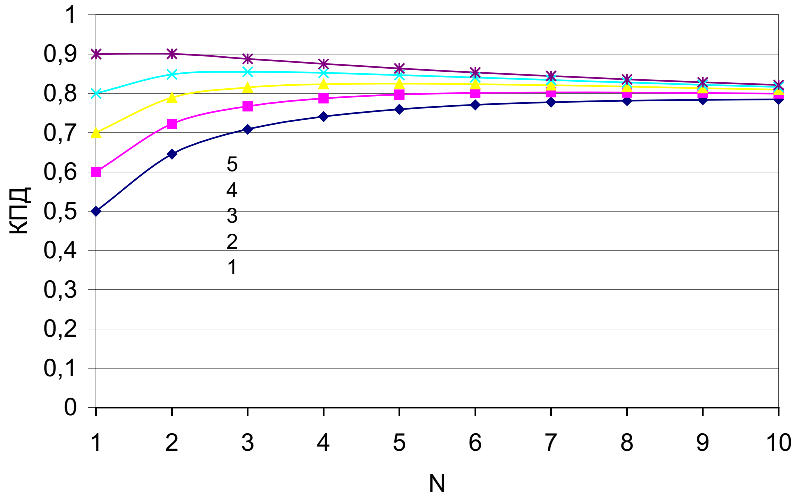

Fig. 4. Relative efficiency cascade PC. A = 2, $J_0 = 10^{-7}$ A/cm^2
Q = 0,5 (1); 0,6 (2); 0,7 (3); 0,8 (4); 0,9 (5).

5. Characteristics of real high-voltage homogeneous photoconverters of a solar energy.

One side cascade PC.

The condition of equality of photocurrents of all PC in the cascade for an any spectrum of falling radiation generally leads to system N-1 of the nonlinear equations for everyone i-th PC with structure n^+-p-p^+ (Strebkov at al. 2008):

$$\int_0^\infty d\lambda \cdot \Phi(\lambda) \cdot e^{-\alpha \sum_{k=i+1}^{N} d_k} Q_i(\lambda) = \int_0^\infty d\lambda \cdot \Phi(\lambda) \cdot e^{-\alpha \sum_{k=2}^{N} d_k} Q_1(\lambda) \qquad i = 2,3, \dots N, \qquad \text{(eq. 15)}$$

where: $\Phi(\lambda)$ - spectral density of a stream of radiation on length of wave λ; Q_i (λ) - spectral coefficient of charge carriers collection to n +-p junction in i-th PC; $d_k = d_{kn+} + d_{kp} + d_{kp+}$, - thickness of k-th PC which represents the sum of thickness doped n^+-layer, base p-layer and p^+-layer.

In real semiconductor structures the coefficient of charge carriers collection Q_i of i-th PC can be presented in the form of the sum of collection coefficients from doped n^+-layer, a base p-layer and p^+-layer,

$$Q_i = Q_{in+} + Q_{ip} + Q_{ip+}, \qquad \text{(eq. 16)}$$

Each of which can be expressed through single function Q(α, d, L, S, D) from factor of absorption α, thickness of a layer d, diffusion lengths of minority charge carriers in it L, speeds of surface recombination S on a surface opposite n^+-p (or p-p^+) junction, and factor of diffusion of minority charge carriers D (Arbuzov and Evdokimov 2008):

$$Q(\alpha, d, L, S, D) = \frac{\alpha L \cdot \left[\frac{\frac{SL}{D} - 1}{1 - \alpha L} \left(e^{-\frac{d}{L}} - e^{-\alpha d} \right) + \frac{\frac{SL}{D} + 1}{1 + \alpha L} \left(e^{\frac{d}{L}} - e^{-\alpha d} \right) \right]}{\left(1 + \frac{SL}{D}\right) e^{\frac{d}{L}} + \left(1 - \frac{SL}{D}\right) e^{-\frac{d}{L}}}. \qquad \text{(eq. 17)}$$

Omitting an index i, it is possible to write down:

$$Q_{n+} = -e^{-\alpha d_{n+}} Q(-\alpha, d_{n+}, L_{n+}, S_{n+}, D_{n+}), \qquad \text{(eq. 18)}$$

$$Q_p = e^{-\alpha d_{n+}} Q(\alpha, d_p, L_p, S_p, D_p), \qquad \text{(eq. 19)}$$

$$Q_{p+} = \frac{2e^{-\alpha(d_{n+} + d_p)}}{\left(1 + \frac{S_p L_p}{D_p}\right) e^{\frac{d_p}{L_p}} + \left(1 - \frac{S_p L_p}{D_p}\right) e^{-\frac{d_p}{L_p}}} \cdot Q(\alpha, d_{p+}, L_{p+}, S_{p+}, D_{p+}). \qquad \text{(eq. 20)}$$

For speed of surface recombination on the back side of base p-area it is necessary to use effective value:

$$S_p = \frac{N_p}{N_{p+}} \cdot \frac{D_{p+}}{L_{p+}} \cdot \frac{\frac{S_{p+} L_{p+}}{D_{p+}} + \operatorname{th} \frac{d_{p+}}{L_{p+}}}{1 + \frac{S_{p+} L_{p+}}{D_{p+}} \operatorname{th} \frac{d_{p+}}{L_{p+}}}, \qquad \text{(eq. 21)}$$

Where N_p - a doped level of a base p-layer, N_{p+} - a doped level p^+-layer.

At the fixed values of parameters doped n^+-and p^+-layers the received system N-1 of the nonlinear equations for values d_{ip} has been solved by numerical methods. Squaring the equations, summing them and taking from the received sum a square root some norm is given which obviously has a minimum equal to zero, on the decision of system turned out. For the numerical decision the method of consequent coordinate descent for a finding of a minimum was used. With this purpose the corresponding program was created.

Most simple of the offered designs of new type is represented with the cascade from two PC (N = 2). Used parameters of semiconductor layers are resulted in tab. 1. Thus was accepted, that doped n^+-and p^+-layers are created on the same technologies and consequently have identical values of parameters.

Table 1. Values of parameters of semiconductor layers.

Type of a layer, number PC	L [micron]	S [cm/s]	D [cm^2/s]	d [micron]	N_p [1/cm^3]
p1	300	10^6	25	500	10^{16}
p2	300	0 - 10^6	25	?	10^{16}
n^+	1	10^6	1	1.0	10^{19}
p^+	1	10^6	1	1.0	10^{19}

As a spectrum of falling radiation the spectrum of absolutely black body with temperature 6000 K (the exoatmospheric sun) has been chosen:

$$\Phi(\lambda) = W\frac{120\cdot\hbar^3c^3}{\pi\cdot(kT_s)^4\lambda^4}\cdot\frac{1}{\exp(\frac{2\pi\hbar c}{kT_s\lambda})-1}, \qquad \text{(eq. 22)}$$

Where W = 136 mW/cm^2 - density of a stream of the energy falling on PC; $\hbar$ - Planck's constant, divided on 2π; c - speed of light; k – Boltzmann's constant; T_s - temperature of a surface of the Sun. Integration on lengths of waves was made in an interval 0,4 - 1,1 microns as for smaller lengths of waves the factor of collecting in real PC is small.

Results of numerical calculation of thickness of a base layer of the second PC for structures with infinitely thin not photoactive p^+-layer at various values of surface recombination speed base layer S_{p2} are resulted in tab. 2. In this table values of a photocurrent of structure J_Φ, an open circuit voltage of separate elements U_{oc1} and U_{oc2} and on all structure U_{oc}, and also efficiency η also are resulted. Results are received for PC with parameter of current voltage characteristic A = 1, corresponding to diffusion dark reverse current, determined the least doped base p-area with concentration of acceptors of 10^{15} cm^{-3}.

Table 2. Values of thickness of a base p-layer and parameters PC for various values S_{p2}.

S_{p2} [cm/s]	d [micron]	J_Φ [mA/cm^2]	U_{oc1} [mV]	U_{oc2} [mV]	U_{oc} [mV]	η [%]
0	3.13	17.36	563	657	1220	13.0
10	3.13	17.36	563	647	1210	12.9
10^2	3.13	17.35	563	563	1176	12.5
10^3	3.14	17.33	563	561	1124	11.8
10^4	3.28	17.09	563	506	1069	11.0
10^5	4.09	15.85	561	468	1029	9.7
10^6	4.78	14.95	560	459	1019	9.1

It is visible, that creation of the cascade favorably if it will be possible to lower surface recombination speed on a back surface of base of the top element to values S_{p2} <10^3 cm/c. At large values of surface recombination speeds the dark reverse current of the top element increases and its efficiency worsens. Thus thickness of its base layer that is necessary for operation of the cascade increases. At S_{p2} = 10^6 cm/c value of efficiency is equal η = 9.1 %, and top limit value at elimination of recombination is equal η = 13.0 %. For comparison, on one base PC following values J_Φ = 35.41 mA/cm^2, U_{oc} = 581 mV, η = 12.5 % are received.

Thus, the open circuit voltage of idealized cascade structure consisting from 2 PC (with elimination of surface recombination) for a sunlight more than in 2 times exceeds an open circuit voltage of usual planar

PC at simultaneous efficiency increase. The increase is achieved due to improvement of characteristics both top, and bottom PC. Top - due to the increased of collection coefficient at elimination of surface recombination. Bottom - because in it more long-wave radiation absorbs and thus negative influence of the doped layer less affects.

Negative effect is reduction of a photocurrent in such structure that leads to reduction of a open circuit voltage. But, apparently from the presented results, it is the negative tendency can be under certain conditions compensated by positive, that as a whole leads to some growth of efficiency of all structure.

At the account of presence p^+-layer in the second PC with the parameters represented in tab. 1, following results are obtained (tab. 3).

Table 3. Values of thickness of a base p-layer of an element and parameters PC at the account p^+-layer.

S_{p2} [cm/s]	d [micron]	$J_Ф$ [mA/cm^2]	U_{oc1} [mV]	U_{oc2} [mV]	U_{oc} [mV]	η [%]
13.06	2.44	16.84	562	645	1207	12.4

Surface recombination speed on the back surface of base area of the second PC decreases to value of 13.06 cm/c. The account of the non zero sizes p^+-layer leads to necessity to reduce thickness of a p-layer. Simultaneously in comparison with top limit values of efficiency, a current of short circuit and an open circuit voltage a little decrease. However as a whole the cascade structure possesses good parameters that speaks about an opportunity of creation of effective high-voltage planar cascade elements.

For the optimized structure from two PC on the basis PC with base thickness d_{p1} = 300 microns numerical calculation results to the following values: d_{p2} =2.61 microns, $J_Ф$ = 17.22 mA/cm^2, U_{oc1} = 571 mV, U_{oc2} = 651 mV and total value of an open circuit voltage on structure U_{oc} = 1223 mV. The efficiency of structure is equal 12.9 %. On one base PC values are received: $J_Ф$ = 36.18 mA/cm^2, U_{oc} = 590 mV, η = 13.0 %.

Thus, the open circuit voltage of real cascade structure from 2 PC for a sunlight more than in 2 times exceeds a open circuit voltage of usual planar PC at actual preservation of efficiency.

Bilateral cascade PC.

At rather small thickness usual planar PC can operate at illumination from two sides, however they appear ineffective besides have small values of a voltage. For increase in efficiency and simultaneously increases of a operating voltage the new type bilateral high-voltage PC is offered. One of the most simple designs of similar type represents offered cascade PC, consisting of three consistently connected PC with structure n^+-p-p^+ so the general cascade PC structure looks like: n^+-p-p^+-n^+-p-p^+-n^+-p-p^+ where base PC 1 it is created on usual technology and provides mechanical hardness of all system.

It is supposed, that p^+-layer provides ohmic transitive contact between p^+ and n^+-layers, eliminates (reduces) surface recombination on the corresponding side of base area of everyone PC and gives the contribution to collection coefficient of the photogenerated charge carriers. The structure bilateral cascade PC is shown on fig. 5.

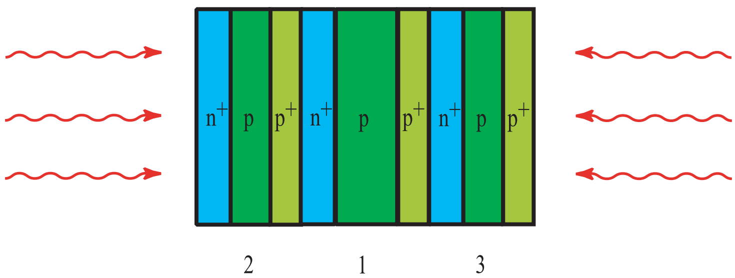

Fig. 5. Structure of the bilateral cascade photoconverter.
Figures designate PC numbers .

At illumination by light from two sides each of 3 consistently connected PC is illuminated with light which has been consistently pass through corresponding previous converters. At such illumination generation function in everyone PC represents the sum of generation functions from a light stream falling from the right and from the left. Thus resulting generation function becomes more homogeneous and the areas far from p-n junction are lit.

The condition of equality of photocurrents of all PC in the cascade for an any spectrum of falling radiation generally leads to system of two nonlinear equations for everyone i-th PC with structure n^+-p-p^+:

$$\int_0^\infty d\lambda \cdot \Phi(\lambda) \cdot \left(F_{il}(\lambda) + F_{ir}(\lambda)\right) = \int_0^\infty d\lambda \cdot \Phi(\lambda) \cdot \left(F_{1l}(\lambda) + F_{1r}(\lambda)\right); \quad i = 2,\ 3 \quad , \qquad \text{(eq. 23)}$$

where $F_{il}(\lambda)$ - spectral coefficient of collection in i-th PC in relation to a stream of the radiation falling on system from the left, $F_{ir}(\lambda)$ - spectral coefficient of collection in relation to a stream of the radiation falling on system from the right. In view of absorption of light in the previous layers their values will be less than own spectral coefficients of charge carriers collection Q_{il} or Q_{ir} and will be equal to:

$$F_{1l}(\lambda) = e^{-\alpha d_2} Q_{1l}; \quad F_{1r}(\lambda) = e^{-\alpha d_3} Q_{1r} \, . \qquad \text{(eq. 24)}$$

$$F_{2l}(\lambda) = Q_{2l}; \quad F_{2r}(\lambda) = e^{-\alpha(d_1 + d_3)} Q_{2r} \, . \qquad \text{(eq. 25)}$$

$$F_{3l}(\lambda) = e^{-\alpha(d_1 + d_2)} Q_{3l}; \quad F_{3r}(\lambda) = Q_{3r} \, . \qquad \text{(eq. 26)}$$

The spectral coefficient of carriers collection Q_i can be presented in the form of the sum of coefficients of collection from doped n^+-layer, a base p-layer and doped p^+-layer:

$$Q_i = Q_{in+} + Q_{ip} + Q_{ip+} \, . \qquad \text{(eq. 27)}$$

They can be expressed through single function entered above Q(α, d, L, S, D) (eq. 17). Omitting an index i, for illumination from the left side it is possible to write down:

$$Q_{n+l} = -e^{-\alpha d_{n+}} Q(-\alpha, d_{n+}, L_{n+}, S_{n+}, D_{n+}) \, , \qquad \text{(eq. 28)}$$

$$Q_{pl} = e^{-\alpha d_{n+}} Q(\alpha, d_p, L_p, S_p, D_p) \, , \qquad \text{(eq. 29)}$$

$$Q_{p+l} = \frac{2e^{-\alpha(d_{n+} + d_p)}}{\left(1 + \frac{S_p L_p}{D_p}\right) \cdot e^{\frac{d_p}{L_p}} + \left(1 - \frac{S_p L_p}{D_p}\right) \cdot e^{-\frac{d_p}{L_p}}} Q(\alpha, d_{p+}, L_{p+}, S_{p+}, D_{p+}) . \qquad \text{(eq. 30)}$$

At illumination from the right side it is accordingly had:

$$Q_{n+r} = e^{-\alpha(d_p + d_{p+})} Q(\alpha, d_{n+}, L_{n+}, S_{n+}, D_{n+}) \, , \qquad \text{(eq. 31)}$$

$$Q_{pr} = -e^{-\alpha d_{p+}} Q(-\alpha, d_p, L_p, S_p, D_p) \, , \qquad \text{(eq. 32)}$$

$$Q_{p+r} = -\frac{2e^{-\alpha d_{p+}}}{\left(1+\frac{S_p L_p}{D_p}\right)\cdot e^{\frac{d_p}{L_p}} + \left(1-\frac{S_p L_p}{D_p}\right)\cdot e^{-\frac{d_p}{L_p}}} Q(-\alpha, d_{p+}, L_{p+}, S_{p+}, D_{p+})$$

. (eq. 33)

Results of numerical calculation of thickness of deposited PC base layers give value $d_{p2} \approx d_{p3} \approx 6.36$ microns. The photocurrent of structure thus is equal $J_{\Phi} = 22.6$ mA/cm^2. Values of an open circuit voltage on separate PC in structure are equal: $U_{oc1} = 578$ mV, $U_{oc2} = 658$ mV, $U_{oc3} = 658$ mV and total value of an open circuit voltage on structure $U_{oc} = 1895$ mV. The efficiency of structure is equal 13.19 %. For comparison, at the same bilateral illumination of the base element has following values: $J_{\Phi} = 60.78$ mA/cm^2, $U_{oc1} = 603$ mV, efficiency of an element is 11.21 %.

Thus, the open circuit voltage of real bilateral cascade structure from 3 PC for a sunlight more than in 3 times exceeds an open circuit voltage of the usual bilateral PC at simultaneous sharp increase in efficiency.

6. The conclusion.

The results presented in the paper speak about greater potential opportunities of the offered new type high-voltage planar PC on the basis of cascade structures of the homogeneous semiconductor.

Top limit characteristics for ideal cascade structures show prospects of creation of designs of photo-electric systems - receivers and converters of radiation with the voltage reaching values, in 7 - 10 times exceeding a voltage of usual planar PC, at sharp increasing of their power efficiency.

Use of similar cascade structures for real photo-voltaic converters of a solar energy will allow to solve effectively a problem of creation of high-voltage and powerful solar power systems at simultaneous preservation or substantial growth their efficiency, increase of PC identity and decrease of power commutation losses.

7. References

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