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Research Article

On The Flexophotovoltaic Effect In Semiconductor P-N-Structures

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Abstract: In this work, the first experimentally discovered effect of flexophotovoltaics (FPV) in silicon p-n-structures under the influence of local mechanical stress on the frontal surface is theoretically substantiated.. The regularities of the manifestation of the FPV effect are determined depending on the magnitude of the local pressure force and the intensity of photoexcitation.. Statistical processing of the experimental data by the least squares method was carried out and a new empirical formula was obtained for the experimentally determined dependence of the short circuit photocurrent of a silicon structure on the local mechanical stress.

Keywords: Silicon, pn-junction, flexophotovoltaics, deformation, mechanical stress, crystal, band gap.

INTRODUCTION

The authors of [1] proposed a new way to increase the efficiency of photoelectric conversion (PC) due to the local pressure of semiconductor crystals when they are illuminated with optical light of a certain wavelength. The application of local pressure to a crystal leads to the appearance of a mechanical stress gradient in it and, therefore, the flexophotovoltaic (PVV) effect is observed. Based on the crystallographic representation of semiconductor materials, it can be assumed that the FPV effect can be observed in all types of semiconductors, including silicon.. However, the physical nature of the FPV is practically not studied.. In order to recommend the FPV effect to improve the efficiency of any electronic device, in particular, the FP, we must present the process of charge transfer in the considered structure. On the other hand, according to the physics of well-known semiconductor devices, we know that if a **p-n**-junction is formed in the volume of a semiconductor, then the sensitivity to external influences of such a (diode) structure is much increased in comparison with a structure without a **p-n**-junction (resistor) [2]. Therefore, it is of important physical and practical interest - a purposeful study of local mechanical stress on the process of photoelectric conversion in silicon structures with **p-n**-transition to which this work is devoted.

In an n-type semiconductor, when an electric field with an intensity **E** is applied, the main charge carriers (ChC) - electrons with a charge **q** and a mobility μe get an ordered motion with a speed $\mathbf{v_e}$. For such an electric current and other basic physical parameters, the following well-known expressions can be taken:

$$I = -qn_e v_e S; \quad v_e = \mu_e E; \quad E = -\operatorname{grad}(\varphi), \tag{1}$$

there φ – is the height of the potential barrier of the pn junction and S – FP area.

In the case of considering the electron flow in only one direction with a length l and an intensity $E = -\Delta U / l$, one can obtain an expression for the [3]:

$$I = -qn_e v_e S\,(\Delta U/l) \tag{2}$$

According to the theory of the phase transition with a **p-n** junction, the current is determined by the expression:

$$I = I_0\,[e^{(Ue/kT)}-1] \tag{3}$$

Taking into account expression (2) and the fact that the dark current I_0 is determined by the sum of the diffusion current of electrons and holes through the **p-n** junction, we obtain:

$$I = S\,qn_i^2\,[(D_p/L_pN_d)+(D_n/L_nN_a)] \times [e^{(Ue/kT)}-1]\,, \tag{4}$$

there n_i - concentration of electrons in its own semiconductor, D_p - hole diffusion coefficient, L_p - hole diffusion length, N_d - concentration of donors in the emitter, D_n - electron diffusion coefficient L_n - electron diffusion length, N_a - concentration of acceptors in the base, U - barrier height, k - Boltzmann coefficient, T - absolute temperature.

In a more generalized form, one can imagine that

$$I = (\beta/L)\,f(U)\,, \tag{5}$$

where a certain form for the coefficient β can be chosen from expressions (2) or (4).

Acceptance of the concept makes it possible to assume that if the I - V characteristic of a semiconductor PC obeys expression (5), then for any diode without bias the condition: U → 0 and f(U) → 0; for lighted ФП: U → 0 and f(U) → 1 .

Now consider the crystal lattice of semiconductor silicon. For the force of attraction between neighboring atoms, one can choose the well-known expression [4]:

$$F = Akq^2/r^2\,, \tag{6}$$

there A – proportionality coefficient depending on the type of interatomic bond, r – interatomic distance.
If the supplied external force F_k causes a change in the interatomic distance and the conditions:

$$r \sim L,\ r = \gamma\ L,\ dr = \gamma dL\ , \qquad (7)$$

there γ – aspect ratio.
then it can be imagined that an external force causes a change in the initial force of interatomic attraction ($F + \Delta F$)due to a change in the interatomic distance ($r+\Delta r$):

$$F + \Delta F = Akq^2/(r+\Delta r)^2 \qquad (8)$$

From this you can get:

$$\Delta F = Akq^2\ [\Delta r(2r-\Delta r)/(r-\Delta r)^2 r^2] \qquad (9)$$

Now we will try to estimate how a small change in the force of attraction F affects the change in the interatomic distance r. Let's do some mathematical transformations:

$$\Delta F/\Delta r = Akq^2\ [(2r-\Delta r)/(r-\Delta r)^2 r^2]$$

$$dF/dr = \lim_{\Delta r\to 0} (\Delta F/\Delta r) = -\ Akq^2\ (2/r^3)$$

and we get:

$$dF = -\ Akq^2\ (2/r^3)\ dr \qquad (10)$$

Considering (7) we can get:

$$dL = -\ (\gamma^2 L^3/2Akq^2)\ dF\ . \qquad (11)$$

Now, in order to determine the dependence of the current on the diffusion length of the ChC, we differentiate (5):

$$dI = -\ (\beta\gamma^2 L/2Akq^2)\ f(U)\ dF\ , \qquad (12)$$

From here we find:

$$L = (Akq^2)^{1/2}/\gamma F\ \ f(U)\ \ , \qquad (13)$$

$$dI = [\beta\gamma/2(Akq^2)^{1/2}]\ f(U)\ dF/F^{1/2}\ \ , \qquad (14)$$

For current short circuit FP you can get the expression:

$$dI_{\text{к.з.}} = [\beta\gamma/2(Akq^2)^{1/2}]\ dF/F^{1/2}\ \ , \qquad (15)$$

Integrating (15) and taking into account $F=F_k+F_0$, we obtain:

$$I_{\text{к.з.}} = I_{\text{к.з.0}} +\ [\beta\gamma/(Akq^2)^{1/2}]\times [(F_k+F_0)^{1/2} - F_0^{1/2}]\ \ , \qquad (16)$$

there F_0 – interatomic force of attraction without external force.

An experimental study was carried out using a special device (block 3, Fig. 1), which, by means of a vertical needle with a sharp end of ≈50 μm, fixed at one end of an elastic thin rod, allowed local pressure on the frontal surface (n-type) of silicon FP 1 s diffusion **p-n-**junction with a depth of 0.5 microns. The thickness of the p-type silicon base was ≈170 μm.

The value of mechanical pressure in block 3 varied in the range from zero to 1 N with an increase in the gravity of the load. The effect of mechanical pressure on the structure under study was assessed by measuring the I - V characteristic of an illuminated photovoltaic system using a 4 FP system using a laboratory measuring complex 2 with a digital display of the readings of the measured photoelectric parameters.

The obtained experimental results are shown in Fig. 2 in the form (curve 2) of the I_{sc}. = f (F_k). As can be seen from the graph (Fig. 2), with an increase in the magnitude of the external force exerting local pressure on the silicon surface, the value of the photocurrent short circuit. The choice of the upper limit for the increase in the external force is due to the fact that higher values exceed the critical value of the mechanical strength of the silicon wafer and cause failure of the structure.

The additional experiments carried out indicated a significant role of the dislocation of the point of local action relative to the frontal electrode strips.. Moreover, a stronger change in the values of the photocurrent sh.c. is clearly manifested. at points closer to the contact than distant. It was also found that the increase in the values of the photocurrent sh.c. at higher light levels becomes more significant than at low light (Fig. 3).

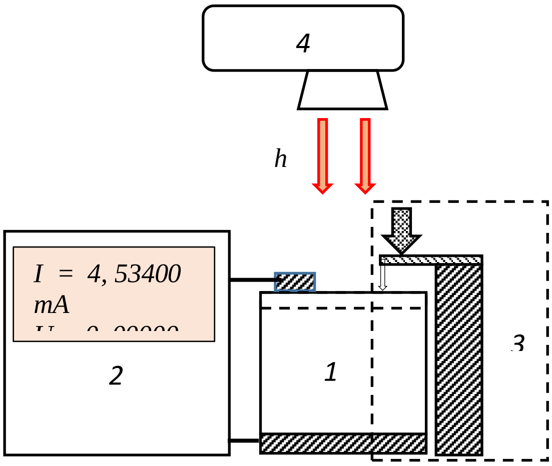

Figure: 1. Block diagram of an experimental device for measuring the dependence of the photocurrent sh.c. silicon **p-n** -structure on the value of local mechanical stress on the frontal surface

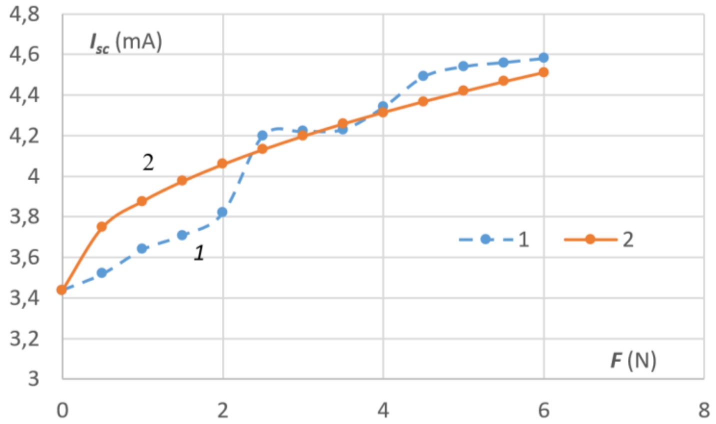

Figure: 2. Dependence of the photocurrent sh.c. silicon **p-n** -structure on the value of local mechanical stress on the frontal surface: 1 - experiment, 2 - calculations

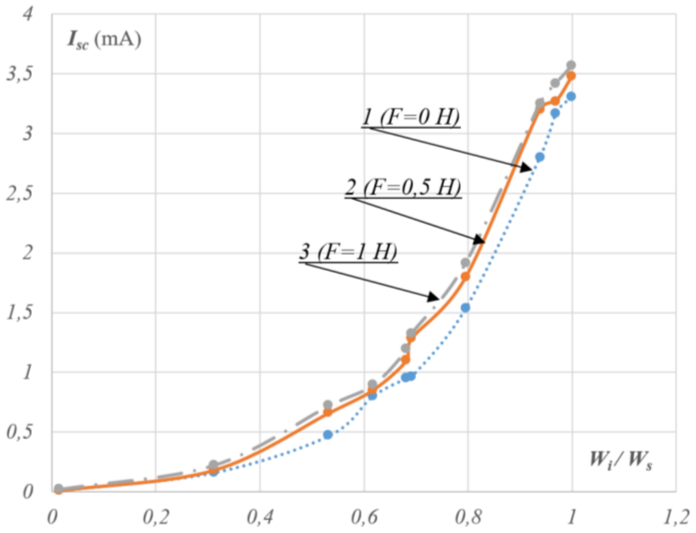

Figure: 3. Dependence of the photocurrent sh.c. silicon **p-n**-structure on the relative increase in illumination at different values of local mechanical stress on the frontal surface

According to Fig. 3, it can be noted that the dependence of the photocurrent sh.c. silicon **p-n**-structure from the relative increase in illumination at different values of the local mechanical stress on the frontal surface there is a significant increase in the increase in the photocurrent sh.c. with an increase in the force of mechanical pressure in the illumination range from zero to 0.8 times solar radiation. With an increase in the pressure force on the local point from zero to 1 N, a gradual increase in the photocurrent is observed due to the flexophotovoltaic effect. Moreover, the increase in the photocurrent sh.c. more significantly in the pressure force range of 0-0.5 N, with more than 0.5 N the gain weakens. On the investigated samples, the upper limit of gravity was no more than 1 N. Exceeding this limit was accompanied by a breakdown of the structure, which is associated with the excess of the mechanical strength of the plate of the studied thickness.

Based on the insignificance of the F_0 values (in the order of 10-9 N), it can be assumed that F_k » F_0.. Therefore, taking into account $\beta\gamma/(Akq^2)^{1/2} = \alpha$, expression (16) can be simplified:

$$I_{\text{к.з.}} = I_{\text{к.з.0}} + \alpha F_k^{1/2}, \qquad (17)$$

where photocurrent sh.c.. in the absence of mechanical stress is expressed as:

$$I_{\text{к.з.0}} = Sqn_i^2[D_p/(L_pN_d) + D_n/(L_nN_a)] .$$

The obtained simplified formula (17) is of practical interest for analyzing the experimental dependences of the photocurrent sh.c. semiconductor FP on the magnitude of the applied external force.

For experimental graphic $I_{\text{sh.c.}} = f(F_k)$ dependence (Fig. 1) corresponded to expression (17). Statistical processing of the experimental data by the least squares method made it possible to determine the values of the proportionality coefficient of expression (17): α = 0,8114.

We believe that the results presented in [5] on an increase in the lifetime, therefore, the diffusion length of charge carriers in silicon wafers after mechanical treatment of ultrasonic frequency, can confirm the hypothesis of the theoretical mechanism of the studied flexophotovoltaic effect.

CONCLUSION

We consider it expedient to finalize and introduce into production a method for increasing the conversion efficiency of silicon PCs by **p-n**-junction. This requires the development of new designs of FPs, allowing them to locally deform their frontal surface.. It seems that as the base thickness of silicon PCs decreases over the next several years, a higher photoelectric sensitivity to local deformation can be observed..

It can also be noted that the presented results can serve as a basis for the creation of mechanical pressure sensors or photodetectors sensitive to mechanical influences based on fairly widespread crystalline silicon..

In conclusion, we note that a theoretical substantiation of the flexophotovoltaic effect discovered by the authors for the first time in silicon **p-n**-structures has been carried out.. The regularities of the manifestation of the flexophotovoltaic effect depending on the local mechanical stress are established, a new empirical formula is obtained for the experimentally determined dependence of the short-circuit photocurrent of a silicon structure on the local mechanical stress.

The predominant correlation between the theoretically proposed regularity and experimental data has been established..

The research results also serve to develop new types of flexophotovoltaic photodetectors..

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