Development and new application of single-crystal silicon solar cells

G.S. Khrypunov*, V.R. Kopach, M.V. Kirichenko, R.V. Zaitsev

National Technical University «Kharkiv Polytechnical Institute», 21, Frunze Str., 61002, Kharkiv, Ukraine
Tel: +38-057-731-5691, E-mail: khrip@ukr.net

Abstract: The aim of research was development of the improved designs of high-efficiency single-crystal Si solar cells (Si-SC), intended for work in the conditions of ordinary and high-concentrated sun radiation, and also finding out of possibility to use of such devices as energy independent and enough sensitive sensors in the optical location systems. It was shown that for increase of the efficiency at cost reduction and production manufacturability of single-crystal Si-SC with base crystals (BC) thickness $180 \leq t_{BC} \leq 200$ μm having a polished light receiving surface (LRS) and back surface reflector (BSR) consisting of a transparent oxide and Al layers, a conductive transparent indium-tin oxide (ITO) layer of $t_{ITO} = 0.25$ μm interference thickness without of perforation is to be used. In case of Si-SC with inverted pyramid type texture of LRS at which the specificity of light distribution in the BC causes essentially total internal reflection of radiation from Si/ITO interface, the t_{ITO} value should be optimized in the 1÷2 μm range independently of t_{BC}. For efficiency increase of vertical multi-junction (VMJ) Si-SC by a factor of 1.2 approximately the modernization of in series connected unit diode structures (UDS) by the introduction along their vertical Si-boundaries single-layer ITO reflectors by thickness more than 1 μm is promising too. Accordingly to results of numerical simulation the character of open circuit voltage U_{OC} dependence on α angle value of light incidence onto LRS of VMJ Si-SC considerable depends on the minority charge carriers lifetime τ value in the BC of VMJ Si-SC, while light reflection coefficient R value for UDS Si/ITO boundaries effects on absolute U_{OC} value. It has been shown that purposeful decrease of τ value and providing of $95 < R < 100$ % should allowed to create the VMJ Si-SC with practically linear and easily registered $U_{OC}(\alpha)$ dependence for use the VMJ Si-SC as energy independent and enough sensitive sensors in the optical location systems.

Keywords: *High-Efficiency, Silicon Solar Cells, ITO Reflectors, New Application*

1. Introduction

Efficiency increasing at cost reduction as well as expansion of single-crystal silicon solar cells (Si-SC) application fields continue to remain the actual research and development tasks. Therefore the research purposes were development of the improved designs of high-efficiency single-crystal Si-SC, intended for work in the conditions of ordinary and high-concentrated sun radiation, and also finding out of possibility to use of such devices as energy independent and enough sensitive sensors in the optical location systems.

2. Results and discussion

2.1. *Single-junction solar cells*

One of the known methods to increase the efficiency of single junction (SJ) Si-SC is creation of back surface reflector (BSR) consisting of perforated SiO_2 and continuous Al films deposited layer-by-layer onto surface of Si base crystal (BC) from the side opposite to SJ Si-SC light receiving surface [1]. Such construction of BSR is used, for example, in most high-efficiency SJ Si-SC with PERL (Passivated Emitter, Rear Locally-diffused) and PERT (Passivated Emitter, Rear Totally-diffused) structures. At the same time the electrical contact of Al layer with Si- BC is realized via numerous through holes in SiO_2 the total area thereof making less than 1 % of the total Si-BC back surface area. Such multipoint contact character results in somewhat increased SJ Si-SC 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, and also from the necessity to decrease the cost of such devices, when manufacturing SJ Si-SC with PERT-structure, it seems to be reasonable to replace the BSR perforated dielectric oxide layer by a continuous layer of transparent conductive material. Accordingly to the results of this problem analysis, it can be solved by using the transparent indium-tin oxide (ITO) in double-layer BSR structure instead of SiO_2. In this connection, one of the research targets was to determine the most optimum thicknesses $l_{OX}^{opt.max}$ of conducting oxide providing a highest integral reflection coefficient R of solar radiation within the required wavelength λ range and to decrease the series resistance for SJ Si-SC of PERT-types both with smooth and with textured light receiving surfaces. As shown in [2], the required λ range depends on thickness t of Si-BC and at $180 \le t_{BC} \le 200$ μm (typical values of serial SJ Si-SC) is $0.88 \le \lambda \le 1.11$ μm.

In case of SJ Si-SC with smooth light receiving surfaces the $l_{OX}^{opt.max}$ determination method for ITO layer was similar to that used in [2] to find interference thicknesses $l_{OX}^{opt.max}$ for SiO_2/Al BSR and TiO_2/Al BSR oxide layers. Conceptually this method consisted of the following. Accordingly to [3], the optimum thicknesses $l_{OX}^{opt}(\lambda)$ of oxide providing the maximum R values for λ values from the above-mentioned λ range were determined first of all. Further, from the obtained $l_{OX}^{opt}(\lambda)$ dependence, the l_{OX}^{opt} values were selected corresponding to $\lambda_1 = 0.8$ μm, $\lambda_2 = 0.9$ μm, $\lambda_3 = 1.0$ μm and $\lambda_4 = 1.1$ 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 dependences $R\left[\lambda, l_{OX}^{opt}(\lambda), n_0\right]$ in the $0.88 \le \lambda \le 1.11$ μm range according to [3] were calculated using appropriate relations in cases when light receiving surface of SJ Si-SC is protected by glass ($n_0 = 1.5$) and when it is not protected ($n_0 = 1.0$). The analysis of all the $R\left[\lambda, l_{OX}^{opt}(\lambda), n_0\right]$ dependences set shows that optimal oxide thickness $l_{OX}^{opt.max}$ providing the maximum integral reflectivity of ITO/Al BSR in the specified λ range is 0.25 μm at both n_0 values. Dependences $R(\lambda, n_0)$ for $l_{OX}^{opt.max} = 0.25$ μm are presented in Fig. 1.

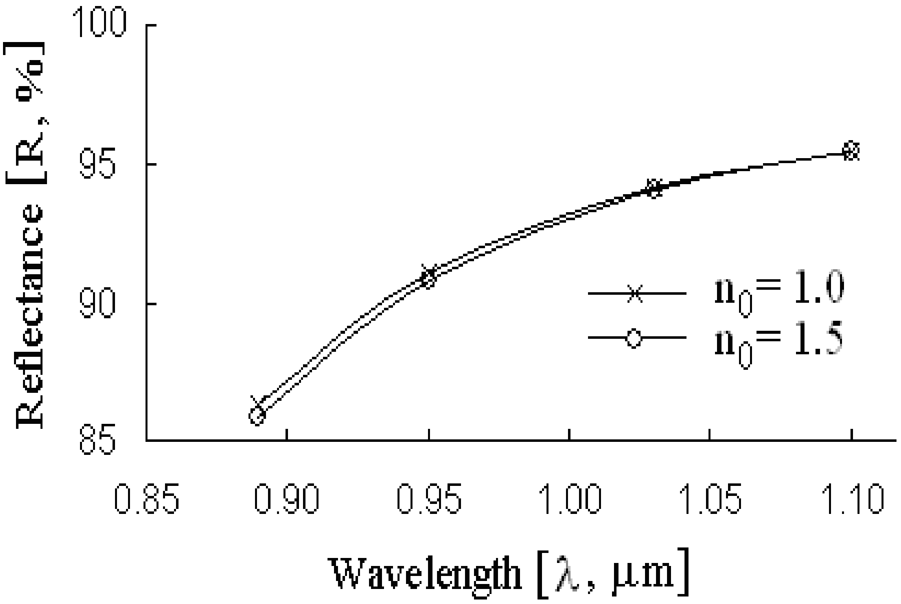

Figure 1: Dependences of R on λ and on n_0 for ITO/Al back surface reflector with $l_{OX}^{opt.\max} = 0.25$ μm

In case of textured light receiving surface with the pyramids faceted by (111) type planes, the optimal oxide thickness for ITO/Al BSR is not so critical. This is due to the specificity of light ray trajectory inside Si-BC shown in Fig. 2 according to [4].

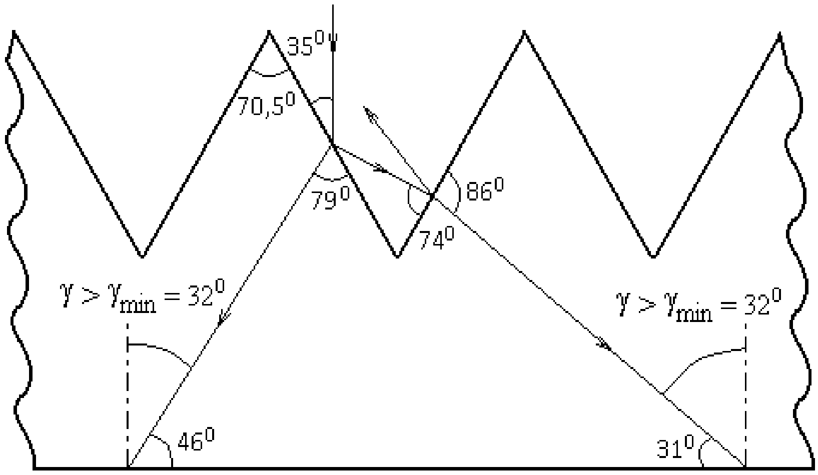

Figure 2: Light rays trajectory inside the Si-BC of the SJ Si-SC with textured frontal surface and smooth back surface

The angles γ of light incidence on a smooth back surface of such SJ Si-SC exceed 40°. It is a more than limit angle γ_{min} of light complete internal reflection from the Si/ITO interface because $\gamma_{\min} = \arcsin\left(n_{ITO}/n_{Si}\right) \approx 32^o$ [5], where $n_{ITO} \approx 1.9$ [6] and $n_{Si} \approx 3.6$ [7] are refractive indexes of ITO and of Si correspondingly at $0.88 \le \lambda \le 1.11$ µm. Thus, the above mentioned texture on the light receiving surface 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 [8] being in contact with ITO and also to minimize the series resistance for SJ Si-SC the ITO layer thickness should be experimentally optimized in the $1 < l_{OX}^{opt.max} < 2$ µm range.

2.2. *Vertical multi-junction solar cells*

Use Si-SC of the special construction in the conditions of high concentrated radiation is perspective direction for the increase of efficiency and cost decreasing of solar energy photovoltaic conversion [9]. Such Si-SC include, in particular [10], vertical multi-junction (VMJ) Si-SC consisting of a monolithic set (more than 10) of single-crystal silicon plane-parallel vertical unit diode structures (UDS) 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 UDS. Let's notice, that at the unitary light reflection coefficient R = 0,89 in case of double light reflection the effective reflection coefficient $R_{EFF} \approx R^2 \approx 0.79$ and it corresponds to losses more than 20 % of solar radiation energy on absorption. From this follows, that elimination of such losses would allow increasing the efficiency of considered type VMJ Si-SC approximately at 1.2 times.

The analysis, carried out by us, indicate a capability of such efficiency increase for VMJ Si-SC with UDS at the expense of maximum approximation to 1 the reflection coefficient of solar radiation with $0.95 < \lambda < 1.11$ µm by vertical boundaries of these cells inside VMJ Si-SC. However, on reasons, to analogical indicated before, highly reflecting SiO_2/Al and TiO_2/Al double-layer reflectors with calculated in [2] optimum thickness of SiO_2 and TiO_2 dielectric layers, contacting with a silicon crystal, concerning to considered type VMJ Si-SC are unacceptable. The above mentioned multipoint character of SC back electrode with a SI-BC contact leads to certain increase of SJ Si-SC series resistance, what partially compensates a benefits in efficiency achieved at the expense of solar radiation energy losses decrease at use of dielectric oxide/metal two-layer reflector. It is natural, that in case of VMJ Si-SC the multidot contact influence effect on t he device series resistance should grow in direct proportion to amount of UDS in-series, and therefore reflectors from side of UDS vertical borders should provide a good electrical contact between the next UDS on all area of the mentioned borders.

For efficiency increase of the VMJ Si-SC the modernization of in series connected UDS by the introduction along their vertical Si-boundaries single-layer ITO reflectors by thickness more than 1 μm is promising too. The VMJ Si-SC of new design is shown schematically in Fig. 3. The new VMJ Si-SC design gives possibility to exclude the photoactive radiation losses depended on partial light absorption by metal interlayers between UDS in case of VMJ Si-SC using for photovoltaic conversion of high concentrated solar radiation the main part of which always incidence onto VMJ Si-SC light receiving surface at the angles $0 < \alpha < 90^o$. Thus taking into account that the highest angle of refraction $\beta_{max} = arcsin(1/n_{Si})$ [5] it is easy obtain $0 \leq \beta \leq 16.1^o$, that for $0.88 \leq \lambda \leq 1.11$ μm gives $73.9 \leq \gamma \leq 90^o$, and consequently $\gamma > \gamma_{min} \approx 32^o$ at $0 < \alpha < 90^o$.

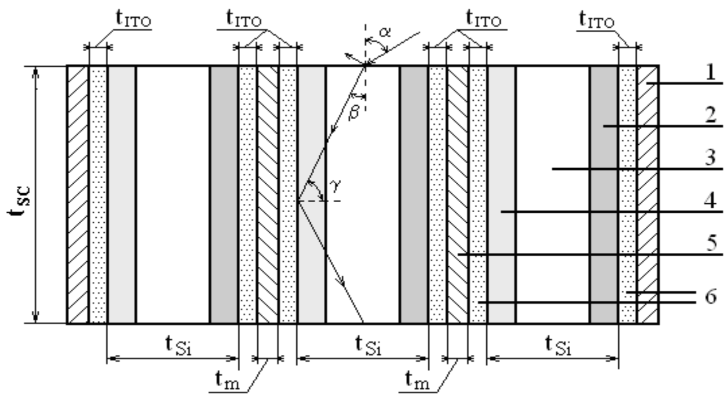

Figure 3: Cross-section of new VMJ Si-SC of $t_{SC} \approx 850$ μm thickness with ITO reflectors belonging to UDS of n^+-p-p^+ type (schematic image): 1 – metal electrode; 2 – p^+-Si layer of less than 1 μm thickness; 3 – p-Si layer of $t_{Si} \approx 160$ μm thickness; 4 – n^+-Si layer of less than 1 μm thickness; 5 - metal interlayer of $t_m \approx 10$ μm thickness; 6 – ITO reflectors of $1 < t_{ITO} < 2$ μm thickness

Therefore, at all actual values of light incidence angle α on the VMJ Si-SC external surface, hitting inside the UDS of such Si-SC, light with $0.9 \leq \lambda \leq 1.1$ μm should experience practically full internal reflection from considered reflectors that should essential approach the optical reflection coefficient from ITO/Si boundaries to unity. Obviously, that this effect will be result in to previously stated increase of VMJ Si-SC efficiency approximately in 1.2 times. Since according to [8] effect of full internal reflection is caused by wave processes in ITO layer by thickness no more wavelength of light, it, on t he one hand, for suppression of radiation energy losses, which can be connected to penetration of radiation energy part into metal, contacting with ITO, and on the other hand, with the purpose of ITO layer resistance minimization to the current carrying through it, the thickness t_{ITO} of this layer should be experimentally optimized in the range of values 1 μm < t_{ITO} < 2 μm.

Besides as is known [6], the modern methods of ITO films with submicron and micron thicknesses deposition, inclusive of pulverization with following pyrolyze, allow to realize the appropriate process at temperatures below 450 ^{o}C. It is well agree with the concept of single-crystal silicon SC manufacturing technology, according to which the most of high-temperature technological process operation should be the operation of submicron and highly-doped n^{+}-Si and p^{+}-Si layers manufacturing realized, as a rule, at 900÷1000 ^{o}C.

Accordingly to results of numerical simulation the character of open circuit voltage U_{OC} dependence upon α value considerable depends on the minority charge carriers lifetime τ value in the VMJ Si-SC base crystals, while R value for vertical UDS Si/ITO boundaries effects on absolute U_{OC} value. It has been shown that purposeful decrease of τ value and providing of $95 < R < 100$ % should allowed to create the VMJ Si-SC with practically linear and easily registered $U_{OC}(\alpha)$ dependence for use the VMJ Si-SC as energy independent and enough sensitive sensors in the optical location systems. The numerical dependence $U_{OC}^{norm}\left(\alpha, R, \Delta\xi\right)$, got as the result of indicated simulation using early resulted in [11] relation

$$U_{OC}^{norm}\left(\alpha, R, \Delta\xi\right) = \frac{U_{OC}\left(\alpha, R, \Delta\xi\right)}{U_{OC}\left(\alpha = 0, R, \Delta\xi\right)} = 1 + \frac{\ln\left[f\left(\alpha, R\right)\cos\alpha\right]}{2.3\left(\xi_2 - \xi_1\right)} \tag{1}$$

where

$$f\left(\alpha, R\right) = R\frac{t_{Si}}{t_{SC}}\sqrt{\frac{n_{Si}^2 - 1 + \cos^2\alpha}{1 - \cos^2\alpha}} + R^2\left(1 - \frac{t_{Si}}{t_{SC}}\sqrt{\frac{n_{Si}^2 - 1 + \cos^2\alpha}{1 - \cos^2\alpha}}\right) \tag{2}$$

and $\xi_1 < \xi_2$ are absolute values of indexes in degrees of short circuit current J_{SC} and diode saturation current J_0 densities accordingly, is presented in Fig. 4.

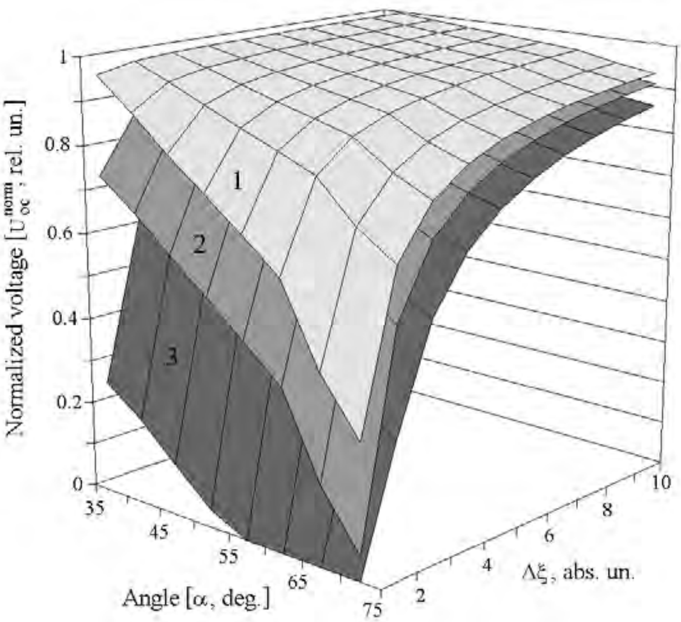

Figure 4: Dependence U_{OC}^{norm} values versus α and Δξ for considered VMJ Si-SC at the light reflection coefficients from vertical UDS boundaries: 1 - R = 100 %, 2 – R = 60 %, 3 - R = 20 %

It is well known [4] that values of J_{SC} and J_0, and consequently $\Delta\xi$, substantially depends from τ value in SC base crystals. Therefore at the use VMJ Si-SC as sensors the required value of $\Delta\xi$ possibly to attain by a purposeful decrease of τ value in Si-BC. In accordance to numerical simulation results for using VMJ Si-SC as sensors in the optical location systems the optimal combination of parameters influencing on $U_{OC}(\alpha)$ dependence are $1 \le \Delta\xi \le 2$ and $95 < R < 100$ %.

3. Conclusions

It was shown that for increase of the efficiency at cost reduction and production manufacturability of single-crystal Si-SC with base crystals thickness $180 \le t_{BC} \le 200$ μm having a polished light receiving surface and back surface reflector consisting of a transparent oxide and Al layers, a conductive transparent ITO layer of t_{ITO} = 0.25 μm interference thickness without of perforation is to be used. In case of Si-SC with inverted pyramid type texture of light receiving surface at which the specificity of light distribution in the base crystals causes essentially total internal reflection of radiation from Si/ITO interface, the t_{ITO} value should be optimized in the 1÷2 μm range independently of t_{BC}. For efficiency increase of vertical multi-junction Si-SC by a factor of 1.2 approximately the modernization of in series connected unit diode structures by the introduction along their vertical Si-boundaries single-layer ITO reflectors by thickness more than 1 μm is promising too. Accordingly to results of numerical simulation the character of open circuit voltage U_{OC} dependence on α angle value of light incidence onto light receiving surface of vertical multi-junction Si-SC considerable depends on the minority charge carriers lifetime τ value in the base crystals of vertical multi-junction Si-SC, while light reflection coefficient R value for unit diode structures Si/ITO boundaries effects on absolute U_{OC} value. It has been shown that purposeful decrease of τ value and providing of $95 < R < 100$ % should allowed to create the vertical multi-junction Si-SC with practically linear and easily registered $U_{OC}(\alpha)$ dependence for use the vertical multi-junction Si-SC as energy independent and enough sensitive sensors in the optical location systems.

Acknowledgment

The work was supported by STCU under Project 4301.

References

[1] M.A. Green, J. Zhao, A. Wang and S.R. Wenham, "Progress and outlook for high-efficiency crystalline silicon solar cells", Solar Energy Materials and Solar Cells, 65, 2001, pp. 9-16.

[2] V.R. Kopach, M.V. Kirichenko, S.V. Shramko, R.V. Zaitsev, I.T. Tymchuk, V.A. Antonova, A.M. Listratenko, "Back surface reflector optimization for thin single crystalline silicon solar cells", Functional Materials, 14, 2007, pp. 555-561.

[3] M.M. Koltun, "Selective optical surfaces of solar energy converters", Nauka, Moscow, 1979 (in Russian).

[4] A.L. Fahrenbruch, R.H. Bube, "Fundamentals of solar cells. Photovoltaic solar energy conversion", Academic Press, New York, 1983.

[5] G. S. Landsberg, "Optics", Nauka, Moscow, 1976 (in Russian).

[6] D.E. Morton, A. Dinca, "Ion-assisted deposition of E-gun evaporated ITO films at low substrate temperatures", http://www.dentonvacuum.com/n-paper.

[7] H.R. Philipp, E.A. Taft, "Optical constants of silicon in the region 1 to 10 eV", Phys. Rev., 120, 1960, pp. 37-38.

[8] V.A. Kizel, "Light refraction" (Series "Physics and technology of spectral analysis"), Nauka, Moscow, 1973 (in Russian).

[9] P.J. Verlinden, "High–efficiency concentrator silicon solar cells", in: "Practical Handbook of Photovoltaics: Fundamentals and Applications", edited by T. Markvart and L. Castaner, Elsevier Science Ltd., Kidlington, Oxford, 2003 pp. 436–455.

[10] B.L. Sater, N.D. Sater, "High voltage silicon VMJ solar cells for up to 1000 suns intensities", Proceedings of the 29th IEEE Photovoltaic Specialists Conference, New Orleans , USA, 2002 pp. 1019–1022.

[11] V.R. Kopach, M.V. Kirichenko, S.V. Shramko, R.V. Zaitsev, S.A. Bondarenko, "New approach to the efficiency increase problem for multi-junction silicon photovoltaic converters with vertical diode cells", Functional Materials, 15, 2008 pp. 253-258.