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Influence of the crystal substrate parameters on the maximum power of silicon heterojunction solar cells

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The effect of the donor impurity concentration and the lifetime of charge carriers in a crystalline silicon substrate on the maximum power of heterojunction thin-film solar cells is studied. The model used in the calculations takes into account the features of photocurrent generation under conditions of medium or high levels of injection of charge carriers at an arbitrary ratio between the diffusion length and the thickness of the semiconductor wafer. The proposed technique makes it possible, with sufficient accuracy for practical purposes, to calculate the permissible variation limits of the substrate parameters, which ensure the specified values of the performance characteristics of photoelectric converters.

Keywords: heterojunction solar cells, crystalline silicon substrates, optimal parameters, maximum power.

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The intensive development of solar energy dictates the need for continuous improvement of photovoltaic transducers' designs. One of the most promising technological solutions for the production of solar cells is the use of heterojunction thin-film structures with crystalline silicon substrates. The efficiency of the best samples of such photovoltaic cells reaches 26.7% [1].

For the production of highly efficient heterojunction thin-film solar cells —HIT-elements (HIT — heterojunction with intrinsic thin-layer solar cells) — crystal substrates of c-Sin-type are usually used. Such a parameter as the initial (equilibrium) volumetric lifetime of free charge carriers τ_0 is an indicator of the quality of the plate $(n)c$-Si. In substrates of modern HIT elements τ_0 ranges from $1.5-8.0$ ms at a concentration of donors $N_d \geqslant 10^{15}$ cm^{-3}. The thickness of the substrate d can vary between $90-170\,\mu$m. It has been experimentally established that the value of this parameter has little effect on the performance characteristics of HIT elements [2,3]: when reducing d by 40%, the output power loss does not exceed 5%. Currently, in the production of photovoltaic transducers of this type, as a rule, substrates with a thickness of $150-170\,\mu$m are used. Films of hydrogenated amorphous silicon α-Si : Hp- and n-type with a thickness of $15-20$ nm grown on top of thin (~ 5 nm) buffer layers with intrinsic conductivity $(i)\alpha$-Si : H, form heterojunctions on the surfaces of the plate $(n)c$-Si. Modern passivation technologies make it possible to effectively suppress surface recombination processes by introducing buffer layers [4]. In high-quality samples of HIT-elcops, the record no-load voltages are more than 0.74 V [5]. Such high rates were achieved, among other things, due to a significant reduction in the total rate of surface recombination (up to tenths of cm/s), so that the resulting losses were close to the levels of recombination processes in the substrate volume [4,6]. The successes of modern technologies in the processing of crystalline silicon surfaces have made it urgent to study in more detail the possibility of improving the performance characteristics of HIT elements due to the optimal choice of τ_0 and N_d.

The purpose of this work is a theoretical study of the correlation between the maximum power of HIT elements and the volume parameters of $(n)c$-Si plates.

The method of optimizing the structure of HIT elements proposed in [7] is based on the analysis of recombination processes [8] and does not take into account the diffusion transfer of charges inside the substrate. The model described in [6] has no such drawback, since it considers the combined effect of recombination and ambipolar diffusion of charge carriers on the distribution of their concentrations in a substrate with arbitrary parameters. In this case, the short-circuit current density J_{sc} is used as an arbitrarily set parameter. The method not only makes it possible to simulate processes in HIT elements at different levels of recombination losses in the volume and on the surfaces of silicon wafers, but also makes it possible to consider separately volumetric and surface factors affecting the type of volt-ampere characteristics.

In order to solve this problem, an idealized semiconductor structure without surface recombination is considered in this paper. Calculations were carried out on the basis of theoretical dependences obtained in the approximation of the absence of bending of the energy zones of the substrate from the side of the n^+-n-contact (Fig. 1) [6]:

$$J = -J_{sc} + q\Delta p\sqrt{\frac{D}{\tau}}\tanh\left(\frac{d}{\sqrt{D\tau}}\right), \tag{1}$$

$$U = \frac{kT}{q}\ln\left\{\frac{\Delta p(\Delta p + N_d)}{n_i^2(T)}\right\}. \tag{2}$$

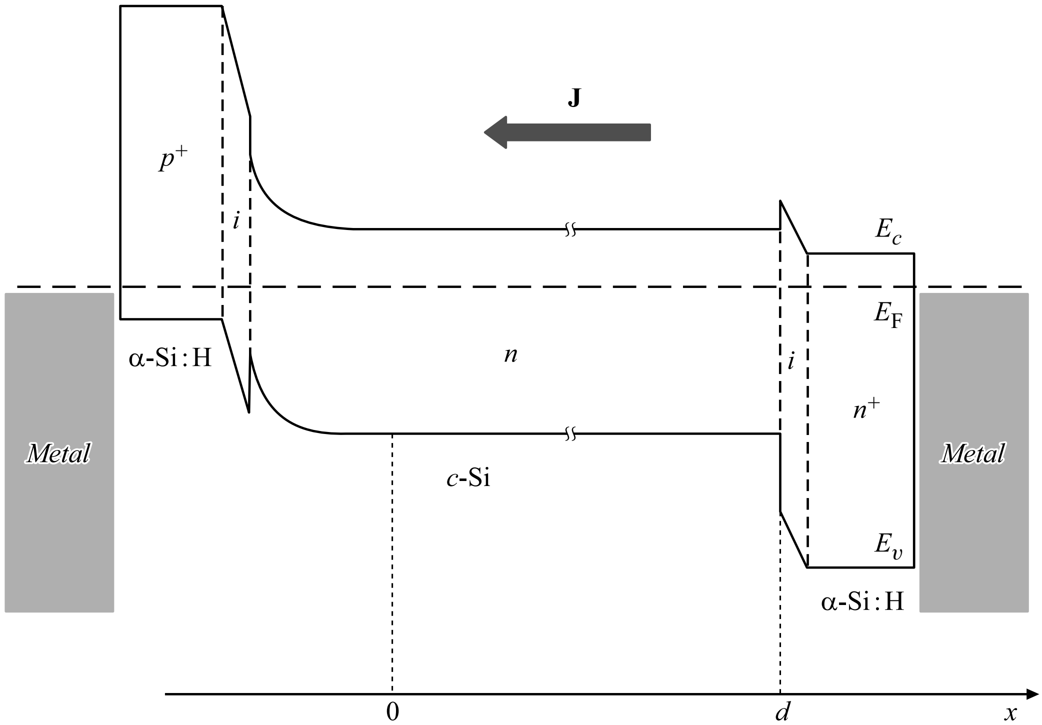

Figure 1. A model of the band diagram of the crystal substrate of the HIT element. E_c, E_v — energy levels of the bottom of the conduction band and the ceiling of the valence band; E_F — Fermi energy level.

Here $J < 0$ — projection on the x axis of the current density vector $\mathbf{J}$; U — the magnitude of the forward displacement p^+-n-heterojunction; Δp — the concentration of excess charge carriers on the right boundary of the spatial charge region p^+-n-heterojunction; T — temperature equal to 300 K;

$$D = D_p \frac{2b\Delta p + bN_d}{\Delta p(b+1) + bN_d} \tag{3}$$

— ambipolar diffusion coefficient [9]; D_p — hole diffusion coefficient; $b = 2.8$ — ratio of diffusion coefficients of electrons and holes in c-Si at $T = 300$ K;

$$\tau = \left[\tau_0^{-1} + \tau_{Auger}^{-1}\right]^{-1} \tag{4}$$

— the resulting volumetric lifetime of charge carriers;

$$\tau_{Auger} = [C_n(N_d + \Delta p)^2 + C_p(N_d + \Delta p)\Delta p]^{-1} \tag{5}$$

— lifetime of charge carriers at auger combination;

$$C_n = [2.8 \cdot 10^{-31} + (2.5 \cdot 10^{-22})/(N_d + \Delta p)^{0.5}]\ \mathrm{cm^6/s},$$

$$C_p = 10^{-31}\ \mathrm{cm^6/s}\ [6];$$

$n_i(T)$ — proper equilibrium concentration of charge carriers in the substrate at a given temperature 300 K; k — Boltzmann constant; q — elementary charge. The expressions (1) and (2) represent the volt-ampere characteristics of the HIT element. If from (2) we find

$$\Delta p(U) = -\frac{N_d}{2} + \sqrt{\frac{N_d^2}{4} + n_i^2(T)\exp\left(\frac{qU}{kT}\right)} \tag{6}$$

Data of intermediate calculations to Fig. 2 for the boundaries of the range τ_0

P_m, mW/cm^2	N_d, cm^{-3}	τ_0, ms	Δp cm^{-3}	τ, ms	D cm^2/s
22.22	10^{15}	1.5	$1.33 \cdot 10^{15}$	1.44	15.21
23.06	$5 \cdot 10^{15}$	1.5	$8.59 \cdot 10^{14}$	1.27	12.70
24.09	10^{15}	8.0	$3.42 \cdot 10^{15}$	4.87	16.20
24.21	$5 \cdot 10^{15}$	8.0	$2.08 \cdot 10^{15}$	3.46	13.65

and substitute into (1), then we get the dependency $J(U)$. The voltage drop on the HIT element is mainly determined by the magnitude of the forward displacement of the p^+-n-heterojunction [8]. The series resistance associated with voltage drops on other layers of the structure is not taken into account in the model. The maximum power density P_m can be numerically calculated using expressions (1) and (2) from the condition $dP/dU = 0$, where $P = JU$. Typical values of d, N_d and J_{sc} were used in calculations of theoretical curves (Fig. 2). The short-circuit current density chosen as an arbitrary parameter, equal to 39 mA/cm^2, is characteristic of modern HIT elements having an efficiency of $\sim 20-22\%$ with reference solar radiation $P_{in} = 100$ mW/cm^2 [2,10].

The conversion of solar energy is accompanied by an intensive accumulation of excess charge carriers inside the substrate, and their concentrations directly depend on the speed of recombination processes. In the maximum power mode, Δp become comparable or higher than the concentration of the donor impurity [6]. At the same time, due to the influence of Auger recombination processes, the resulting lifetime of electrons and holes τ turns out to be much less than τ_0 [11]. In addition, there is a significant increase in the ambipolar diffusion coefficient of charge carriers relative to the value of D_p. According to the expressions (3)−(5), the higher the Δp, the weaker the D and τ depend on the doping level of the crystal substrate. Therefore, as τ_0 increases, it occurs as a decrease in the difference between the maximum power densities of HIT elements made with low resistance ($N_d = 5 \cdot 10^{15}$ cm^{-3}) and high-resistance ($N_d = 10^{15}$ cm^{-3}) on substrates, and a significant slowdown in the growth of the function $P_m(\tau_0)$ (Fig. 2). The table contains data of intermediate calculations to Fig. 2 for the boundaries of the range τ_0. Thus, when using c-Si plates with an increased concentration of donor impurity, the gain in the maximum power value is noticeable only at relatively small values of the initial lifetimes of charge carriers.

The theoretical curves of the maximum current density J_m generally repeat the course of the dependencies $P_m(\tau_0)$ and also converge as the initial lifetime of the charge carriers increases (Fig. 3, *a*). However, when $N_d = 5 \cdot 10^{15}\,\mathrm{cm}^{-3}$ the function $J_m(\tau_0)$ grows noticeably slower than when $N_d = 10^{15}\,\mathrm{cm}^{-3}$. Fig. 3, *b* presents the results of calculations of the maximum voltage U_m. The type of graphs of functions $U_m(\tau_0)$ indicates that

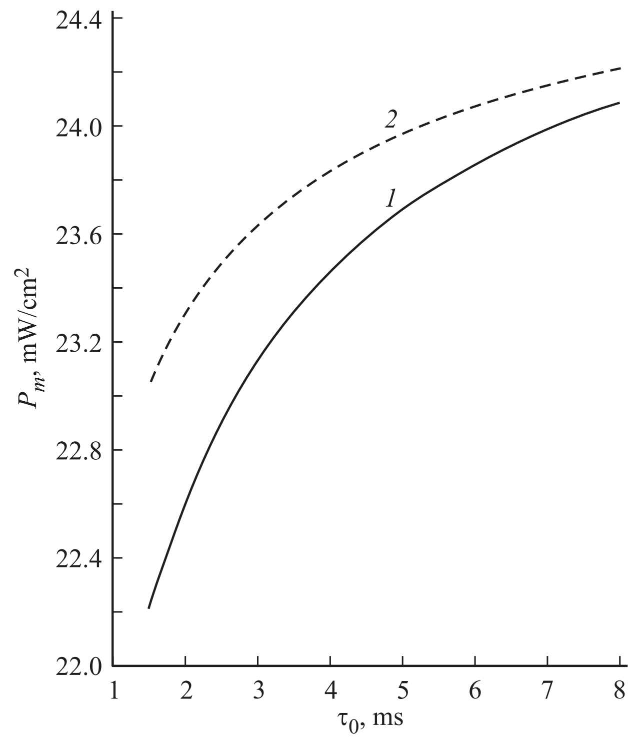

Figure 2. The dependence of the maximum power density on the value of the initial lifetime of charge carriers in the substrate of the HIT element. $J_{sc} = 39\,\mathrm{mA/cm^2}$, $d = 160\,\mu$m. $N_d = 10^{15}$ (*1*) and $5 \cdot 10^{15}$ cm^{-3} (*2*).

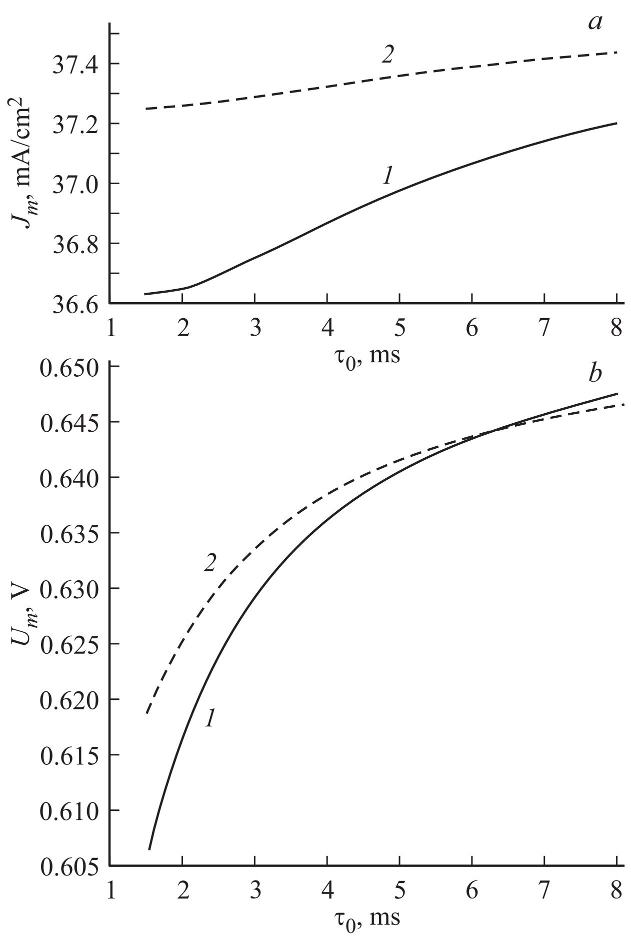

Figure 3. The dependence of the maximum power density on the value of the initial lifetime of charge carriers in the substrate of the HIT element. $J_{sc} = 39\,\mathrm{mA/cm^2}$, $d = 160\,\mu$m. $N_d = 10^{15}$ (*1*) and $5 \cdot 10^{15}$ cm^{-3} (*2*).

the advantage of using low-resistance substrates in order to increase the maximum voltage disappears if the initial lifetime of charge carriers in the plate $(n)c$-Si exceeds 6.48 ms. For $\tau_0 > 6.48$ ms recombination losses are such that, as follows from expression (2), the product value of $\Delta p(\Delta p + N_d)$ turns out to be greater in high-resistance substrates than in low-resistance ones. As per the estimates, the lifetimes and concentrations of charge carriers at the intersection point of the curves $U_m(\tau_0)$ in Fig. 3, *b*, respectively, are $\tau \approx 4.35$ ms, $\Delta p \approx 3.23 \cdot 10^{15}\,\mathrm{cm}^{-3}$ at $N_d = 10^{15}\,\mathrm{cm}^{-3}$ and $\tau \approx 3.17$ ms, $\Delta p \approx 1.96 \cdot 10^{15}\,\mathrm{cm}^{-3}$ when $N_d = 5 \cdot 10^{15}\,\mathrm{cm}^{-3}$.

The results obtained can be used in research projects aimed at finding optimal parameters of substrates for HIT elements.

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Conflict of interest

The author declares that she has no conflict of interest.

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