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SENSITIVITY OF SILICON PHOTOVOLTAIC CONVERTERS TO THE LIGHT INCIDENCE ANGLE ON THEIR RECEIVING SURFACE

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Abstract. The results of output parameters dependences researches for multijunction silicon photovoltaic converters (PVC) upon solar radiation incidence angle on their receiving surface are presented. It has been shown that for improving of PVC efficiency is necessary to achieve the increased values of minority charge carriers lifetime in their base crystals as well as the optical reflection coefficient for metal/Si boundaries (interfaces) inside multijunction PVC, while for using multijunction PVC in the optical location systems the forced reduction of these values is reasonable.

Keywords: photoconverter, photovolt, light incidence angle, reflection coefficient, parameters

ЧУТЛИВІСТЬ КРЕМНІЄВИХ ФОТОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ ДО КУТА ПАДІННЯ СВІТЛА НА ЇХ ПРИЙМАЛЬНУ ПОВЕРХНЮ

М. В. Кіріченко, В. Р. Копач, Р. В. Зайцев, С. О. Бондаренко

Анотація. Наведено результати досліджень залежностей вихідних параметрів багатоперехідних кремнієвих фотоелектричних перетворювачів (ФЕП) від кута падіння сонячного випромінювання на їх приймальну поверхню. Показано, що для збільшення ККД ФЕП необхідно забезпечити підвищені значення часу життя неосновних носіїв заряду в базових кристалах та коефіцієнта оптичного відбиття від границь метал/Si всередині багатоперехідних ФЕП, у той час, як при використанні багатоперехідних ФЕП у системах оптичної локації визначення напряму розповсюдження випромінювання доцільним є примусове зниження цих величин.

Ключові слова: фотоперетворювач, фотовольт, кут падіння світла, коефіцієнт відбиття, параметри

ЧУВСТВИТЕЛЬНОСТЬ КРЕМНИЕВЫХ ФОТОЭЛЕКТРИЧЕСКИХ ПРЕОБРАЗОВАТЕЛЕЙ К УГЛУ ПАДЕНИЯ СВЕТА НА ИХ ПРИЕМНУЮ ПОВЕРХНОСТЬ

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Аннотация. Приведены результаты исследований зависимостей выходных параметров многопереходных кремниевых фотоэлектрических преобразователей (ФЭП) от угла падения солнечного излучения на их приемную поверхность. Показано, что для увеличения КПД ФЭП необходимо обеспечить повышение значений величин времени жизни неосновных носителей заряда в базовых кристаллах и коэффициента оптического отражения от границ металл/Si внутри многопереходных ФЭП, в то время как при использовании многопереходных ФЭП в системах оптической локации целесообразным является принудительное снижение этих величин.

Ключевые слова: фотопреобразователь, фотовольт, угол падения света, коэффициент отражения, параметры

Introduction

The short circuit current density J_{SC} and open circuit voltage U_{OC} of photovoltaic converters (PVC) are increased with the intensity growth of illumination flux penetrating into the semiconductor base. It causes the expediency of concentrated solar radiation (CSR) using for increasing of such devices efficacy η, since $\eta \sim J_{SC}U_{OC}$ and $U_{OC} \sim \ln(J_{SC} / J_0)$, where J_0 — diode saturation current density [1-4].

One of the most favorable types of multi-junction Si-PVC specially created for the use in CSR conditions [3,4] named "photovolt", represents a monolithic design from set (more then 10) of single crystal silicon flatly-parallel diode cells with p—n junctions oriented perpendicularly to reception surface and connected in-series by means of metal layers between the adjacent cells.

The essential advantages of considered PVC type at CSR conditions in comparison with single-junction Si-PVC of planar design p—n junction which is oriented parallel to reception surface, are: i) potential capability to much more effective conversion of CSR into electric energy and ii) generating i10—30 times greater output voltage. The last circumstance simplifies the problem of high-voltage photoelectric systems development and provides reduction of electrical energy losses in solar batteries interconnections as well as in electrical energy transmission line from solar batteries to the consumer.

Besides, the manufacturing of "photovolt" type PVC, the necessity of using of sufficiently expensive photolithography process disappears since on the receiving surface (in difference from planar design PVC [2]) crested or grid current-collecting electrode with narrow and thin (~10 μm) streaky elements divided by the gaps less than 1 mm is absent. However, it is necessary to take into account that the significant part of CSR goes to PVC receiving surface under the angle $\alpha > 0$ to it normal [5]. Therefore, J_{SC}, U_{OC} and efficacy should depend on α, as far as the irradiance E of PVC receiving surface changes with α according to the law $E = E_0 \cos\alpha$, where $E_0 = E$ at $\alpha = 0$ [6]. Therefore, the angular dependence of multi-junction Si-PVC output parameters minimization is one from the urgent problems with regard to creation of such type PVC with increased efficacy for the use at CSR conditions.

On the other hand in optical location systems the Si-PVC of "photovolt" type could be serious alternative to the well-known semiconductor radiation sensors requiring the external source of electrical energy. Thus in this case the angular dependence of J_{SC} and U_{OC} should be so more tangible as it possible.

In the present work the influence of single crystal Si-PVC "photovolt" design features on J_{SC} and U_{OC} dependence upon α was investigated in connection with practical importance of two above mentioned problems. Concerning to both problems simultaneously the greatest interest represents the $U_{OC}(\alpha)$ dependence owing to simplicity of this parameter measurement.

Experimental detales

In connection with above mentioned the serial "photovolt" type Si-PVC with the area of receiving surface about 2 cm^2 manufactured on the basis of p-type conductivity single crystal silicon with resistivity about 10 Ohm·cm were investigated. Schematic image of the samples is presented at Fig 1. Devices had overall dimensions 33 mm × 6 mm × 1 mm and consisted from 35 elementary diode cells by thickness 150 μm everyone with n^+-p-p^+-structure which were connected in-series through the metal interlayers by thickness about 10 μm.

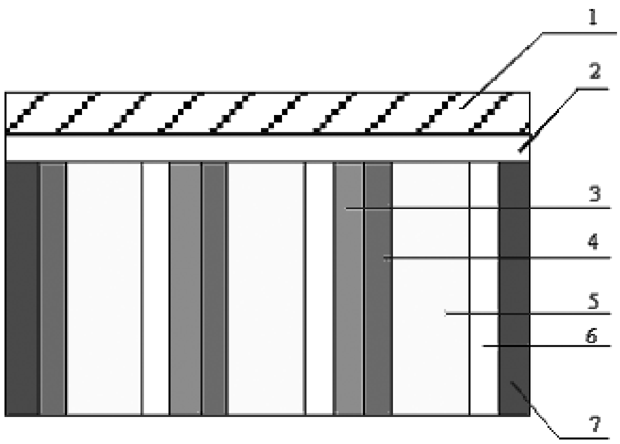

Fig. 1. Schematic image of "photovolt" type multi-junction Si-PVC cross–section: 1 — metal layer by thickness $t_m \approx 10$ μm; 2 — layer of n^+-type conductivity silicon; 3 — layer of p-type conductivity silicon; 4 — layer of p^+-type conductivity silicon; 5 — solid metal electrode.

Determination of J_{SC} and U_{OC} values for investigated Si-PVC was carried out by measurement and following analytical processing of loading illuminated current versus voltage characteristics LI CVC. The measurement of LI CVC was carried out similarly to [7] under the Si-PVC receiving surface irradiation power of 5712 W/m², that corresponds to the degree of AM0 irradiation concentration equal to 4.2.

For light incidence angle α change on its surface the investigated Si-PVC was fixed on goniometer device allowing varying the angle α in the range from 0° up to 90° with the accuracy of 0.01°. Measurements of LI CVC were carried out at the following values of α : from 0° up to 20° with a step 2°; from 20° up to 40° with a step 4°; from 40° up to 60° with a step 5°; also LI CVC were measured at angles 70°, 80°, 85° and 90°. Temperature of samples 25 °C at LI CVC measurements was supported with the help of the thermostat. The analytical processing of LI CVC realized similarly to [8].

Results and discussion

The normalized angular dependences of open circuit voltage $U_{OC}^{norm}(\alpha)$ (curve 1) and short circuit current $J_{SC}^{norm}(\alpha)$ (curve 2), calculated according to the experimental values of the corresponding magnitudes in the following way: $J_{SC}^{norm}(\alpha) = J_{SC}(\alpha) / J_{SC}(\alpha = 0)$, $U_{OC}^{norm}(\alpha) = U_{OC}(\alpha) / U_{OC}(\alpha = 0)$, are presented on the Figure 2. Earlier [9] it was shown that in the range of α values from 40° up to the Brewster angle φ_B (74.5° for silicon) trend of $U_{OC}^{norm}(\alpha)$ dependence is well described by the ratio $U_{OC}^{norm}(\alpha) \approx 1 + \frac{\ln[f(R,\alpha)\cos\alpha]}{2.3(\xi_2 - \xi_1)}$, where $0 \le f(R,\alpha) \le 1$ is a correcting function, taking into account the real values of reflection coefficient from the metal/Si boundaries into "photovolt" type Si-PVC. In expanded form this ratio is presented in [9], where $\xi_1 < \xi_2$ are absolute values of indexes in degrees of short circuit current and diode saturation current densities, accordingly. As a result of analysis of such $U_{OC}^{norm}(\alpha)$ dependence it has been established that, varying parameters R and $\Delta\xi = \xi_2 - \xi_1$ it is possible to purposefully effect on its character. So, for example, it is necessary to maximally increase parameters R and $\Delta\xi$ for minimization of $U_{OC}^{norm}(\alpha)$ angular dependence with the purpose of "photovolt" type Si-PVC efficiency rising.

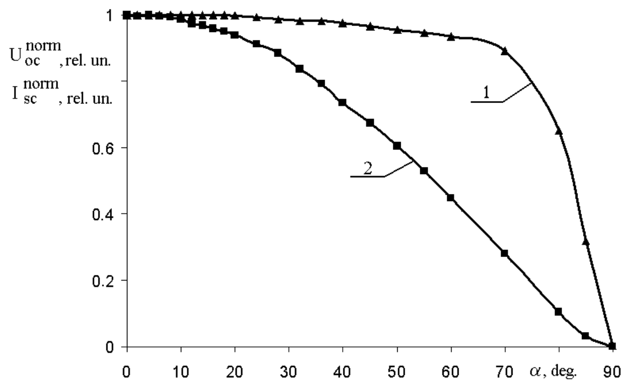

Fig. 2. Normalized values of open circuit voltage (1) and short circuit current density (2) versus light incidence angle on Si-PVC of "photovolt" type receiving surface.

In the present work it is suggested to using "photovolt" type Si-PVC as sensor in the optical location systems. Obviously, that for the successful solving of such problem the device, using in the specified capacity, must provide the possibility of output signal registration, and also to have the strikingly expressed, desirably linear, dependence of the registered parameter from the α angle. As follows from above stated, the characteristic peculiarity of "photovolt" type Si-PVC is high photovoltage that provides simple and reliable registration of this parameter. At the same time, from Fig. 2 evidently, that concerned “photovolt” type Si-PVC has the weakly expressed $U_{OC}^{norm}(\alpha)$ dependence in the range of light incidence angles on their receiving surface from 0 up to 74°. However, the results of work [9] let to suppose that varying parameters R and $\Delta\xi$ will allow to provide the strikingly expressed character of $U_{OC}^{norm}(\alpha)$ dependence.

Therefore, we carried out the numerical simulation of $U_{OC}^{norm}(\alpha) \approx 1+\dfrac{\ln\left[f(R,\alpha)\cos\alpha\right]}{2.3\Delta\xi}$ dependence at $40^{o} \leq \alpha \leq 70^{o}$ for different values of R and $\Delta\xi$. Results of the simulation as a family of $U_{OC}^{norm}(\alpha,\Delta\xi)$ surfaces for different values of parameter R are presented at Fig. 3. From Fig. 3 it is evident, that varying of parameter R practically does not result in the varying $\partial U_{OC}^{norm}(\alpha)/\partial\alpha$ — speed of change U_{OC}^{norm} from α, but provides the change of U_{OC}^{norm} absolute value, i.e. this magnitude growth with R growing.

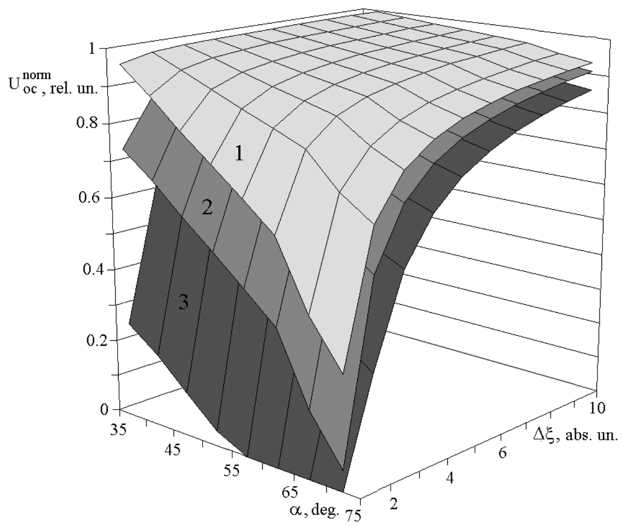

Fig. 3. Theoretical U_{OC}^{norm} values versus α and $\Delta\xi$ for considered Si-PVC of “photovolt” type at the light reflection coefficients from metal/silicon boundaries: 1 — $R=1.0$; 2 — $R=0.6$; 3 — $R=0.2$.

At the same time, as it evidently from Figure 3, the determining influence on the $\partial U_{OC}^{norm}(\alpha)/\partial\alpha$ renders $\Delta\xi$ parameter, being the difference of J_{SC} and J_0 orders values. Really, from stated Figure evidently that by realization of situation, characteristic for concerned “photovolt” type Si-PVC, when $\Delta\xi \approx 7-8$, the value $\partial U_{OC}^{norm}(\alpha)/\partial\alpha \to 0$ as well as on Figure 2 at $\alpha < 74°$. However at decrease of difference between J_{SC} and J_0, that corresponds to $\Delta\xi$ decrease, dependence of $U_{OC}^{norm}(\alpha)$ suffers substantial changes and at $\Delta\xi = 1-2$ obtains practically linear character in the concerned range of α angles with sufficiently large value $\partial U_{OC}^{norm}(\alpha)/\partial\alpha \approx$ -(7.3·- 14.6)·10^{-3} relat.un./deg.

Thus, the obtained results argues that in the case of using “photovolt” type Si-PVC as sensors in the optical location systems the U_{OC} sensitivity of such sensors to the light incidence angle on their receiving surface increased with decreasing of difference between J_{SC} and J_0, characterized by parameter $\Delta\xi$. Value of the registered parameter U_{OC} increased with growth of reflection coefficient from metal/Si boundaries into “photovolt” type Si-PVC. At the same time it is necessary to take into account the technological difficulties of $R \to 1$ achievement in the conditions of Ukrainian Si-PVC production, and, also, that, as it evidently from Figure 3, the value of U_{OC}^{norm} less than at $R=1$ only on 5% is provide at $R=0.6$.

Therefore for using “photovolt” type Si-PVC as sensor in the optical location systems optimum is the next combination of parameters influencing on $U_{OC}^{norm}(\alpha)$ dependence: $\Delta\xi = 1-2$ and $R=0.6$.

At the same time achievement of such reflection coefficient from the metal/Si boundaries into “photovolt” type Si-PVC offers no special complication in conditions of national Si-PVC production.

It is well known [1] that values of J_{SC} and J_0, and consequently $\Delta\xi$, substantially depends from minority charge carriers lifetime $\tau_{n,p}$ in PVC base crystals. Therefore, the required value of $\Delta\xi$ at using such PVC as sensors, it is possible to achieve by a purposeful decrease of $\tau_{n,p}$ values in base crystals bulk. Since $\tau_{n,p} \sim N_r^{-1}$, where N_r is bulk concentration of recombination centers, then with above mentioned purpose the base crystals for such sensors in the process of appropriate devices manufacturing can be subject to thermal, mechanical or other types of processing directed at introduction in their bulk as greater as possible amount of recombination centers. It will be result in substantial decrease of $\tau_{n,p}$ value. A similar effect can be achieved and by using of heavily doped silicon single crystal for manufacturing of concerned sensors. Such silicon, intended for electronic industry, has small $\tau_{n,p}$ values due to high doping level.

Conclusions

The results of carried out experimental and theoretical researches of silicon photo-converters sensitivity to the light incidence angle on their receiving surface allow to make the following conclusions:

1. The character of $U_{OC}(\alpha)$ dependence for multi-junction "photovolt" type Si-PVC considerable depends on the minority charge carriers lifetime $\tau_{n,p}$ value in the PVC base crystal, while reflection coefficient R from metal/Si boundaries into PVC effects on absolute value of U_{OC}.

2. It has been shown that purposeful decrease of $\tau_{n,p}$ value and increase of R value will allow tocreate the PVC with practically linear and easily registered $U_{OC}(\alpha)$ dependence. Such character of $U_{OC}(\alpha)$ dependence will allow to use the multi-junction "photovolt" type Si-PVC as sensors in the optical location systems.

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