Double-layer ITO/Al back surface reflector for single-junction silicon photoconverters

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It has been shown that to increase the efficiency and manufacturability of single-crystal silicon photovoltaic solar energy converters (Si-PVC) with 180–200 μm thick base crystals having a polished photoreceiving surface and double-layer back surface reflector (BSR) consisting of a transparent oxide and aluminum layers, a conductive transparent indium-tin oxide (ITO) layer of 0.25 μm interference thickness is to be used as the nonmetallic BSR layer. It provides the ITO/Al BSR reflection coefficient in the range of $85 < R < 96$ % for solar radiation photoactive component incident the Si-PVC back surface at substantially zero contribution of ITO layer resistance to the device series resistance. In the case of Si-PVC with inverted pyramid type texture of crystal photoreceiving surface at which the specificity of light distribution in the crystal causes total reflection of radiation from Si/ITO interface, the ITO layer thickness should be experimentally optimized in the 1–2 μm range independently of base crystal thickness to minimize the photoactive radiation losses and ITO layer resistance.

Показано, что для повышения эффективности работы и технологичности изготовления монокристаллических кремниевых фотоэлектрических преобразователей (Si-ФЭП) солнечной энергии с толщиной базовых кристаллов 180÷200 мкм, имеющих полированную фотоприемную поверхность и двухслойный тыльно-поверхностный рефлектор (ТПР), состоящий из слоев прозрачного оксида и алюминия, необходимо в качестве неметаллического слоя ТПР использовать проводящий прозрачный слой из индий-оловяного оксида (ITO) с интерференционной толщиной 0.25 мкм. Это обеспечивает коэффициент отражения ITO/Al ТПР в пределах $85 < R < 96$ % для поступающей на тыльную поверхность Si-ФЭП фотоактивной компоненты солнечного излучения при практически нулевом вкладе сопротивления слоя ITO в последовательное сопротивление прибора. В случае Si-ФЭП с текстурой фотоприемной поверхности кристалла типа инвертированных пирамид, при которой специфика распространения света в кристалле обусловливает реализацию эффекта полного внутреннего отражения излучения от границы раздела Si/ITO, для минимизации потерь энергии фотоактивного излучения и сопротивления слоя ITO его толщину следует экспериментально оптимизировать в пределах значений 1÷2 мкм независимо от толщины базового кристалла.

The back surface reflectors (BSR) consisting of SiO_2 and Al films deposited layer-by-layer onto one planar surface of silicon base crystal (Si-BC) are the major part of the solar spectrum photoactive component trapping and confinement system in the single-junction silicon photovoltaic converters (Si-PVC). Such Si-PVC fragments are presented schematically in Fig. 1 (a, b): (a) PERL-structure (Passivated Emitter, Rear Locally-diffused [1] — passivated emitter, local diffusion of acceptor impurity on the side of crystal back surface) and (b) PERT-structure (Passivated Emitter, Rear Totally-diffused [2] — passivated emitter, total diffusion of acceptor impurity on the side of crystal back surface). The PERL structure devices show initial efficiency up to 24.7 %

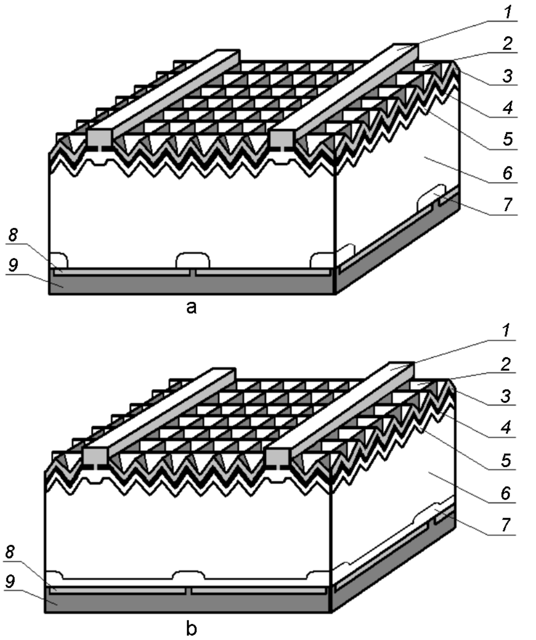

Fig. 1. Schematic image of Si-PVC with PERL- (a) [1] and PERT- (b) [2] structure fragments: *1* − front current-collecting electrode; *2* − inverted pyramids type texture; *3* − antireflection coating; *4* − SiO_2 passivation layer; *5* − n^+-Si diffusion layer; *6* − p-Si (a) or n-Si (b) base crystal; *7* − p^+-Si (a) or p/p^+-Si (b) diffusion area; *8* − SiO_2 layer of back surface reflector; *9* − Al layer of back surface reflector, also functions as back current-collecting electrode.

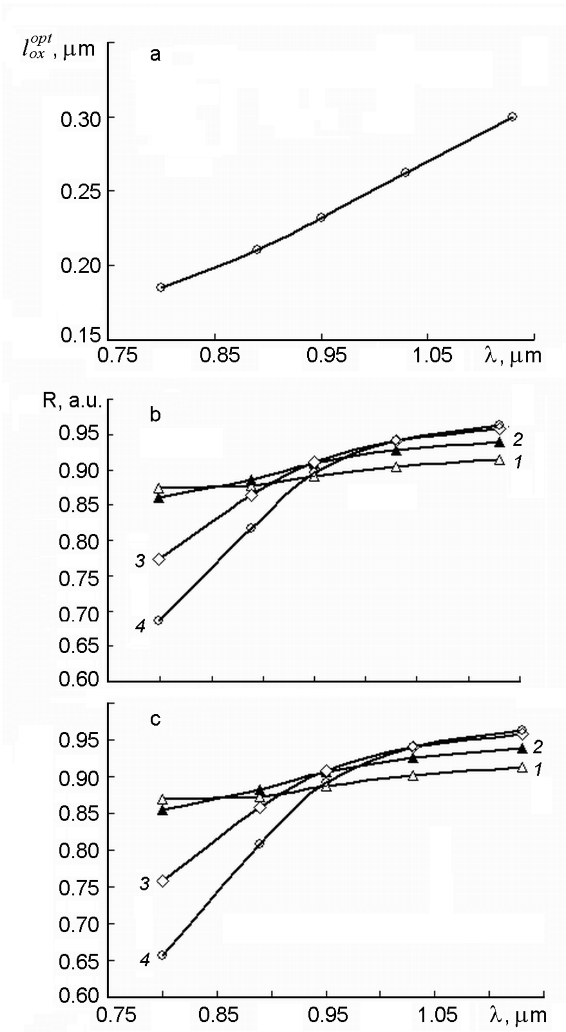

Fig. 2. Dependences calculated for ITO/Al back surface reflector: l_{OX}^{opt} on λ (a); *R* on λ for l_{OX}^{opt}: *1* − 0.18 μm (λ_1 = 0.8 μm), *2* − 0.21 mm (λ_2 = 0.9 μm), *3* − 0.25 μm (λ_3 = 1.0 μm), *4* − 0.28 μm (λ_4 = 1.1 μm) at n_0 = 1.0 (b) and at n_0 = 1.5 (c).

[1], however, the photon degradation is inherent therein. The PERT structure devices have initial efficiency up to 22.7 %, but are not degraded under illumination [2, 3]. It was shown [4] that in large-scale production of single-junction single-crystal Si-PVC, the double-layer TiO_2/Al BSR is good alternative to double-layer SiO_2/Al BSR.

At the same time, as it is seen in Fig. 1, in case of BSR with dielectric oxide layer, the electrical contact of Al layer (that simultaneously functions as the back solid electrode) with Si-BC is realized via numerous through holes in the BSR dielectric layer, the total area thereof making less than 1 % of the total Si-BC back surface area [5]. In contrast to the continuous Si/Al contact in the absence of intermediate dielectric oxide, such multipoint contact character results in somewhat increased Si-PVC series resistance that compensates in part the efficiency gain attained due to reduction of solar radiation power losses resulting from using the double-layer BSR with dielectric oxide. Therefore, when manufacturing Si-PVC with PERT-structure, it seems to be reasonable to replace the BSR perforated dielectric oxide layer by a continuous layer of transparent conductive material which, similar to SiO_2, hinders the diffusion interaction of Si with Al. In this connection, the goal of this work was to determine the optimum design for double-layer BSR consisting of such transparent conductive material and aluminum, providing a high integral reflection coefficient of solar radiation photoelectrically active component and to decrease the series resistance of the device mentioned. The problem can be solved by using the transparent indium-tin oxide (ITO) [6–9] in double-layer BSR structure instead of SiO_2 or

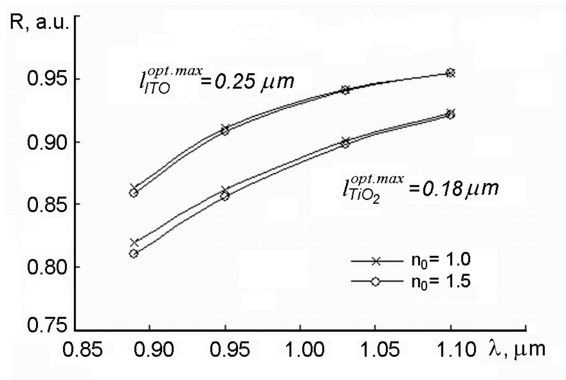

Fig. 3. Dependences of R on λ and on n_0 for ITO/Al and TiO_2/Al [4] back surface reflectors with $l_{OX} = l_{OX}^{opt.\max}$.

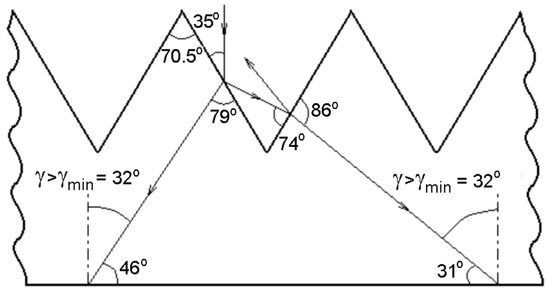

Fig. 4. Schematic image of light rays trajectory inside the Si-BC of the single-junction photovoltaic converter with textured frontal surface and smooth back surface [18].

TiO_2. The modern methods of ITO film deposition make it possible to carry out that process at temperatures below 450°C [6–8, 10] that are in agreement with the single-crystal Si-PVC manufacturing technology [11–13].

In this case, it is necessary to determine the ITO layer thickness $l_{OX}^{opt.max}$ at which the ITO/Al BSR will provide the maximum integral reflectance within the required wavelength λ range. As shown in [4], this range depends on the material PVC base crystal and thickness t and in case of Si-PVC at t = 180–200 μm (typical values of modern serial Si-PVC), is 0.88≤λ≤1.11 μm. The $l_{OX}^{opt.max}$ determination method for ITO layer was similar to that used in [4] to find $l_{OX}^{opt.max}$ for double-layer SiO_2/Al BSR and TiO_2/Al BSR oxide layers.

Accordingly to [14], the optimum thickness l_{OX}^{opt} of oxide providing the maximum reflection coefficient R for specific λ values from the 0.88 to 1.11 μm range were determined first of all. The $l_{OX}^{opt}(\lambda)$ dependence obtained for 0.80≤λ≤1.13 μm range at $m = 1$ and $n_{OX}(\lambda)$ values for ITO taken from [7] as well as $n_M(\lambda)$ and $k_M(\lambda)$ for Al taken from [15, 16] is shown in Fig. 2a. Further, from the received $l_{OX}^{opt}(\lambda)$ dependence, the l_{OX}^{opt} values were selected corresponding to λ_1 = 0.8 μm, λ_2 = 0.9 μm, λ_3 = 1.0 μm and λ_4 = 1.1 μm, being l_{OX1}^{opt} ≈0.18 μm, l_{OX2}^{opt} ≈0.21 μm, l_{OX3}^{opt} ≈0.25 μm and l_{OX4}^{opt} ≈0.28 μm, respectively. For these l_{OX}^{opt} values, the spectral dependences of $R(\lambda)$ in the 0.80≤λ≤1.13 μm range according to [14].

When calculating $R(\lambda)$, the spectral dependence of $n_{Si}(\lambda)$ was taken from [17]. In case of Si-PVC frontal surface contact with air, n_0 = 1.0, and in case of this surface contact with protective glass, it is supposed that n_0 = 1.5, by analogy to [14]. The $R[(\lambda), l_{OX}^{opt}(\lambda)]$ dependences at n_0 = 1.0 and n_0 = 1.5 for ITO/Al BSR are presented in Fig. 2b, 2c. The analysis of all the $R[\lambda, l_{OX}^{opt}(\lambda), n_0]$ dependences set shows what follows. The optimal oxide thickness $l_{OX}^{opt.max}$ providing the maximum integral reflectivity of ITO/Al BSR in the specified wavelength range is 0.25 μm at both n_0 values. The $R(\lambda)$ gain of such reflector in comparison with the TiO_2/Al BSR [4] is seen most distinctly in Fig. 3 and in the Table. Within the 0.88≤λ≤1.11 μm range, the ITO/Al BSR provides the reflection coefficient exceeding that for TiO_2/Al BSR by 3–5 %.

In case of a textured frontal surface with the inverted pyramids faceted by (111) type surfaces (e.g., Fig. 1), the optimal oxide thickness for ITO/Al BSR is not so critical. This is due to the specificity of light ray

Table. Values of $R(\lambda)$ for ITO/Al and TiO_2/Al [4] back surface reflectors with the optimal transparent oxide thickness in 0.88≤λ≤1.11 μm wavelength range

Reflector	ITO/Al	TiO_2/Al
$l_{OX}^{opt.max}$, μm	0.25	0.18
n_0 = 1.0 $R(0.88)\div R(1.11)$, %	86.4÷95.9	81.3÷92.3
n_0 = 1.5 $R(0.88)\div R(1.11)$, %	85.8÷95.3	80.1÷92.1

trajectory inside Si-BC shown in Fig. 4 according to [18]. The angles of light incidence on a smooth back surface of such Si-PVC exceed 40°. It has been shown before [19] that the limiting total reflection angle γ_{min} at light incidence from silicon onto ITO makes about 32°. Thus, the above mentioned texture on the frontal surface side makes it possible to use a quite other approach to $l_{OX}^{opt,max}$ determination based on the account for light total reflection from the Si/ITO interface. In this case, to suppress the possible partial radiation power losses in the metal [20] being in contact with ITO and also to minimize the ITO layer resistance, the ITO layer thickness should be experimentally optimized in the $1 < \lambda_{OX}^{opt,max} < 2$ μm range, as in [19].

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Двошаровий ITO/Al тильно-поверхневий рефлектор для одноперехідних кремнієвих фотоперетворювачів

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Показано, що для підвищення ефективності роботи і технологічності виготовлення монокристалічних кремнієвих фотоелектричних перетворювачів (Si-ФЕП) сонячної енергії з товщиною базових кристалів 180÷200 мкм, які мають поліровану фотоприймальну поверхню та двошаровий тильно-поверхневий рефлектор (ТПР), що складається з шарів прозорого оксиду та алюмінію, необхідно в якості неметалічного шару ТПР використовувати провідний прозорий шар із індій-олов'яного оксиду (ITO) з інтерференційною товщиною 0.25 мкм. Це забезпечує коефіцієнт відбиття ITO/Al ТПР у межах $85 < R < 96$ % для фотоактивної компоненти сонячного випромінювання, що падає на тильну поверхню Si-ФЕП, при практично нульовому внеску опору шару ITO у послідовний опір приладу. У випадку Si-ФЕП з текстурою фотоприймальної поверхні кристала типу інвертованих пірамід, при якій специфіка поширення світла у кристалі обумовлює реалізацію ефекту повного внутрішнього відбивання випромінювання від границі розділу Si/ITO, для мінімізації втрат енергії фотоактивного випромінювання та опору шару ITO його товщину слід експериментально оптимізувати у межах значень 1÷2 мкм незалежно від товщини базового кристала.