

## Cost-effective Silicon Solar Cells Efficiency Increase by the Magnetic Field Treatment

R.V. Zaitsev

National Technical University «Kharkiv Politechnic Institute», 21, Frunze Str., 61002 Kharkiv, Ukraine

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It is experimentally established that efficiency of single-junction (SJ) single-crystal silicon solar cells (Si-SC) with horizontal  $n^+p-p^+$  diode structure can increase approximately in 1.1 time after their processing at a room temperature during 7 days by perpendicularly oriented stationary magnetic field (SMF) with induction 0,2 T. It can be explained by the reduction of recombination centers quantity in SJ Si-SC base crystals, on what is indicates the increase of minority charge carriers lifetime in silicon under the influence of SMF. The possibility of the achieved positive effect subsequent stabilizing is shown due to attachment to SJ Si-SC from the side of back electrode the thin layer of magnetic vinyl, creating in base crystal magnetic field with induction no more than 0.05 T.

**Keywords:** Single-crystal silicon solar cell, Magnetic field, Magnetic vinyl.

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### 1. INTRODUCTION

According to actual expert estimations no less than 12 % of world electric production power to 2020 must be provided at the expense of photoelectroenergetics [1]. At that more than the half of base semiconductor materials for solar cells general volume goes on silicon [2]. The stated circumstances attach the special actuality to search the economically expedient techniques of single-crystal silicon solar cells (Si-SC) efficiency ( $\eta$ ) increase. At the same time, currently exactly here the crisis of «genre» begins to be perceptible, as far as the possibilities of construction-technological solutions economically acceptable improvement is practically exhausted. Thus, for further progress in the solution of the proper problem in essence new approaches are needed.

The background for realization by us one of them there was the research on a magnetomechanical effect in single-crystal silicon [3], the results of which indirectly indicates that the prolonged influence by stationary magnetic field (SMF) with induction  $B \approx 0.2$  T on single-crystal silicon can result to reconstruction in him the initial ensemble of point defects and their complexes. As is known [4], the efficiency of single-crystal Si-SC improves with the increase of minority charge carriers (MCC) lifetime  $\tau$  in the silicon base crystals (Si-BC), and  $\tau \approx N_r^{-1}$  (where  $N_r$  – bulk concentration of point defects in Si-BC, which effects as recombination centers). Therefore we supposed, that if processing of single-crystal Si-SC in SMF with  $B = 0.2$  T will be able to provide the reduction of  $N_r$  and consequently to increase  $\tau$ , ipso facto at the expense of such processing it will be succeeded to increase  $\eta$  of the examined objects.

Therefore one of the present work problems consisted in experimental verification of the above formulated idea. At the same time, it is known [3], that result of SMF influence on single-crystal silicon relaxes after termination of operation on him the magnetic field per time, commensurable with duration of sample in SMF preceding exposure. In connection with stated and practical importance of stabilizing the supposed effect

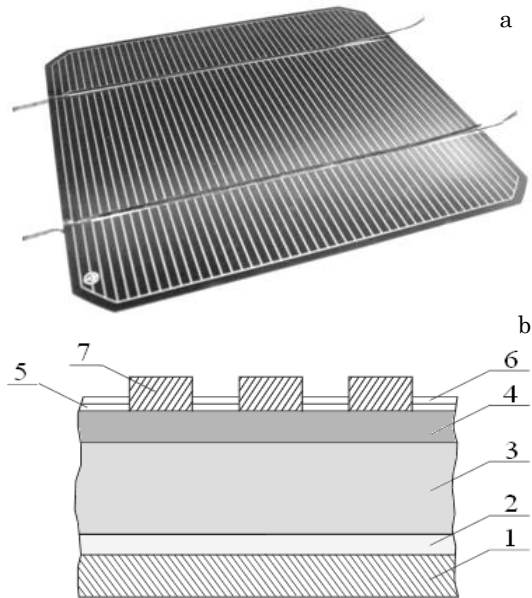
of single-crystal Si-SC efficiency increase the second problem of work was the finding out the possibility of saving the achieved result during long time.

### 2. OBJECTS AND METHODS OF INVESTIGATION

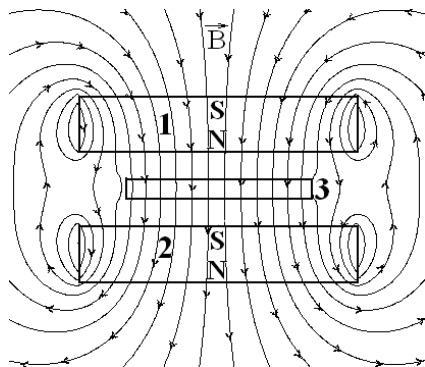
In research was investigated the single-junction (SJ) single-crystal Si-SC, which were the fragments of serial Ukrainian such type devices with planar sizes  $125 \times 125$  mm. The last had horizontal  $n^+p-p^+$  diode structure and were made from SHB-2 mark silicon, grown by Czochralski method. The sizes of investigated fragments planar surfaces were  $40 \times 40$  mm, thickness of them Si-BC was  $200 \mu\text{m}$ . The view of serial device from the side of frontal surface, of which the stated fragments were cut out, and schematic image of his vertical cross-section, presented on Fig. 1. Technology of SJ Si-SC manufacturing is not adduced, because is the object of Manufacturer's «know-how».

For processing of investigated SJ Si-SC in SMF was using the device, consisting from two permanent magnets with 70 mm diameter and thickness 15 mm, located in the distance 20 mm from each other, between which was practically homogeneous field with  $B = 0.2$  T, measured by tesla meter EM4305. On Fig. 2 the distribution of this field induction lines is schematically shown both in area of investigated objects placing and out of its limits, obtained by simulation using the Vizimag 3.193 program [5] and results of the own experimental measurements.

For the further stabilizing of the considered effect was chosen the inexpensive industrially manufactured plastomagnet – flexible magnetic vinyl [6, 7] with thickness about 1.5 mm. By means of direct measurements using above mentioned tesla meter and method of powder patterns [8] was carried out researches of magnetic field, created by this material directly at his working surface distribution features. On Fig. 3a is shown a photograph of magnetic vinyl, using in present research, with magnetic suspension applied on its working surface. In addition, in central part of vinyl working surface was placed the rectangular fragment of FTA



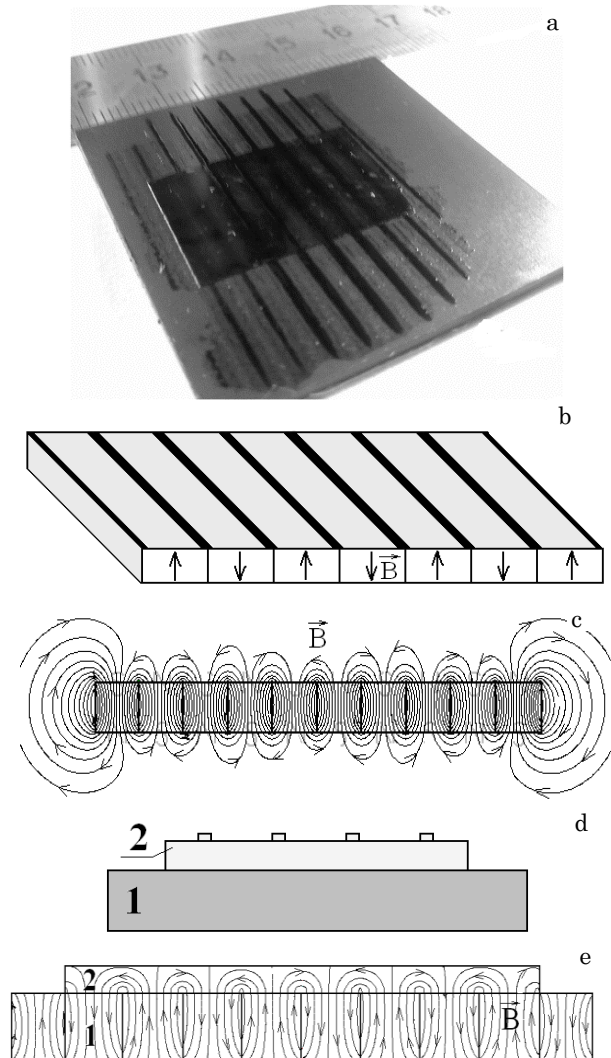
**Fig. 1** – View of Ukrainian serial solar cell from the side of frontal surface (a) and schematic image of his vertical cross-section (b): 1 – back solid electrode; 2 – layer of  $p^+$ -type conductivity silicon; 3 – layer of p-type conductivity silicon; 4 – layer of  $n^+$ - type conductivity silicon; 5 – passivating layer from silicon dioxide; 6 – antireflection coating, from silicon nitride; 7 – front metallization



**Fig. 2** – Schematic image of SJ Si-SC treatment method in the stationary magnetic field of two permanent magnets and result of simulation by the Vizimag 3.193 program this field distribution in area of investigated object placing, and also after its limits: 1, 2 – permanent magnets; 3 – sample

brand mica with thickness about 20  $\mu\text{m}$ , imitating a SJ Si-SC presence, the surface of which also moistened by magnetic suspension. The analysis of presented image showed that magnetic vinyl created in external near-surface space ribbon areas (wide light stripes on Fig. 3a, separated by narrow dark boundaries from the accumulations of magnetic powder) with differently directed vertical component of magnetic field induction in the centers of intervals between narrow dark boundaries. The stated fact is schematically represented on Fig. 3b. It is confirmed: i) the results of magnetic field distribution simulation by the Vizimag 3.193 program, shown on Fig. 3c, and ii) proper measurements according to which the vertical constituent of magnetic field induction in limits up to 1 mm above the vinyl working surface on the average reaches 0,05 T, periodically changing its direction on opposite.

After SJ Si-SC processing in SMF of permanent magnets (Fig. 2) the investigated objects were placed by back electrode on the working surface of such vinyl (Fig. 3d). The result of magnetic field distribution in the double-layer system magnetic vinyl (1)/SJ Si-SC (2) simulation, obtained by using the Vizimag 3.193 program, is shown on Fig. 3e.



**Fig. 3** – Distributing of the magnetic field, created by magnetic vinyl: a – visualization by magneto-powder method (the details of image discussed in a text); b – schematic image of magnetic field induction direction in sections of vinyl which corresponds to clear stripes on fragment a; c – result of simulation by the Vizimag 3.193 program; d – method of placing the magnetic vinyl (1) relative to SJ Si-SC (2); e – result of simulation by the Vizimag 3.193 program magnetic field distribution in the two-layer system magnetic vinyl (1)/SJ Si-SC (2)

The determination of SJ Si-SC efficiency on all stages of researches carried out according to standard technique at 25  $^{\circ}\text{C}$  and AM1.5 illumination regime [9]. The basic constituents of this technique was measuring illuminated current-voltage characteristic of SJ Si-SC by compensation method and subsequent computer processing of measurements results with using appropriate software. Measurements of effective electrons lifetime  $\tau_n^{ef}$  in  $p$ -type of conductivity Si-BC carried out

by open circuit voltage decay after cutoff the square pulse of radiation proceeding on sample photoreceiving surface [4, 10]. Necessary at the measuring of illuminated current-voltage characteristics continuous and at measuring  $\tau_n^{ef}$  pulse illumination of SJ Si-SC was realized by developed and earlier manufactured universal light-emitting diode illuminator [11].

3. RESULTS AND DISCUSSION

Experimental determination of  $\eta$  and  $\tau_n^{ef}$  was carried out for SJ Si-SC in the original state, after processing in SMF of permanent magnets during 7 days and after their storage both with magnetic vinyl, applied on a back surface, and without it. Values of  $\eta$  and  $\tau_n^{ef}$  obtained in the process presented in a Table 1.

As it obviously from a table,  $\eta$  of the investigated objects decreases with the lapse of time after processing in SMF of permanent magnets, however applying the magnetic vinyl on the back surface of SJ Si-SC changes a situation to a considerable degree. After storage of investigated objects on magnetic vinyl during three weeks their  $\eta$  decrease insignificantly, from 11.8-12.5 to 11.5-12.2 %, in a difference from samples without attached magnetic vinyl, for which  $\eta$  only for the first 7 days decrease up to 9.2-10.5 %. Following storage of SJ Si-SC in contact with magnetic vinyl in the course of 9 days was quite not conducted a change of  $\eta$ , achieved after analogical three-week storage. Thus, it is possible to conclude that application of magnetic vinyl allows to support initially increased by the stationary magnetic field value of  $\eta$  within the limits of 11.5-12.2 %, that considerably exceeds the initial values of this parameter, which were 10.3-11.1 %.

The finding out increase of SJ Si-SC efficiency from 10.3-11.1 % up to 11.8-12.5 % after processing of these devices in SMF with the subsequent stabilizing by magnetic vinyl at the level of 11.5-12.2 % well correlates with MCC lifetime change in p-type of conductivity Si-BC of SJ Si-SC from 34-40  $\mu$ s up to 50-54  $\mu$ s with the subsequent stabilizing by magnetic vinyl at the level of 48-52  $\mu$ s. It can be conditioned, for example, by following processes in the Si-BC crystal structure. As is known [12],  $V_{Si}-O_i$ ,  $O_i-Si-O_i$ ,  $V_{Si}-Si-V_{Si}$  complexes which presents in single-crystal silicon are effective recombination centers, that results to the reduction of MCC lifetime. It is shown in the mentioned work that under the action of pressure and temperature the ensemble of stated complexes is able to reconstruct in containing the  $SiO_2$  and

$SiO_xV_y$  complexes, being not recombination centers. Not excluded, that similar transformations taking place and in p- type of conductivity Si-BC of SJ Si-SC under the influence of SMF at  $B = 0.2$  T, because in [3] a noticeable accent is done on activating behavior of oxygen in silicon by magnetic field.

It is experimentally established that  $\eta$  of single-junction single-crystal silicon solar cells with a horizontal  $n^+-p-p^+$  diode structure can increase approximately in 1.1 time after their processing at room temperature during 7 days by the perpendicularly oriented stationary magnetic field with induction 0.2 T. It is explained by reduction of recombination centers quantity in such devices base crystals, on that point out the increase minority charge carriers lifetime in silicon under influence of stationary magnetic field. It is shown the possibility of achieved positive effect subsequent stabilizing due to attached to investigated type solar cells from the side of back electrode the thin layer of magnetic vinyl, creating in a base crystal the magnetic field with induction no more than 0.05 T. Using of magnetic vinyl in contact with investigated type devices enables economically advantageously applying in industrial scales the finding out effect of their  $\eta$  increase under influence of stationary magnetic field.

4. CONCLUSIONS

It has been experimentally established that the efficiency of single crystal silicon one-junction solar cells with horizontal  $n^+-p-p^+$  diode structure may increase approximately in 1.1 time after their treatment at room temperature during 7 days by perpendicularly oriented stationary magnetic field with 0.2 T induction.

This can be explained by decreasing the quantity of recombination centers in such devices base crystals, as it indicates the increase of minority charge carriers lifetime in silicon under stationary magnetic field influence.

It has been shown the possibility of achieved positive effect subsequent stabilization by attaching to investigated type solar cells rear electrode thin layer of magnetic vinyl, creating in base crystal magnetic field with induction not more than 0.05 T.

Using of magnetic vinyl in contact with the investigated type devices enables the possibility of cost-effective using an industrial scales the observed effect of increasing their efficiency under the influence of a stationary magnetic field.

**Table 1** – Efficiency ( $\eta$ ) and effective electrons lifetime  $\tau_n^{ef}$  in p-type of conductivity Si-BC before and after the processing SJ Si-SC in SMF at  $B = 0.2$  T

Parameters	Original state ( $B = 0$ )	After processing in SMF					
		Initial state ( $B = 0$ )	After storage				
			$B = 0$	In contact with magnetic vinyl ( $B = 0.05$ T)			
			7 days	7 days	14 days	21 days	30 days
$\eta, \%$	10.3-11.1	11.8-12.5	9.2-10.5	11.8-12.4	11.6-12.2	11.5-12.2	11.5-12.2
$\tau_n^{ef}, \mu$ s	34-40	50-56	25-33	50-54	48-52	48-52	48-52

## Застосування обробки в магнітному полі для низькозатратного підвищення ККД кремнієвих фотоелектричних перетворювачів

Р.В. Зайцев

*Національний технічний університет «Харківський політехнічний інститут»,  
вул. Фрунзе, 21, 61002 Харків, Україна*

Експериментально встановлено, що ККД одноперехідних (ОП) монокристалічних кремнієвих фотоелектричних перетворювачів (Si-ФЕП) із горизонтальною діодною  $n^+p-p^+$  структурою може зростати приблизно у 1,1 рази після їх обробки при кімнатній температурі на протязі 7 діб перпендикулярно орієнтованим стаціонарним магнітним полем (СМП) з індукцією 0,2 Тл. Це пояснюється зниженням числа рекомбінаційних центрів у базових кристалах ОП Si-ФЕП, на що вказує збільшення часу життя неосновних носіїв заряду у кремнії під впливом СМП. Показано можливість наступної стабілізації досягнутого позитивного ефекту за рахунок пристикування до ОП Si-ФЕП з боку тилового електроду тонкого шару магнітного вінілу, що створює у базовому кристалі магнітне поле з індукцією не більше 0,05 Тл.

**Ключові слова:** Монокристалічний кремнієвий фотоелектричний перетворювач, Магнітне поле, Магнітний вініл.

## Применение обработки в магнитном поле для низькозатратного повышения КПД кремниевых фотоэлектрических преобразователей

Р.В. Зайцев

*Національний технічний університет «Харківський політехнічний інститут»,  
вул. Фрунзе, 21, 61002 Харків, Україна*

Експериментально встановлено, що КПД одноперехідних (ОП) монокристалічних кремнієвих фотоелектричних преобразователей (Si-ФЭП) с горизонтальной диодной  $n^+p-p^+$  структурой может возрасти примерно в 1,1 раза после их обработки при комнатной температуре в течение 7 суток перпендикулярно ориентированным стационарным магнитным полем (СМП) с индукцией 0,2 Тл. Это объясняется снижением числа рекомбинационных центров в базовых кристаллах ОП Si-ФЭП, на что указывает увеличение времени жизни неосновных носителей заряда в кремнии под влиянием СМП. Показана возможность последующей стабилизации достигнутого положительного эффекта за счет пристыковки к ОП Si-ФЭП со стороны тыльного электрода тонкого слоя магнитного винила, создающего в базовом кристалле магнитное поле с индукцией не более 0,05 Тл.

**Ключевые слова:** Монокристаллический кремниевый фотоэлектрический преобразователь, Магнитное поле, Магнитный винил.

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