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Contribution of the region depleted of charge carriers to the current-voltage characteristic of photoconverters

© N.M. Bogatov[1], V.S. Volodin[1], L.R. Grigoryan[1], M.S. Kovalenko[1], L.S. Lunin[2]

[1] Kuban State University, Krasnodar, Russia
[2] Southern Scientific Center, Russian Academy of Sciences, Rostov-on-Don, Russia
E-mail: bogatov@phys.kubsu.ru, lunin_ls@mail.ru

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The contribution of the recombination current of a soft $n-p$ junction with a diffusion doping profile to the current-voltage characteristic of silicon photoconverters has been analyzed. It is shown that the locations of the space charge region (SCR) and the charge carrier depleted region (CCDR) do not coincide. The value of the electric potential barrier of the $n-p$ junction V_0 is equal to the change in the electric field potential in the CCDR, and not in the entire SCR. This fact significantly limits the open circuit voltage and efficiency of photoconverters.

Keywords: photodiode, $n-p$ junction, space charge region, current-voltage characteristic.

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The analysis of current–voltage characteristics (CVCs) with determination of their parameters is an important method for diagnostics of photodiodes and photoconverters [1,2] that relies on classical theories of generation and recombination processes in the space charge region (SCR) and carrier transport: the Sah–Noyce–Shockley theory, diode theory at low and high injection levels, etc. [3].

The structure of semiconductor devices with an $n-p$ junction is set by the distribution of donors and acceptors. The fundamentals of the $n-p$ junction theory were formulated by Shockley. The existence of a charge carrier depleted region (CCDR) with the concentrations of electrons and holes in it being much lower than the concentrations of ionized donors and acceptors is a key tenet of this theory. The Shockley theory is modified for structures with abrupt and soft $n-p$ junctions [3,4]. The analysis of the charge density distribution in the SCR of an $n-p$ junction is a relevant task [5], since classical $n-p$ junction theories do not provide a sufficiently accurate description of the specifics of CCDRs. The results of modeling of the distribution of equilibrium electrons and holes [5] suggest that the structure of a highly asymmetric abrupt $n-p$ junction differs from the structure predicted by classical models in that the SCR features neighboring regions depleted of charge carriers and enriched with them and that the CCDR size is smaller than the one determined within Shockley and Sah–Noyce–Shockley theories.

The aim of the present study is to analyze the contribution of recombination current of a soft $n-p$ junction with a diffusion doping profile to CVCs.

The doping profile in a diffusion $n-p$ junction depends on coordinate x. In the model of diffusion from an unlimited source,

$$N(x) = N_{D0}\,\mathrm{erfc}\left(\frac{x+w_n}{x_0}\right) - N_A \text{ at } -w_n \leqslant x \leqslant w_p,$$

where N_{D0} is the donor concentration on surface $x = -w_n$; w_n is the $n-p$ junction depth; N_A is the acceptor concentration; w_p is the base thickness; $x_0 = 2\sqrt{D_d t_d}$; D_d is the temperature-dependent donor diffusion coefficient; and t_d is the diffusion time. In calculations, x_0 is determined based on a set w_n value as a solution of equation $N(0) = 0$.

We determine the equilibrium distributions of electric field potential $\varphi(x)$ and electron $n(x)$ and hole $p(x)$ concentrations in a $n-p$ junction by solving the Poisson equation

$$\frac{d^2}{dx^2}\varphi(x) = -\frac{q}{\varepsilon\varepsilon_0}\big(p(x) - n(x) + N^{ion}(x)\big), \qquad (1)$$

where q is the elementary charge, ε is the permittivity of matter, ε_0 is the dielectric constant, $N^{ion}(x)$ is the distribution profile of ionized donors and acceptors,

$$n(x) = N_c e^{\frac{F-E_g+q\varphi(x)}{kT}}, \qquad p(x) = N_v e^{\frac{-F-q\varphi(x)}{kT}}, \qquad (2)$$

N_c is the effective density of electron states in the vicinity of the conduction-band minimum, F is the electrochemical potential (Fermi level) measured relative to the valence-band top at point $x = w_p$, k is the Boltzmann constant, T is the absolute temperature, N_v is the effective density of electron states in the vicinity of the valence-band top, and E_g is the band gap width. The condition of overall electroneutrality is an additional one:

$$\int_{-w_n}^{w_p} \big(p(x) - n(x) + N^{ion}(x)\big)dx = 0. \qquad (3)$$

Equation (1) with account for (2) and (3) was solved in difference form by successive iterations.

Dependences $\varphi(x)$, $n(x)$, $p(x)$, and $N^{ion}(x)$ calculated numerically for silicon at $T = 300\,\mathrm{K}$ are shown in Fig. 1.

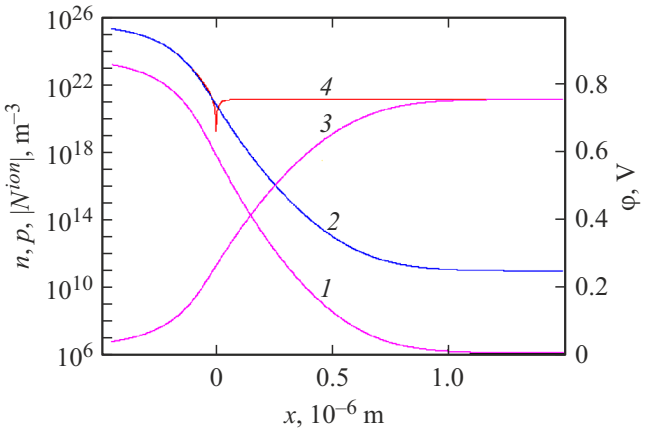

Figure 1. Results of numerical calculations of electric field potential $\varphi(x)$ (*1*) and concentrations of electrons $n(x)$ (*2*), holes $p(x)$ (*3*), and ionized impurities (in magnitude) —$N^{ion}(x)$— (*4*).

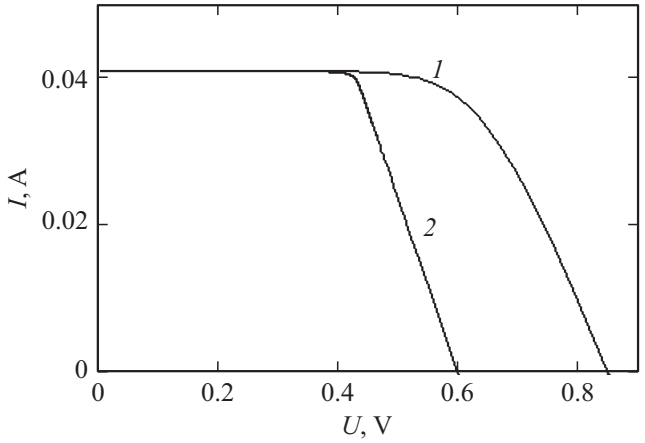

Figure 2. Current–voltage characteristics. *1* — $V_0 \approx 0.89$ V, efficiency = 16.5%; *2* — $V_0 = 0.6$ V, efficiency = 12.6%.

The doping profile parameters correspond to photovoltaic converters [6]: $N_{D0} = 10^{26}\,\mathrm{m}^{-3}$, $N_A = 10^{21}\,\mathrm{m}^{-3}$, and an $n-p$ junction with $w_n = 0.45 \cdot 10^{-6}$ m is not abrupt; thus, the SCR part enriched with electrons (Fig. 1) is small compared to the structures examined in [5].

The concentration of ionized donors is $N^{ion} = 1.46 \cdot 10^{25}\,\mathrm{m}^{-3}$ at $x = -w_n$ (Fig. 1), $N^{ion} < N_c = 2.74 \cdot 10^{25}\,\mathrm{m}^{-3}$; therefore, electrons are non-degenerate. The CCDR with $n(x)$, $p(x) \ll |N^{ion}(x)|$ is located at $0 < x < 0.75 \cdot 10^{-6}$ m. The $\varphi(x)$ variation in the CCDR of an equilibrium $n-p$ junction is $V_0 = 0.6$ V. The SCR part containing positive charge density starts at the $x = -w_n$ surface and extends to the metallurgical boundary $x = 0$. In this region, $n(x)$ is of the same order of magnitude as $N^{ion}(x)$, but lower than it; therefore, the series resistance of the n layer is much lower than the one of the p layer.

If the electrical bias at contacts is U, electrical bias U_{np} in a soft diffusion $n-p$ junction is localized to the CCDR instead of covering the entire SCR. Let us estimate the contribution of recombination current of a soft $n-p$ junction with a diffusion doping profile to CVCs. We divide the volume into three parts: 1) n-type emitter with $n(x) \approx N^{ion}(x)$ located at $-w_n \leqslant x < 0$; 2) CCDR located at $0 \leqslant x < d_p$ ($d_p \approx 0.75 \cdot 10^{-6}$ m); 3) p-type base with $p(x) \approx |N^{ion}(x)|$ located at $d_p \leqslant x < w_p$ ($d_p \ll w_p$). In the general case, all three parts contribute to the $I(U)$ CVC.

The drift component of hole transport in the emitter, which is induced by the internal electric field created by the donor concentration gradient, reduces recombination losses in this region. Recombination losses in the base are reduced significantly if the diffusion length of holes is several times greater than its thickness [4]. A series of samples with a predominant recombination component in the SCR and the doping profile parameters matching those specified in the above calculations was examined in [6]. Let us compare the recombination currents of the entire SCR and the CCDR with these parameters.

The CVC of an illuminated photoconverter is

$$I(U) \approx I_{ph} - \frac{I_{r0}}{\sqrt{1 - (U + IR_s)/V_0}} \times \left\{ \exp\left(\frac{q(U + IR_s)}{akT} \right) - 1 \right\} - \frac{U + IR_s}{R_{sh}}, \tag{4}$$

where I_{ph} is the photocurrent, R_s is the lumped series resistance, R_{sh} is the shunt resistance, and a is the nonideality factor of an $n-p$ junction. In the Sah–Noyce–Shockley theory, $a \approx 2$ and

$$I_{r0} = \frac{Sqn_i}{2\tau} \frac{\frac{kT}{q}\sqrt{\frac{\varepsilon\varepsilon_0}{4\pi q V_0}}}{\sqrt{(N_D^+ + N_A^-)}} \left(\sqrt{\frac{N_A^-}{N_D^+}} + \sqrt{\frac{N_D^+}{N_A^-}} \right), \tag{5}$$

where S is the $n-p$ junction area, n_i is the intrinsic charge carrier concentration, τ is the effective lifetime of inequilibrium charge carriers, V_0 is the electric potential barrier of an $n-p$ junction, N_A^- is the concentration of ionized acceptors, and N_D^+ is the concentration of ionized donors.

The traditional approach is to calculate the recombination current within the entire SCR of an $n-p$ junction; then, according to [3],

$$V_0 \approx \frac{kT}{q} \ln \frac{N_D^+ N_A^-}{n_i^2}. \tag{6}$$

Let us insert concentrations $N_D^+ = N^{ion}(-w_n)$ and $N_A^- = N_A$ corresponding to the calculation results presented in Fig. 1 into formula (6). We then obtain $V_0 \approx 0.89$ V.

In the approach advanced in the present study, the recombination current is calculated in the CCDR; thus, $V_0 = 0.6$ V and $N_D^+ \to \infty$ and $N_A^- \approx N_A$ in formula (5).

The calculated CVCs are shown in Fig. 2. The values of $S = 1\,\mathrm{cm}^2$, $\tau = 6.4 \cdot 10^{-7}$ s, $R_s = 4.2\,\Omega$, and $R_{sh} = 3.4 \cdot 10^5\,\Omega$ corresponding to the reference sample in [6] were used in calculations; $I_{ph} = 41$ mA models the

AM0 conditions. Open circuit voltage $V_{oc} \approx 0.85\,\mathrm{V}$ exceeds the one observed in silicon solar converters ($V_{oc} \approx 0.6\,\mathrm{V}$).

Thus, it was demonstrated that the height of electric potential barrier V_0 of an $n-p$ junction matches the $\varphi(x)$ change in the CCDR (and not the entire SCR) and is determined by the dopant profile. Formula (6) is valid for a step symmetric junction and requires refinement in the case of a diffusion $n-p$ junction. If the value of U approaches V_0, an $n-p$ junction is „filled" with charge carriers, and the CCDR vanishes. The Sah–Noyce–Shockley theory is inapplicable in this case, and photogenerated electrons and holes are separated by the pulling field produced by the composition gradient. The existence of a fundamental limit of the open circuit voltage and the efficiency of silicon photoconverters was thus demonstrated. Heterojunctions with asymmetric doping will be analyzed in further studies.

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Conflict of interest

The authors declare that they have no conflict of interest.

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