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THE MECHANISM OF HOLE TRANSPORT IN PHOTOCELLS BASED ON a-Si: H.

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A B S T R A C T

Investigate the hole transfer mechanism in a-Si:H films using photovoltage characteristics (photo-CVCH) of a vidicon target.
Theoretically obtained, if the concentration of photogenerated injected holes exceeds the concentration of defective states, then in the a-Si: H mobility gap in photo-CVCH, a portion is observed that obeys the quadratic law ($I \sim U^2$).
It was explained that in order to obtain reliable information from this section on the hole transport mechanism, it is necessary to take into account changes in the a-Si: H dielectric constant and hole lifetime depending on the applied voltage.

K E Y W O R D S

Amorphous hydrogenated silicon, vidicon target, hole trap, energy positions of traps, mobility gap, sticking centers.

Introduction

At present, the quality and efficiency of photovoltaic devices, including solar cells based on amorphous hydrogenated a-Si: H silicon, cannot adequately satisfy the requirements imposed on semiconductor photovoltaic cells. The efficiency of solar cells based on a-Si:H under standard conditions (AM spectrum 1.5-1000 W/m^2) reached 8-10% [1,2], and tandem structures calculations show what can be achieved up to 12-15% or more [3,4].

There are a number of papers that are devoted to the study of the photoelectric parameters of a-Si:H films and solar cells based on it [1-6], and these works revealed that the photoelectric parameters directly depend on the density of states in the mobility gap and carrier transport [5.6]. It is also known that in solar cells the photocurrent consists of two components, that is, electron and hole. The difference in the mobility of these components is very significant ($\mu_e = 13\ cm^2 / V \cdot s$ and $\mu_n = 0.67\ cm^2 / V \cdot s$). This means that the fraction of the hole photocurrent in the photocurrent is insignificant. Therefore, in many studies, to study the transfer mechanism, the dependences of the electron and hole photoconductivity of a-Si: H and a-Si: H (B) on samples were investigated, and it was found that in qualitative samples of a-Si: H the photoconductivity of electrons depends on temperature, and in a-Si: H samples lightly doped with boron, the photoconductivity of holes depended on the temperature at which photoconductivity was measured in planar samples [6–7].

Such measurements do not allow one to obtain monopolar photoconductivity, and in turn it is impossible to obtain the interaction of current carriers with the density of states in the mobility gap separately. To analyze the characteristics of solar cells and find ways to further improve the efficiency of their photoconversion requires a detailed study of the proportion of each type of current carrier and establish their transfer mechanism. This paper is devoted to a theoretical study of the current-voltage characteristics (CVCH) of a hole photocurrent and the possibility of obtaining information from individual sections of the photo – IV characteristic on the hole transfer mechanism is shown.

Analysis and calculation of the photo-CVCH of the Vidicon target. To study the mechanism of hole transport in a photocurrent of structures based on a-Si: H, one must have a unipolar photocurrent in which only photogenerated holes are current carriers. We will consider the structure p-i-n that is the structure of the target of the vidicon (Fig. 1.a.), in which all layers consist of a-Si: H.

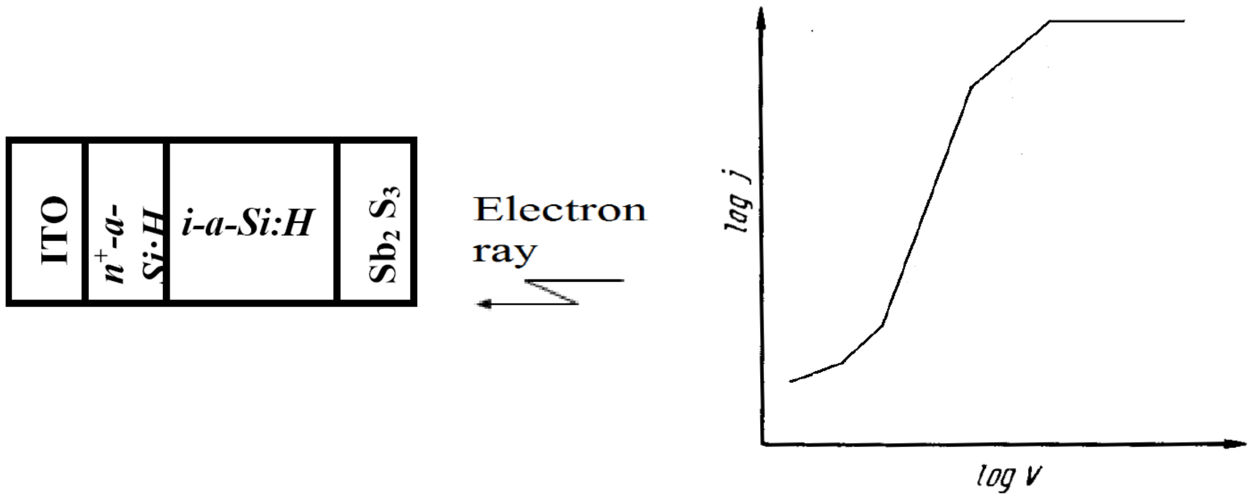


Fig.1. Structure of Vidicon target (a) and ideal photo-CVCH of Vidicon Target(b)

If illumination is made from the side of the n layer with light of a wavelength $\lambda \sim 400$ nm, then light is absorbed at the surface of the i - layer and a "reservoir" of carriers or a hole-rich layer forms in this part of the i - layer. When reverse voltage is applied, only holes are current carriers. Such a phenomenon was discovered during measurements of photoconductivity by the Vidicon method [7–8].

From the results of studies of the photovolt-ampere characteristic of such structures, it is known that the photo-CVCH consists of several sections [7–8].

This behavior of the photo-CVCH can be explained as follows: suppose that at low temperatures the entire volume charge is formed by photogenerated mobile holes in the valence band, then the transfer phenomena can be represented as follows. Hole traps create deep energy levels, so that the reverse thermal emission of holes can be neglected, and the traps are evenly distributed throughout the volume. The concentration of traps is much higher than the concentration of equilibrium holes in the i-layer, this confirms the low value of the dark current.Then, at low voltages, almost all injected photogenerated holes are trapped by traps, so the concentration of holes in the depth of the i-layer will not increase. This position corresponds to the ohmic section on the photo-CVCH obtained at low temperatures. With increasing voltage, all traps are filled with injected holes and the hole concentration begins to grow.

At some voltages, the concentration of injected holes is much higher than the concentration of deep traps. This will occur if the concentration of photogenerated holes is greater than the concentration of traps. If these conditions are met, then for this case we have the following equations:

For current density:

$$j = ep\mu_p E + D\nabla p \tag{1}$$

For the distribution of the electric field in the region of i-a-Si:H, we have the Poisson equations

$$\frac{\partial E}{\partial x} = \frac{4\pi e}{\varepsilon}(p + N(f-1)) \tag{2}$$

and equation for recharge kinetics

$$N\frac{\partial f}{\partial t} = \frac{\Delta p}{\tau_p} - (f-1)\frac{\Delta N}{\tau_n} - g \tag{3}$$

Here, N is the concentration of hole traps in the mobility gap, p is the concentration of injected photogenerated holes, τp is their lifetime, μp is hole mobility, g is the rate of thermal generation of the main carriers of i-regions, f is the fill factor of hole traps, and this is the value for thermodynamic equilibrium is defined by the following expression:

$$f = \frac{1}{1 + \frac{N_d}{G\tau}}$$

Here is the G-speed of photogeneration.

To solve these equations, we will evaluate some terms in these equations. Because of the smallness of the diffusion coefficient, the second terms of (1) are neglected. Due to the dependence of the dark current on the voltage [7-8], it can be seen that the thermal generation g is insignificant, therefore we will not take it into account. The values of ΔN, Δp, ε and f depend on the applied voltage. As the voltage increases, the number of injected holes in the i-layer greatly increases and all traps become filled, as mentioned above, then the fill factor f = 1, if there is a thermodynamic equilibrium between the traps and the injected holes. Then the following condition is satisfied:

$$\frac{\partial f}{\partial t} = 0 \qquad \text{and} \qquad p >> N$$

Given the above conditions from equation (3) we have $\frac{\Delta p}{\tau_p} = 0 \Rightarrow \Delta p = 0$ or then $p = const$ (1) and (2) the equation takes the following form:

$$j = ep\mu_p E \quad (4)$$

$$\frac{\partial E}{\partial x} = \frac{4\pi e}{\varepsilon} \cdot p \quad (5)$$

Solving together (4) and (5) the equation we have the following expression of the relationship between E and j

$$\frac{\mu_p \varepsilon E}{4\pi} \partial E = j \partial x$$

To integrate this expression it is necessary to estimate the lower bounds of the integral. As you know, in the vidicon mode, the incident light is absorbed when the surface of the i-layer reaches a depth of x0. This thickness, in which holes are photogenerated, can be called a “virtual” cathode. With increasing external voltage, this section expands, but at lower voltages, we can assume x << L, L- thickness of the i -layer, so we will integrate from 0 till L. Given the above conditions, we get the relationship between the current applied voltage.

$$j = \frac{\mu_n \varepsilon}{8\pi} \cdot \frac{U^2}{L^3} \quad (6)$$

Thus, we obtained the quadratic Mott law.

As can be seen from (6), the value of the photocurrent depends only on the parameters of the hole. Therefore, information can be obtained on the hole transport mechanism. To show the validity and applicability of this expression for the photo-CVCH of the Vidicon target, let us analyze the experimentally obtained graphs and carry out a numerical calculation. Photo-CVCH were obtained in [8–9] at various thicknesses and temperatures (Fig. 2).

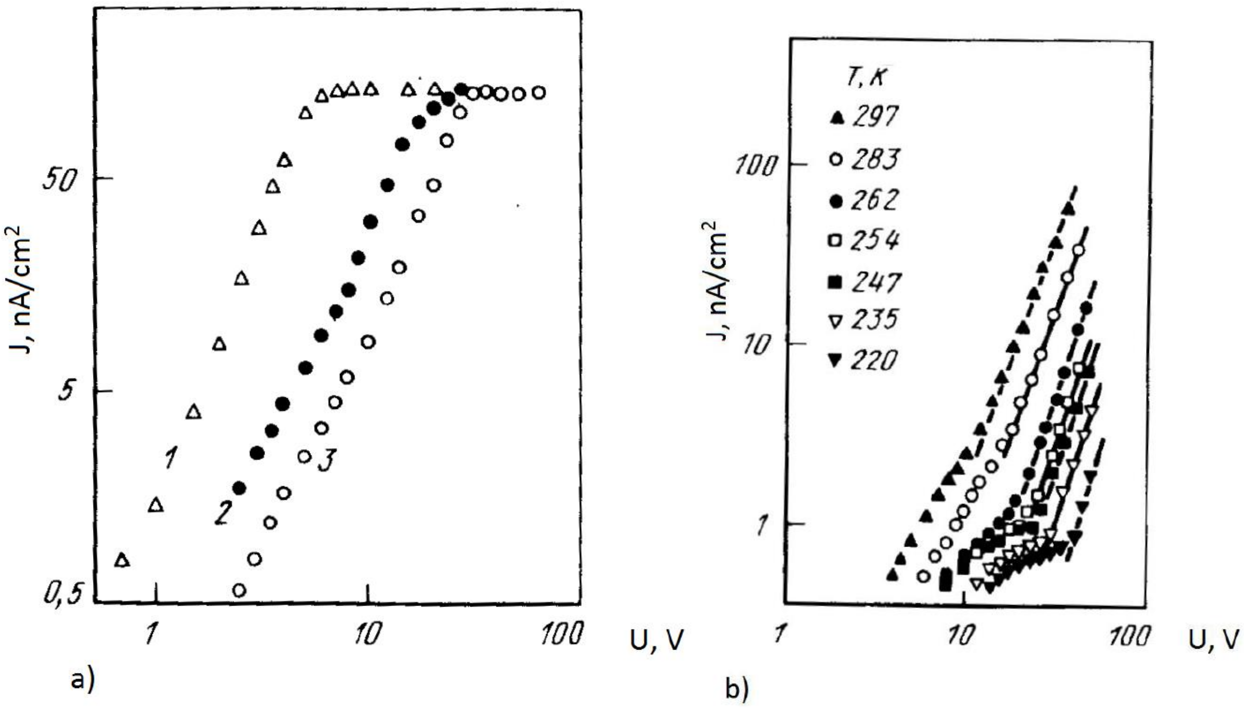


Fig.2. a). Photo-CVCH of triple a-Si:H targets based on a-Si:H with various thicknesses. b). Photo-CVCH obtained at different temperatures.

As can be seen, depending on the thickness and temperature, the portion of the photo-CVCH, which obeys the “quadratic” law, is almost parallel to the high-voltage region. This behavior of the photo-CVCH for samples with different thicknesses satisfies (6) the equation. The photoelectric parameters of holes depend on temperature, therefore, from this section of the photo-CVCH, one can obtain the temperature dependence of the photoelectric parameters of holes. And this case requires additional research.

To carry out a numerical calculation, we first calculate the concentration of photogenerated holes, we have .

To determine the rate of photogeneration of holes, we used the following expressions [4].

$$G_p^{(s)} = G_{p.0}^{p(s)}(\lambda)[\exp(-\alpha_i(\lambda)x) + R_{ip}^{p(s)}(\lambda)\exp[-2\alpha_i(\lambda)d_0]\exp(\alpha_i(\lambda)x)]$$

Where d0 = dn + di, dn and di are the thickness of n and i-layer, respectively, Rip is the reflection coefficient of the border surface i and p layer.

$$G_{p.0}(\lambda) = \frac{(1-m)\alpha_i(\lambda)I_0^{p(s)}(\lambda)T_{ni}^{p(s)}(\lambda)}{1 - R_{31}(\lambda)R_{pi}(\lambda)\exp(-2\alpha_i(\lambda)d_0)}$$

Where is the spectral density of the incident light, αi(λ) is the incident light coefficient in the i-a-Si:H layer, Tni- the transmittance of the n - layer in the i-layer, p and s -indices of polarization to get the photo-CVCH section of the subordinate " square law " is used the following values and estimates of some parameters i-a-Si:H.

When measuring the photoconductivity of a target of a vidicon, the light falls off normally and is completely absorbed in the i - layer; moreover, the thickness of the n-layer is slightly relative to the i-layer. Then Rpi = 0,

$$T = \frac{n_{in}}{(n_{ni} + 1)^2}$$

Where nin is the relative refractive index. If we take into account that the n and i layer consists only of a-Si: H, then nin ≈ nni = 1 and T = 1. The values of the defect absorption coefficient α (λ) ~ 1–10 cm – 1, hole mobility μp = 0.67 cm2 / (V · s), m = 34 ÷ 35, and di≈1 μm. When light is absorbed in the surface i-layer, the carrier "reservoir", that is, the holes, appears as above and a potential difference appears between the part of the i-layer that absorbs and does not absorb light. Photogenerated holes must overcome this potential barrier. The height of the potential barrier depends on the energy width of the density distribution of the state of defects near the Fermi level.As is known, the density of the state of defects near the Fermi level is several orders of magnitude lower than the density of the state in the rest of the mobility gap. Therefore, when the incident light is absorbed at these levels, all the electrons in these states go into the conduction band and due to this, the Fermi level shifts down. The distribution of these states obeys the Gaussian law [10].

$$N(E) = (2\pi\sigma^2)^{-\frac{1}{2}} \exp\left(-\frac{(E - E_0)^2}{2\sigma^2}\right)$$

Here, the E0 is the peak of the density of the state of the Gaussian distribution, the σ-energy width of this distribution. Given the above data, we can assume that the height of the potential barrier is comparable to that value.

When the Δφ = U condition is satisfied, all photogenerated holes without an obstacle are injected into the entire i-layer. And then two conditions p >> N and p = const are fulfilled, therefore a section that obeys a quadratic law begins with this voltage.

If the total concentration of photogenerated holes is less than the concentration of defects, that is, p <N, the portion that obeys the "quadratic law" is not observed. This is evidenced by the obtained photo-CVCH with low illumination or samples with a large concentration of defects [7,11]. Thus, we will be able to determine the voltage in which the "quadratic" segment begins. Since hole-traps in lightly doped a-Si:H samples are the main trapping centers for non-equilibrium holes [7]. In this case, the hole lifetime τp is determined by the concentration of hole traps Nd

$$\tau_p = \left(C_p^0 \cdot N^0\right)^{-1}$$

Here,   is the hole capture coefficient. With the injection of holes with a greater concentration, that is, p> N0, gradually with increasing stresses, hole traps capture more and more holes. This leads to recharging of these traps, with the result that the concentration of hole traps decreases. Accordingly, the hole lifetime increases and, as a result, an additional increase in the photocurrent should occur.
At high voltages, the entire i-layer is filled with injected holes with a practically constant concentration p on volume, which means that the photocurrent does not obey the square law.
This voltage can be estimated by equation the hole transfer time to the thickness of the i-layer with the Maxwell relaxation time, the ohmic section or saturation current begins with this voltage. Comparing the hole transfer time with the Maxwell relaxation time, we can estimate the voltage at which the quadratic segment ends.
Discussion of the obtained results and their comparison by experiments.
Formula (6) shows that the photocurrent as a whole depends on the voltage. In addition, it is possible that the a-Si:H dielectric constant and other hole parameters depend on the distribution of injected holes. As we know, the concentration of the distribution of injected holes also depends on the applied external voltage. As a result, there is an additional dependence on the voltage of the current.
To compare the theory with the experimental data, we use the results of   [7, 11], in which a-Si:H samples with different parameters and under different illumination by the vidicon method were studied.
In [11], measurements were performed on samples of two types: Type I samples differed from Type II samples by a higher defect concentration ND, which creates deep levels. The obtained experimental data confirm our assumptions that if the concentration of photogenerated holes is less than the concentration of hole traps in the photo-CVCH, the region that obeys the quadratic law is not observed (Fig. 3).

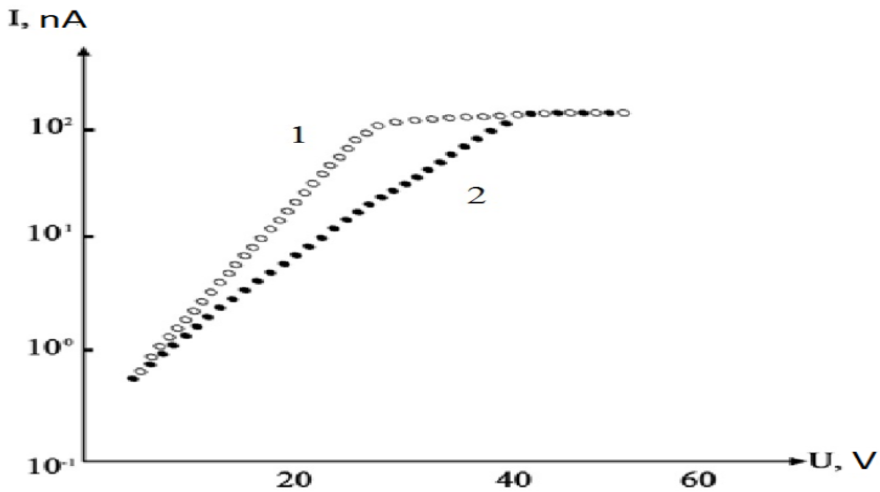
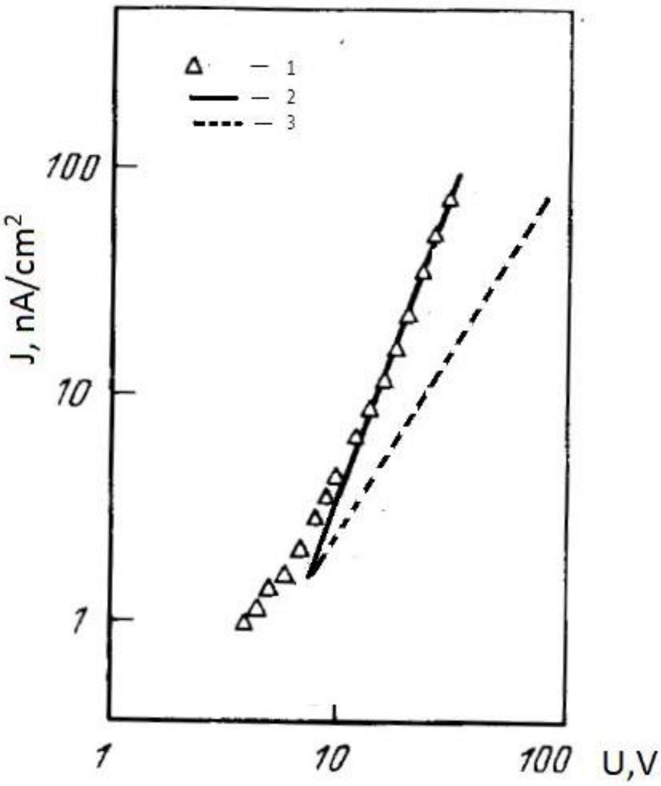


Fig. 3. Photo-current-voltage characteristics of vidicon targets based on: 1-boron doped sample, 2-undoped sample.

In [7], the measurement was performed on a sample of the same type, but with different lighting powers. As can be seen with a decrease in the power of illumination, the number of photogenerated holes decreases, when the concentration of photogenerated holes descends below the p = ND boundary, a quadratic segment is not observed. This is also an additional proof of our assumption.
From the experimental plots obtained in [7, 11], it can be seen that prior to the beginning of the quadratic segment, the other dependences of the photocurrent on the applied voltage were no longer

observed. That is, when a voltage is applied, a section begins that obeys a quadratic law. This behavior of the photo-CVCH can be explained by the low concentration of defects in the mobility gap. In works [7], a-Si:H samples were studied using the vidicon method at different temperatures [Fig. 2b]. From the graph it is possible to distinguish different parts of the photocurrent depending on the temperature. The calculated data of the photo-CVCH of a vidicon target by the formula (6) using the dependence of some photoelectric parameters on the applied voltage and without it are shown in Fig.4.



Voltage of target, V

Fig.4. Experimental (1) and calculated (2,3) photo- CV characteristics of a vidicon target. (2) - taking into account the change in ε and τ from the applied voltage, (3) - obtained without taking into account changes in ε and τ

As can be seen, if we take into account the above-mentioned dependences, then the calculated photo-CV characteristics agree well with the experimental data.

The decrease in the photocurrent at low temperatures can be explained as follows: a decrease in temperature reduces the probability of thermal release of holes from the states of traps into the valence band. In addition, the potential barrier size also depends on temperature, therefore, the behavior of the photo-CVCH at low temperatures requires additional study.

Conclusion.

Based on the above, it can be concluded that in the quadratic part of the photo-CVCH of the a-Si:H-based vidicon target, the photocurrent not only depends on the applied voltage directly, but it is necessary to take into account changes in the dielectric constant of the i-a-Si:H layer, the lifetime holes τ from the applied voltage. Thus, it is impossible to obtain reliable information about the hole mobility from (6) equations. To determine the hole mobility, it is necessary to take into account changes in the dielectric constant of the sample under the influence of an external voltage.

As mentioned above, with a change in the distribution of injected holes, the lifetime increases and, in turn, hole transport decreases. Therefore, these changes are also appropriate to consider.

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