

New approach to the efficiency increase problem for multi-junction silicon photovoltaic converters with vertical diode cells

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It is shown, that for efficiency increase of multi-junction photovoltaic solar energy converters with vertical diode cells (VDC) on the basis of single-crystal silicon the modernization of VDC by the introduction along their vertical Si-boundaries single-layer indium-tin oxide reflectors by thickness more than 1 μm is necessary.

Показано, что для повышения КПД многопереходных фотоэлектрических преобразователей солнечной энергии с вертикальными диодными ячейками (ВДЯ) на основе монокристаллического кремния необходима модернизация ВДЯ путем введения вдоль их вертикальных Si-границ однослойных рефлекторов из индий-оловянного оксида толщиной более 1 мкм.

A well-known concept in development of environment-friendly energy supplying technologies is to use solar batteries (SB) consisting of photovoltaic converters (PVC) in the conditions of concentrated solar radiation [1–5]. Such PVC include, in particular, multi-junction photovoltaic converters (MJ Si-PVC) consisting of a monolithic set (more than 10) of single-crystal silicon plane-parallel vertical diode cells (VDC) with *p-n* junctions oriented perpendicular to the light receiving surface and connected in series by the metal interlayers between the appropriate planes of adjacent VDC [4, 5]. A MJ Si-PVC with VDC is shown schematically in Fig. 1.

The essential advantages of considered type MJ Si-PVC in the concentrated solar radiation conditions in comparison with single-junction (SJ) single-crystal Si-PVC based on the diode structure parallel to the light receiving surface, include a potential capability of much more effective conversion of this radiation into electric energy and generation a 10–40 times higher output voltage. At manufacturing of MJ Si-PVC corresponding to that shown in Fig. 1, the rather expensive photolithography process is unnecessary, since, unlike the SJ Si-PVC, the crested or screen current collecting electrode with narrow and thin (~10 μm) streaky elements divided by the gaps less than 1 mm is absent on their light receiving surface [3].

At the same time, a serious lack is inherent in MJ Si-PVC with VDC as well as in SJ Si-PVC. It consist in decreasing light-receiving surface irradiance E when the angle α of solar radiation incidence increases, that decrease being in accordance with the well known [6] ratio $E = E_0\cos\alpha$, where E_0 is the PVC light receiving surface irradiance at the normal light incidence ($\alpha_0 = 0$; situation (a) in Fig. 1). That is why at PVC operating in the concentrated solar radiation conditions, the ensuring of the concentrating system (CS) automatic Sun position tracking is especially necessary for the maximum re-

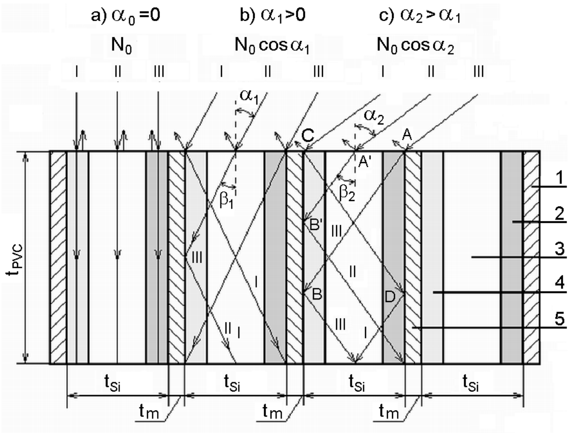

Fig. 1. Cross-section of MJ Si-PVC of $t_{PVC} \approx 850$ μm thickness with vertical diode cells of n^+-p-p^+ type (schematic image): *1*, solid metal electrode; *2*, p^+-conductivity silicon layer of less than 1 μm thickness; *3*, p-type conductivity silicon layer of $t_{Si} \approx 160$ μm thickness; *4*, n^+-conductivity silicon layer of less than 1 μm thickness; *5*, metal layer of $t_m \approx 10$ μm thickness (other designations as in text).

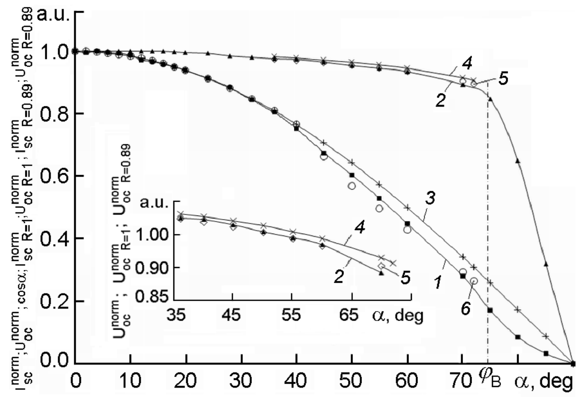

Fig. 2. Experimental (*1*, *2*) and theoretical (*3–6*) dependences for normalized values of short circuit current (*1*, *3*, *6*) and open circuit voltage (*2*, *4*, *5*) vs light incidence angle α on MJ Si-PVC with n^+-p-p^+ type VDC light receiving surface at the light reflection coefficients at metal/silicon boundaries $R = 1$ (*3*, *4*) and $R = 0.89$ (*1*, *2*, *5*, *6*). (Curve 3 corresponds to both cosα function as well as $I_{SC}^{norm}(\alpha)$ dependence at $R = 1$ because $I_{SC}^{norm}(\alpha)_{R=1} = \cos\alpha$.

duction of radiation energy losses. Here we do not consider the luminescent concentrators which are still far from practical application and are at the development stage [7]. However, even in case of ideal CS orientation, the solar radiation concentrated by lenses, as well as linear, polyhedral or round reflectors, is always incident onto PVC light receiving surface at the angle $\alpha > 0$ at low ($C \le 10$) and moderate ($10 < C < 1000$) concentration levels C [8].

For MJ Si-PVC with VDC, (situation (b) and (c) in Fig. 1), that fact must influence much more negatively the efficiency and output power in comparison with SJ Si-PVC. The difference, in our opinion, can be caused by an essential reduction of solar energy losses at the interaction with SJ Si-PVC back surface due to highly effective double-layer oxide/metal type back surface reflector [9, 10] developed to date for SJ Si-PVC, while at known MJ Si-PVC with VDC (Fig. 1), similar type reflectors along internal surfaces of VDC silicon basis are absent. Therefore, in MJ Si-PVC being considered with real geometrical dimensions $t_{PVC} \approx 850$ μm and $t_{Si} \approx 160$ μm, the long-wave solar radiation component of ((0.95 to 1.00) $< \lambda < 1.11$ μm) which is photoelectrically active for crystalline silicon and characterized by the full absorption length $X_{100} \ge$ (624 to 2060) μm [10] and maximal photon flux density [8], when passing through VDC can lose energy because of insufficient light reflection coefficient R from the mentioned metal surfaces (situation (b) and (c) in Fig. 1). At the same time, the influence of that process on MJ Si-PVC output parameters has been not investigated until now. In this connection, this work is aimed at the study of that problem to elucidate the expediency and substantiate the way to increase the reflectivity of internal vertical VDC boundaries in MJ Si-PVC.

We have confirmed the considerable influence of such solar radiation energy losses mechanism on the efficiency of considered MJ Si-PVC by experimental dependences of a short circuit current I_{SC} and open circuit voltage U_{OC} on the angle α for MJ Si-PVC. The experimental values of I_{SC} and U_{OC} were determined at an error not exceeding 2 % by measuring and analytical processing of loading illuminated current-voltage characteristics method similar to that used before [11] in the research of SJ Si-PVC output and diode parameters. The efficiency η is related to the mentioned output parameters as [12]

$$\eta \sim I_{SC} U_{OC}. \quad (1)$$

Fig. 2 (curves *1* and *2*) presents these dependences for one of investigated MJ Si-

PVC after normalization of each mentioned output parameters to its maximum value at $\alpha_0 = 0$. When comparing the curve *1* corresponding to dependence $I_{SC}^{norm}(\alpha)$, with the curve *3* for $\cos\alpha$, at $\alpha < 40°$, these dependences practically coincide, thus evidencing the direct proportionality between I_{SC} and $\cos\alpha$ similar to the dependence for MJ Si-PVC photoreceiving surface irradiance E. Therefore, for considered MJ Si-PVC at $\alpha < 40°$

$$I_{SC} \sim E_0\cos\alpha, \quad (2)$$

that is equivalent to relationship [13]

$$I_{SC} \sim (1 - R_{Si})N_0\cos\alpha \sim (1 - R_{Si})N, \quad (3)$$

where N_0 is the number of photons out of wavelength range photoelectrically active for crystalline silicon entering per unit time the unit PVC light receiving surface area at $\alpha_0 = 0$ (situation (a) in Fig. 1); N, the same but at $\alpha > 0$ (situations (b) and (c) in Fig. 1); R_{Si}, the light reflection coefficient from frontal surface (silicon) of MJ Si-PVC for the appropriate wavelength interval.

However, at $\alpha > \alpha_1^* \approx 40°$, the $I_{SC}^{norm}(\alpha)$ magnitude decreases appreciably in comparison with $\cos\alpha$, and at $\alpha > \alpha_2^* \approx 72°$, the specified difference becomes especially considerable. The character of $dU_{OC}^{norm}(\alpha)/d\alpha$ variation in $0° \le \alpha < \alpha_1^*$ and $\alpha_1^* < \alpha < \alpha_2^*$ ranges correlates well with that observed for $dI_{SC}^{norm}(\alpha)/d\alpha$, but at the $\alpha > \alpha_2^*$, the $dU_{OC}^{norm}(\alpha)/d\alpha$ becomes significantly larger than $|dI_{SC}^{norm}(\alpha)/d\alpha|$ in absolute value.

To establish the relationship between the peculiarities of radiation interaction with metal/silicon vertical interfaces in VDC and values of critical angles α_1^* and α_2^*, two characteristic relations between the light incidence angle on MJ Si-PVC light receiving surface and light refraction angle in silicon were calculated for situations (b) and (c) in Fig. 1. As is seen from Fig. 1, the situation (b) corresponds to the limiting case of single interaction of light beam penetrating the VDC with metal/silicon interface ($\alpha = \alpha_1$, $\beta = \beta_1$). At further α increase from α_1 up to α_2, and thus β increase from β_1 up to β_2, the light beam one-fold reflected and weakened due to partial absorption in metal ($R \le 0.9$ [10] in Al/Si and $0.95 < \lambda < 1.11$ μm case) begins to cooperate for the still greater part with opposite metal/silicon interface. The beam fraction interacting with the second interface and reflected from it (with the additional losses) increases.

According to Fig. 1 (situation (b))

$$\sin\beta_1 = \frac{t_{Si}}{(t_{PVC}^2 + t_{Si}^2)^{1/2}}. \quad (4)$$

To find $\sin\alpha_1$, we use the relation $\sin\alpha_1 = n_{Si}(\lambda)\sin\beta_1$, where $n_{Si}(\lambda)$ is the refractive index for silicon depending on the radiation wavelength.

The calculation using $n_{Si} = 3.6$ for $0.95 < \lambda < 1.11$ μm [14] has shown that in case $t_{PVC} \approx 850$ μm and $t_{Si} \approx 160$ μm the corresponding angles amount $\beta_1 \approx 10.7°$, $\alpha_1 \approx 41.8°$. As is seen from Fig. 1, in situation (c) the ABC triangle is similar to a A′B′C one and $t_{PVC} = |BC|+|B'C|$, thus, $|BC| = 2|B'C| = (2/3)t_{PVC}$. Then

$$\sin\beta_2 = \frac{t_{Si}}{\left((4/9)t_{PVC}^2 + t_{Si}^2\right)^{1/2}}. \quad (5)$$

Similarly, for $\sin\alpha_2$ and $\sin\beta_2$, using (5) we get $\beta_2 \approx 15.8°$; $\alpha_2 \approx 78°$.

Comparing the calculated angles $\alpha_1 \approx 41.8°$ and $\alpha_2 \approx 78°$ with experimental values $\alpha_1^* \approx 40°$ and $\alpha_2^* \approx 72°$, it is possible to conclude what follows. When passing from one-fold to two-fold light reflection at the metal/silicon interfaces in a MJ Si-PVC ($\alpha = \alpha_1^*$, situation (b) in Fig. 1), the appreciable deviation of $I_{SC}^{norm}(\alpha)$ dependence (curve *1* in Fig. 2) from that for $\cos\alpha$ (curve *3* in Fig. 2) is really connected with essentially increasing losses of long-wave photoactive solar radiation component energy due to its absorption in metal. It is to note that this is resulted in a decreased photovoltaic converter efficiency not only directly according to (1), but also due to the device heating at the expense of radiation energy absorbed in metal [12].

Reduction of α_2^* in comparison with α_2 can be explained by the fact that in case of light incidence from air environment on MJ Si-PVC silicon surface at $\alpha > \varphi_B = \mathrm{arctg}\, n_{Si}$ (where φ_B is the Brewster angle [6], which makes 74.5° for $n_{Si} = 3.6$), the R_{Si} (see Eq.(3)) begins to increase sharply from $R_{Si} \approx 32$ % [16] which remained essentially unchanged at $\lambda > 0.7$ μm [6, 15] up to $R_{Si} = 100$ % at $\alpha = 90°$. As is seen from Fig. 2 where the vertical dotted line corresponds to the Brewster angle for silicon, it is just the above-mentioned effect of rapid R_{Si} increase that causes increasing rate of $I_{SC}^{norm}(\alpha)$ and $U_{OC}^{norm}(\alpha)$ drop at $\alpha > \alpha_2^*$.

In the $\alpha_1^* \le \alpha \le \varphi_B$ range, the behavior of $U_{OC}^{norm}(\alpha)$ function (curve *2* in Fig. 2)) is explained as follows. According to [5, 12]

$$U_{OC} \approx M\frac{AkT}{e}\ln\frac{J_{SC}}{J_0}, \tag{6}$$

where M is the number of in-series connected VDC included in MJ Si-PVC structure; A, the diode ideality factor; k, the Boltzmann constant; T, temperature; e, electron charge; J_0, the diode saturation current density. In the right part of Eq.(6), only J_{SC} depends on α. Therefore, taking into account (2) and (3), in absence of radiation energy losses due to absorption in metal inside the MJ Si-PVC ($R = 1$), Eq.(6) can be transformed to the form

$$U_{OC}(\alpha)_{R=1} \approx M\frac{A\,kT}{e}\ln\frac{J_{SC}^{\max}\cos\alpha}{J_0}, \tag{7}$$

where $J_{SC}^{\max}$ is the short circuit current density at $\alpha_0 = 0$.

Taking into account the normalization of output parameters introduced before,

$$U_{OC}^{norm}(\alpha)_{R=1} \approx \frac{U_{OC}(\alpha)_{R=1}}{U_{OC}^{\max}} = \frac{\ln J_{SC}^{\max} + \ln\cos\alpha - \ln J_0}{\ln J_{SC}^{\max} - \ln J_0}, \tag{8}$$

where $U_{OC}^{\max}$ is the open circuit voltage at $\alpha_0 = 0$. If the current densities in (8) are presented as $J_{SC}^{\max} = 10^{-\xi_1}$ A/cm^2 and $J_0 = 10^{-\xi_2}$ A/cm^2, where ξ_1 and ξ_2 are any positive numbers, and $\xi_1 < \xi_2$ (that corresponds to the real ratio of $J_{SC}^{\max}$ and J_0 values [11, 12]) we get

$$U_{OC}^{norm}(\alpha)_{R=1} \approx 1 + \frac{\ln\cos\alpha}{2.3(\xi_2 - \xi_1)}. \tag{9}$$

The curve *4* in Fig. 2 corresponds to Eq.(9) at $\xi_2 - \xi_1 = 5.50$, i.e. at $J_{SC}^{\max} = 1.67\cdot10^{-2}$ A/cm^2 ($\xi_1 = 1.78$) and $J_0 = 5.25\cdot10^{-8}$ A/cm^2 ($\xi_2 = 7.28$), as was established by us in analytical processing of experimental loading illuminated current-voltage characteristics of investigated MJ Si-PVC. As is seen from comparison of that curve with the curve *2* in the same Figure for experimental $U_{OC}^{norm}(\alpha)$ dependence, starting from $\alpha > \alpha_1^*$ the latter decreases with α increase faster than according to (9). It is obviously that these distinctions confirm the negative influence of metal/silicon boundaries inside the MJ Si-PVC on the efficiency of such type devices due to their insufficient reflectivity ($R < 1$). This influence can be taken into consideration in $U_{OC}^{norm}(\alpha)$ dependence at $R < 1$ in the following way:

$$U_{OC}^{norm}(\alpha)_{R<1} \approx 1 + \frac{\ln[f(R,\alpha)\cos\alpha]}{2.3(\xi_2 - \xi_1)}, \tag{10}$$

where $0 < f(R,\alpha) < 1$ is the correction function taking into consideration the real values of $R < 1$, which, as is established in this work, is described as

$$f(R,\alpha) \approx R\frac{t_{\mathrm{Si}}}{t_{PVC}}\left(\frac{n_{\mathrm{Si}}^2 - 1 + \cos^2\alpha}{1 - \cos^2\alpha}\right)^{1/2} + R^2\left(1 - \frac{t_{\mathrm{Si}}}{t_{PVC}}\left(\frac{n_{\mathrm{Si}}^2 - 1 + \cos^2\alpha}{1 - \cos^2\alpha}\right)^{1/2}\right). \tag{11}$$

The first item in (11) takes into consideration the losses energy of radiation entering the MJ Si-PVC only as a result of one-fold initial interaction of that radiation with metal inside the device. The second item takes into consideration additional energy losses inside the device caused by the repeated interaction of the radiation residual fraction after the first interaction with metal. It is natural that at $\alpha < \alpha_1$ this component should be equal to zero and, in this connection, the value corresponding to it, for physical reasons, should be taken into consideration only at $\alpha_1^* \le \alpha \le \varphi_B$.

It follows from the above that at $\alpha \ge \alpha_1^*$, the correction function $f(R,\alpha)$ is less than 1 and decreases not only as α increases, but also as R decreases. Thus, lower experimental values of $I_{SC}^{norm}(\alpha)$ (curve *1* in Fig. 2) and $U_{OC}^{norm}(\alpha)$ (curve *2* in Fig. 2) in comparison with $I_{SC}^{norm}(\alpha)_{R=1}$ (curve *3* in Fig. 2) and $U_{OC}^{norm}(\alpha)_{R=1}$ (curve *4* in Fig. 2) at $\alpha > \alpha_1^*$ can be explained in fact by the negative influence of metal/silicon boundaries inside MJ Si-PVC due to their insufficient reflectivity. It is possible to show that at $\xi_2 - \xi_1 = 5.50$, the function $U_{OC}^{norm}(\alpha)_{R<1}$ (the curve 5 in the inset of Fig. 2), is coincides well with the experimental $U_{OC}^{norm}(\alpha)$ dependence (curve *2* in Fig. 2) at $R = 0.89$.

The accounting for $R < 1$ influence on experimental $I_{SC}^{norm}(\alpha)$ values is connected with $f(R,\alpha)$ function by the relationship

$$I_{SC}^{norm}(\alpha)_{R<1} = \frac{I_{SC}(\alpha)_{R<1}}{I_{SC}^{\max}} \approx f(R,\alpha)\cos\alpha, \quad (12)$$

where $I_{SC}^{\max}$ is the short circuit current at $\alpha_0 = 0$. As follows from Fig. 2, the points of the curve *6* corresponding to (12) at $R = 0.89$ coincide well with experimental $I_{SC}^{norm}(\alpha)$ dependence presented by the curve *1*. Note that at the single light reflection coefficient $R = 0.89$, the effective reflection coefficient in case of double light reflection $R_{EFF} \approx R^2 \approx 0.79$ and it corresponds to solar radiation energy losses due to absorption exceeding 20 %. It follows that elimination of such losses should allow to increase the efficiency of considered MJ Si-PVC type approximately by a factor of 1.2.

The above results indicate a possibility of efficiency increase for MJ Si-PVC with VDC by approximating to 1 the $0.95 < \lambda < 1.11$ μm solar radiation reflection coefficient at vertical boundaries of these cells inside MJ Si-PVC. It is possible by using the single-layer reflectors of transparent tin-doped In_2O_3 oxide of n^+-type conductivity (ITO) [17]. In the $0.4 \le \lambda \le 1.1$ μm wavelength range, the extinction factor of this material $\chi << 0.1$ [18, 19] at its spesific resistance $\rho \sim 10^{-4} \div 10^{-3}$ Ω·cm. That is, the light energy losses due to heat release inside the ITO are rather small at relatively low specific resistance of the considered material. Therefore, it is possible to speak about practically full internal light reflection inside MJ Si-PVC from ITO/Si interface at light incidence angles $\gamma = 90° - \beta$ on the corresponding boundary (Fig. 3), exceeding $\gamma_{min} = \arcsin(n_{ITO}/n_{Si}) \approx 32°$, where $n_{ITO} \approx 1.9$ is the ITO refractive index at the indicated values of ρ and $0.9 \le \lambda \le 1.1$ μm [18].

The real γ values satisfy to reation

$$(90^0 - \beta^{\max}) \le (\gamma = 90^0 - \beta) \le 90^0, \quad (13)$$

where $\beta^{max} = \arcsin(1/n_{Si})$. At $n_{Si} = 3.6$, $\beta_{max} \approx 16.1°$, we get $73.9° \le \gamma \le 90°$.

According to [15], effect of full internal reflection is caused by wave processes in ITO layer with a thickness not exceeding one light wavelength. Therefore, on the one hand, to suppress the radiation energy losses which may be associated with penetration of a part of the radiation energy into metal contacting with ITO, and on the other hand, to minimize the ITO layer resistance to the current passing therethrough, the thickness t_{ITO} of this layer should be experimentally optimized in the range of values 1 μm $< t_{ITO} <$ 2 μm.

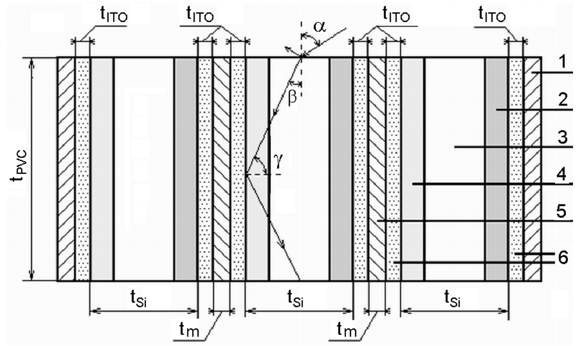

Fig. 3. Cross-section of MJ Si-PVC of $t_{PVC} \approx 850$ μm thickness with ITO reflectors belonging to VDC structure of n^+-p-p^+ type (schematic image): *1*, solid metal electrode; *2*, p^+-conductivity silicon layer of less than 1 μm thickness; *3*, p-type conductivity silicon layer of $t_{Si} \approx 160$ μm thickness; *4*, n^+-conductivity silicon layer of less than 1 μm thickness; *5*, metal layer of $t_m \approx 10$ μm thickness; *6*, ITO reflectors of $1 < t_{ITO} < 2$ μm thickness (other designations as in text).

The contribution of ITO layer series resistance $R^*_{S_{ITO}}$ in vertical diode cell series resistance $R^*_{S_{VDC}}$ per unit of its area (being perpendicular to the direction of current through the MJ Si-PVC) can be calculated using the ratio $R^*_{S_{ITO}} = R^*_{ITO} t^2_{ITO}$, where R^*_{ITO} is longitudinal resistance of a homogeneously thick ITO layer having the square form. At $R^*_{ITO} \le 100$ Ω/□, what is typical for $\rho \sim 10^{-4}$ to 10^{-3} Ω·cm [17], and $t_{ITO} < 2$ μm, we get $R^*_{S_{ITO}} \le 4\cdot10^{-6}$ Ω·cm^2, that is, approximately five orders of magnitude less than $R^*_{S_{VDC}}$ of investigated MJ Si-PVC without ITO interlayers. The latter shows that the use of single-layer ITO reflectors with 1 μm $< t_{ITO} <$ 2 μm in the MJ Si-PVC structure should not contribute negatively to the device efficiency.

Besides, it is known [17–20] that the modern deposition methods of ITO films with submicrometer and micrometer thickness, including pulverization followed by pyrolysis, allow to realize the appropriate process at temperatures below 450°C. This agrees well with the concept of single-crystal silicon PVC production technology according to which the highest temperature operation should be the manufacturing of submicron highly-doped n^+-Si and p^+-Si layers realized, as a rule, at 900 to 1000°C [21, 22]. Thus, the efficiency increase (approximately by a factor of 1.2) of multijunction silicon photovoltaic converters with vertical diode cells perspective for use in concentrated solar radiation conditions can be achieved using single-layer ITO reflectors of 1 $\mu m < t_{ITO} < 2$ μm thickness along the vertical boundaries of these cells.

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Новий підхід до проблеми підвищення ККД багатоперехідних кремнієвих фотоелектричних перетворювачів з вертикальними діодними комірками

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Показано, що для підвищення ККД багатоперехідних фотоелектричних перетворювачів сонячної енергії з вертикальними діодними комірками (ВДК) на основі монокристалічного кремнію необхідна модернізація ВДК шляхом введення уздовж їх вертикальних Si-границь одношарових рефлекторів з індій-олов'яного оксиду товщиною більше 1 мкм.