IMPACT OF EXCESS CHARGE CARRIER CONCENTRATION ON EFFECTIVE SURFACE RECOMBINATION VELOCITY IN SILICON PHOTOVOLTAIC STRUCTURES

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Within the framework of a self-consistent approach, a special attention is paid to the impact of the density and polarity of a surface charge formed at the insulator-semiconductor interface on the effective surface recombination velocity S_{eff}. The parameters of surface recombination centers, as well as the concentrations of doping impurities and excess charge carriers in the emitter and base regions of a solar cell (SC), are taken into consideration. It is shown that the passivation of a rather weakly doped emitter or a base region by a dielectric film containing a built-in charge of the same polarity, as the polarity of majority charge carriers in the substrate, can result in a catastrophically high increase of surface recombination losses. At the same time, the formation of the accumulation or inversion layers at the surface essentially reduces the effective surface recombination velocity S_{eff} at low injection levels. The slope of $S_{\text{eff}}(\Delta n)$ curves can be both positive and negative depending on the density and polarity of a surface charge. However, in the region of very high injection levels, S_{eff} ceases to depend on the injection level and the SC design and is defined only by the parameters of surface recombination centers.

1. Introduction

In the theoretical modeling of photovoltaic energy conversion processes in silicon SCs, surface recombination losses are usually determined via the surface recombination velocity S (SRV) which is included into a surface recombination current flow boundary condition as a functional parameter. If a space charge region (SCR) exists in the emitter or base region of SC, then the so-called “true” SRV referred to the geometric surface of SC differs from the effective SRV S_{eff} determined on the boundary of SCR and a silicon quasineutral region. On the recalculation of the “true” SRV to the effective one, the representations of diode or diffusion rectifying theories are usually used, i.e. the approximations of constant or variable quasi-Fermi levels for mobile charge carriers in the SCR. In silicon, as shown in many papers, in the calculation of S_{eff}, the approximation of constant quasi-Fermi levels can be used in most cases [1, 2].

It should be noted that, in most papers devoted to the modeling of nonequilibrium processes in SCs, S_{eff} is introduced as a parameter of the SC model, i.e. it is not determined self-consistently. In such an approximation, many important features of the surface recombination mechanism are not taken into consideration, in particular, the dependence of S_{eff} on a mode of SC operation, base resistivity, illumination intensity, surface charge density, concentration and energy distribution of surface recombination centers, configuration of a metal contact grid, etc. In modern highly efficient silicon SCs, the base region, as a rule, is not highly doped, and a minority carrier diffusion length exceeds the SC thickness [3—7]. Therefore, under natural (not concentrated) solar illumination conditions, such SCs work at high injection level conditions, the excess concentration of electron-hole pairs in the base exceeding the equilibrium concentration of majority carriers and being constant within the base thickness. The mentioned regularities are peculiar not only to commonly used silicon SCs with the double-sided arrangement of contacts [3, 4], but also to SCs with interdigitated contact system [5—7], in which both contacts are located on the rear (not illuminated) surface, and heavily doped regions at the illuminated surface are absent. In last case, the results of experimental investigations of the recombination processes performed in [8] on homogeneously doped silicon samples thermally oxidized in a chlorine ambient are applicable directly. The authors of [8] have found out that S_{eff} can both increase or decrease with increase in the excess concentration of minority carriers, Δn, the slope of $S_{\text{eff}}(\Delta n)$ curves being essentially dependent on the conductivity type and resistivity of the silicon substrate. In [9] with the use of the experimental technique [10] based on the effective lifetime vs sample thickness measurements, it was established that the shape of $S_{\text{eff}}(\Delta n)$ curves is essentially dependent on the insulator layer material and its deposition technology, as well as on the injection level and substrate resistivity. At the same time, the physical nature of such a behaviour of $S_{\rm eff}(\Delta n)$ was not clarified.

In the present work, a self-consistent approach to the analysis of surface recombination losses in high-efficiency silicon SCs is proposed. Within the framework of this approach, the effect of the surface charge, characteristics of insulator-semiconductor interface recombination centers, concentration of doping impurities both in the emitter and base regions, and injection level on $S_{\rm eff}$ is taken into account.The first and second parts of the work are devoted, respectively, to the analysis of the surface recombination processes in interdigitated SCs and in SCs with double-sided contact metallization.

2. Theoretical Considerations

At first, we will perform a self-consistent consideration of $S_{\rm eff}(\Delta n)$ in interdigitated SCs, in which SCR is formed at the frontal p-base surface in the process of deposition of an insulator layer. Let the surface charge Q_0 per unit area induce a SCR of the width $x = w_p$ at the SC surface. If the surface recombination is carried out through one discrete surface recombination center with the concentration N_t, energy position E_t with respect to the middle of the forbidden band, and capture coefficients $C_{ns} = \nu_n \sigma_{ns}$ for electrons and $C_{ps} = \nu_p \sigma_{ps}$ for holes, then the effective recombination velocity at the boundary of SCR and the quasi-neutral region $S_{\rm eff}(w_p)$ can be written down as [1,2]

$$S_{\rm eff}(w_p) = C_{ns}C_{ps}N_t(p_p + n_p + \Delta n)/$$

$$/\{C_{ps}[(p_p + \Delta n)\exp(-Y_s) + n_i \exp(-E_t/kT)]+$$

$$+C_{ns}[(n_p + \Delta n)\exp(Y_s) + n_i \exp(E_t/kT)]\}, \qquad (1)$$

where p_p and n_p are the concentrations of equilibrium holes and electrons in the base, Δn is the steady-state concentration of excess electron-hole pairs at $x = w_p$, n_i is the intrinsic carrier concentration, Y_s is the non-equilibrium surface bending of bands under illumination, k is the Boltzmann's constant, and T is the absolute temperature. Analytically, $Y_s(\Delta n)$ can be determined from the integral electroneutrality equation. In the approximation of a constant Q_0 under illumination, this equation can be written down as [2]

$$\frac{Q_0}{\sqrt{2\varepsilon_{Si}\varepsilon_0 kT}} \pm [(n_p + \Delta n)(e^{Y_S} - 1)+$$

$$+(p_p + \Delta n)(e^{-Y_S} - 1) + Y_S(p_p - n_p)]^{\frac{1}{2}} = 0, \qquad (2)$$

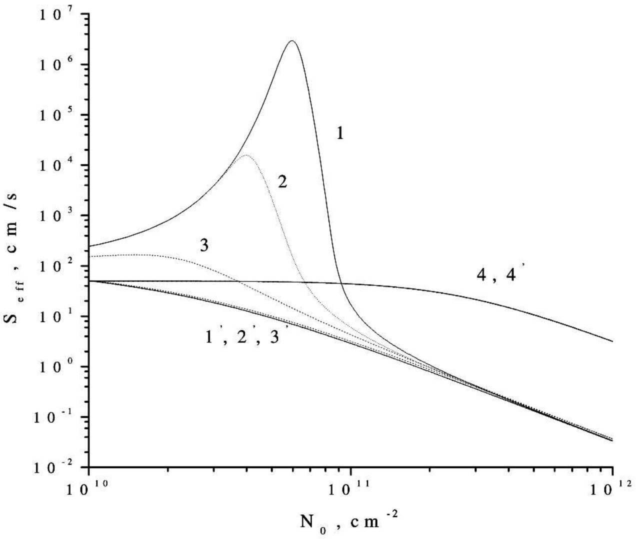

Fig. 1. $S_{\rm eff}$ vs N_0 calculated for $Q_0 > 0$ (curves *1—4*) and for $Q_0 < 0$ (curves *1'—4'*). $p_p = 10^{15}$ cm^{-2}, $T = 300$ K, $N_t = 10^{11}$ cm^{-2}, $E_t = 0$, $C_n = C_p = 10^{-9}$ cm^3/s, $\Delta p = 10^0$ (*1, 1'*), 10^{10} (*2—2'*), 10^{14} (*3—3'*) and 10^{17} cm^{-3} (*4—1'*)

where $\varepsilon_{\rm Si}$ is the dielectric constant of silicon, ε_0 is the permittivity of vacuum, the sign "+" is taken at $Y_S < 0$, and vice versa. The joint solution of Eqs. (1) and (2) allows us to define the interrelation of $S_{\rm eff}$, the surface and bulk electrical parameters of the insulator–semiconductor system, and the excess concentration of nonequilibrium minority carriers Δn which is assumed to be equal to Δp.

At first, we analyze the regularities caused by the effect of Q_0 on the effective SRV. The typical $S_{\rm eff}$ vs surface charge density $N_0 = \frac{1}{q}\,|Q|$ relations at different Δn plotted for the positive and negative polarity of Q_0 are shown in Fig. 1 (q is the electron charge). At $Q_0 > 0$, $S_{\rm eff}$ firstly grows some orders of magnitude with N_0 due to the Schottky layer enhancement, passes through a maximum at the beginning of the inversion layer formation, and then sharply decreases with increase in the surface electron concentration in the channel (curve *1*). With increase in the injection level, the position of the maximum is shifted to smaller N_0 values, and its height decreases (curves *2, 3*). At last, at $\Delta n \sim 10^{17}$ cm^{-3} when the concentration of excess charge carriers exceeds the concentration of majority dark carriers, the effect of N_0 on $S_{\rm eff}$ is essentially weakened (curve *4*).

A qualitatively different behaviour of $Q_0(N_0)$ is observed at $Q_0 < 0$, when an accumulation layer is formed at the illuminated surface. In this case, $S_{\rm eff}$ monotonously decreases with N_0, and the concentration of excess charge carriers does not practically influence

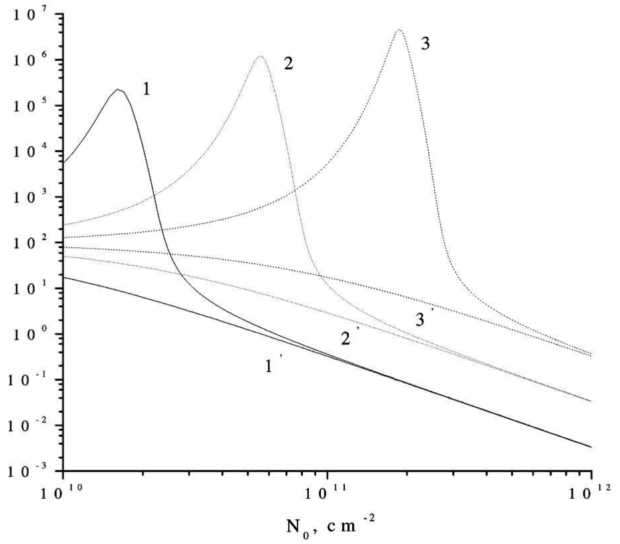

Fig. 2. S_{eff} vs N_0 at $Q_0 > 0$ (*1—3*) and at $Q_0 < 0$ (*1′—3′*). $\Delta n = 10^6$ cm^{-3}, $p_p = 10^{14}$ (*1, 1′*), 10^{15} (*2—2′*) and 10^{16} cm^{-3} (*3—3′*). Other parameters are the same as in Fig. 1

the shape of $S_{\text{eff}}(N_0)$ in a significant range of Δn (curves *1′—3′*). At high injection levels $\Delta n \sim 10^{17}$ cm^{-3}, S_{eff} does not depend at all on the polarity of Q_0 and is defined only by its value (curves *4, 4′*). The increase of the doping admixture concentration at $Q_0 > 0$ results in a shift of the position of the maximum on the $S_{\text{eff}}(N_0)$ curves to larger N_0 values and in the increase of S_{eff} values at the maximum (Fig. 2, curves *1—3*). In the region of high inversion potentials, S_{eff} monotonically decreases with increase in N_0 in the whole range of Y_S and, at high Q_0, coincides with ones calculated for the accumulating bending of bands (Fig. 2).

The above-discussed significant increase in S_{eff} at the depleted or poorly inverted SC surface is also seen in the temperature change of the effective SRV (Fig. 3). Thus, if SCR is depleted by majority charge carriers in the range of room or lightly increased temperatures, and if the injection level is not very high (for example, $\Delta n = 10^6$ cm^{-3}), then the decrease of a sample temperature results in the monotonous increase of S_{eff} (Fig. 3, curve *1*). On the other hand, at high inversion or accumulation potentials when the initial S_{eff} values are sufficiently low (< 10 cm/s), the decrease of temperature results in the monotonous (curves *1′—3′*) or non-monotone (curve *3*) reduction of S_{eff} within insignificant limits. Only in the case of a poorly inverted initially surface, a decrease of the SC temperature results in a sharp non-monotone change of S_{eff} in large limits (Fig. 3, curve *2*). For this reason, a characteristic minimum on the temperature dependences of the SC short-circuit current can appear in some cases.

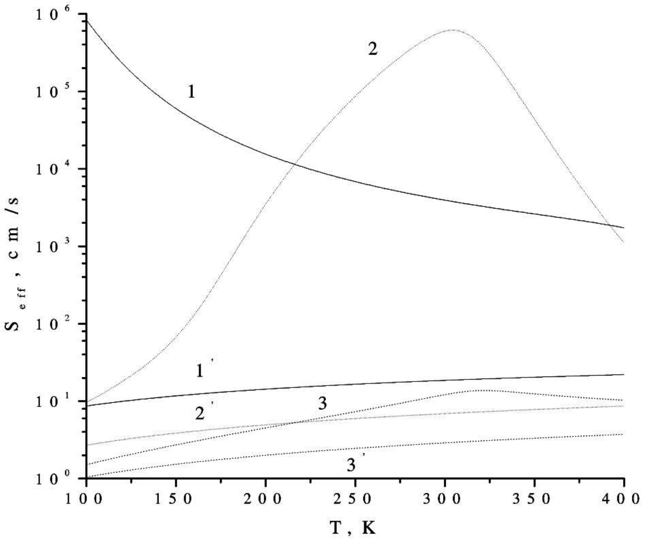

Fig. 3. Temperature dependences of S_{eff} calculated for $Q_0 > 0$ (*1—3*) and for $Q_0 < 0$ (*1′—3′*). $p_p = 10^{15}$ cm^{-3}, $\Delta n = 10^6$ cm^{-3}, $N_0 = 3 \times 10^{10}$ (*1,1′*), 6×10^{10} (*2—2′*) and 1×10^{11} cm^{-2} (*3—3′*). Other parameters are the same as in Fig. 1

The polarity and density of the surface charge, as well as the concentration of doping impurities in the silicon substrate essentially affect also the shape of the $S_{\text{eff}}(\Delta n)$ dependences (Fig. 4). In particular, at $p_p = 10^{16}$ cm^{-3} even at a rather small positive surface charge ($N_0 = 6 \times 10^{10}$ cm^{-2}), a surface SCR depleted by majority charge carriers is created. As a result, S_{eff} monotonously decreases with increase in Δn (curve *1*) due to an increase of the mobile carrier concentration in the SCR and the corresponding increase of the denominator value in (1). The decrease of the concentration of doping impurities in the base results in the transformation of the shape of $S_{\text{eff}}(\Delta n)$ due to the formation of a weakly (curve 2) or highly conducting inversion channel (curve *3*).

A qualitatively different type of the $S_{\text{eff}}(\Delta n)$ dependences is realized at $Q_0 < 0$, when the accumulation layer is formed at the surface. In this case, S_{eff} becomes weakly dependent on the injection level at $p_p = 10^{16}$ cm^{-3} (curve *1′*), and the $S_{\text{eff}}(\Delta n)$ curves approach ones calculated at $Q_0 > 0$ for lower concentrations of doping impurities (Fig. 4, curves *3, 3′*).

The conclusion concerning the strong effect of a surface charge polarity and density on the effective SRV in silicon insulator-semiconductor structures is qualitatively confirmed by experimental data performed in [8,9]. Thus, in the case of thermally oxidized *p*-silicon samples when a positive built-in charge is formed at the Si—SiO$_2$ interface, the increase of the doping impurity concentration in a substrate was really accompanied by a transformation of the $S_{\rm eff}(\Delta n)$ curves similar to that shown in Fig. 4 (curves *1—3*). On the other hand, after the thermal oxidation of n-type silicon samples [8] or after the plasma deposition of a SiN_x layer at the surface of p-Si [7], no $S_{\rm eff}(\Delta n)$ curves with negative slope (like curve *1* in Fig. 4) were observed at all. The latter regularities, as follows from the foregoing, are specific of the samples, in which the field-induced surface depletion layer is absent.

Now we consider $S_{\rm eff}(\Delta n)$ in SCs of the traditional design. At the beginning, we obtain and study the expression for that part of the effective SRV in the emitter which is related to passivated insulator–semiconductor regions between metal electrodes. The analysis is performed in assumptions that the degeneration of majority charge carriers in the emitter is absent, and the emitter thickness is small in comparison with the diffusion length.

If the quasi-Fermi levels for electrons and holes are constant within the interval $0 \le x \le x_n + w_p$, where x_n is the width of the n^+-emitter and w_p is a width of SCR in a $p-n$-junction, then the following relation between the effective SRV at $x = w_n$ and at $x = x_n + w_p$ exists:

$$S_0(x_n + w_p) = S_{\rm eff}(w_n)\frac{n_p + p_p + \Delta n}{n_n + p_n + \Delta p} \approx$$
$$\approx S_{\rm eff}(w_n)\frac{p_p + \Delta n}{n_n + \Delta p}. \qquad (3)$$

Here, w_n is a SCR width in the n^+ emitter, p_p and n_p are the concentrations of equilibrium holes and electrons in the base, respectively, n_n and p_n are the concentrations of equilibrium electrons and holes in the emitter, respectively, Δn is the concentration of excess electrons at $x = x_n + w_p$, and Δp is the concentration of excess holes at $x = w_n$. The expression for $S_{\rm eff}(w_n)$ can be obtained from (1) by the replacement of p_p by n_n, n_p by p_n, and Δn by Δp. The excess concentrations of electrons in the base Δn and holes in the emitter Δp are connected by the relation

$$\Delta n[p_p + \Delta n] = \Delta p[n_n + \Delta p]. \qquad (4)$$

By taking this into account, the effective SRV at the passivated part of the SC frontal surface reduced to the plane $x = x_n + w_p$ can be expressed as follows:

$$S_0(x_n + w_p) = [C_{ns}C_{ps}N_t(p_p + n_p + \Delta n)]/$$
$$/\{C_{ps}[(p_n + \Delta p)\exp(-Y_S) + n_i\exp(-E_t/kT)]+$$
$$+C_{ns}[(n_n + \Delta p)\exp(Y_S) + n_i\exp(E_t/kT)]\}. \qquad (5)$$

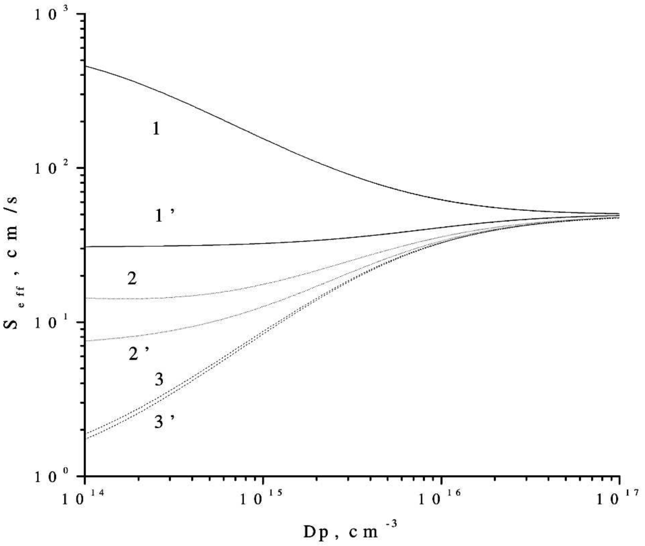

Fig. 4. $S_{\rm eff}$ vs Δp at $Q_0 > 0$ (*1-3*) and at $Q_0 < 0$ (*1′—3′*). $N_0 = 6 \times 10^{10}$ cm^{-2}, $p_p = 10^{16}$ (*1, 1′*), 10^{15} (*2—2′*) and 10^{14} cm^{-3} (*3—1′*). Other parameters are the same as in Fig. 1

With regard for (4), the interrelation between Δn and Δp is defined by solving a quadratic equation and looks as

$$\Delta p = -\frac{n_n}{2} + \sqrt{\frac{n_n^2}{4} + \Delta n(p_p + \Delta n)}. \qquad (6)$$

The joint solution of Eqs. (5), (6), and (2) has allowed us to plot $S_0(w_p)$ vs Δn for various SC parameters (Fig. 5). The calculations were made at several concentrations of majority carriers in the emitter n_n and in the base p_p for positive and negative polarities of a surface charge Q_0. As seen in Fig. 5,*a*, the S_0 values are small enough at low injection levels due to the small p_p/n_n ratio, the shape of the $S_0(\Delta n)$ curves being dependent both on the density and polarity of a surface charge, on the one hand, and on the concentration of doping impurities in the emitter n_n, on the other. In particular, at the initial inversion bending of bands, the $S_0(\Delta n)$ curve has a negative slope, and absolute S_0 values are rather high (Fig. 5,*b*, curve *1*). At the initial exhaustion (curves *2, 3*) or enrichment (curves *1′—3′*) of the surface SCR by majority carriers, S_0 increases at first with Δn some orders of magnitude and then tends to saturation. It is essential to emphasize that the S_0 values in the saturation region depend only on parameters of the surface recombination center (N_T, E_t, C_{ns}, and C_{ps}) and do not depend on other parameters of SC.

The analysis of expressions (5) and (6) shows that S_0 increases with Δn linearly if the excess concentration of

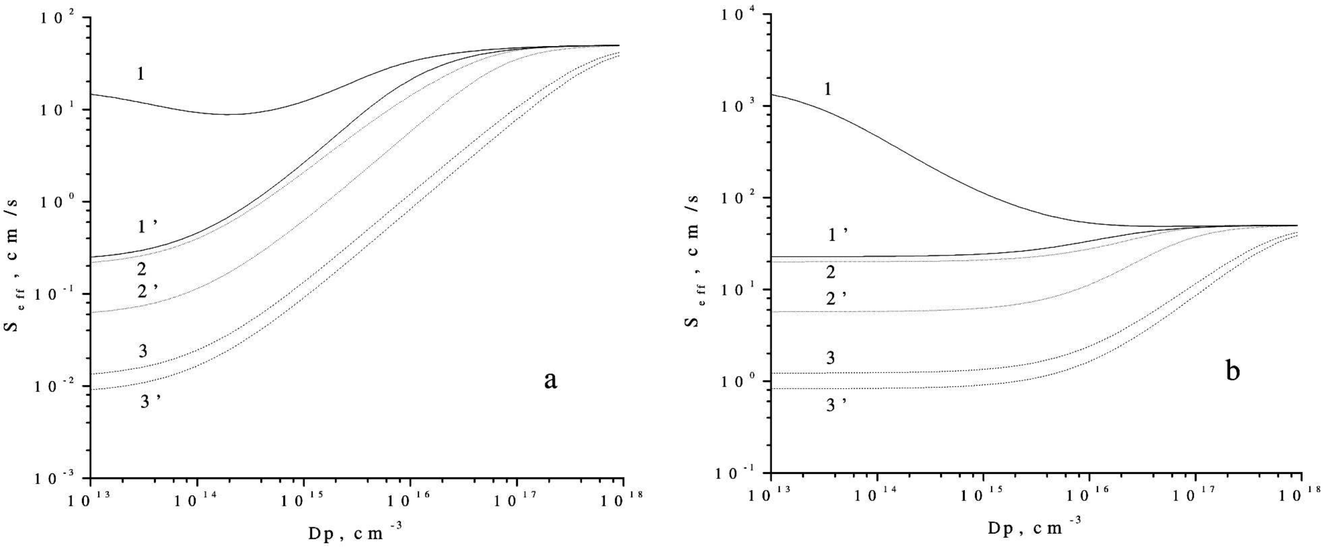

Fig. 5. Effective surface recombination velocity S_0 reduced to the boundary of SCR and quasi-neutral base region vs Δn at $Q_0 < 0$ (*1—3*) and $Q_0 > 0$ (*1′—3′*). $N_0 = 8 \times 10^{10}$ cm^{-2}, $n_n = 10^{16}$ (*1, 1′*), 10^{17} (*2—2′*) and 10^{18} cm^{-3} (*3—3′*), $p_p = 10^{14}$ (*a*) и 10^{16} cm^{-3} (*b*). Other parameters are the same as in Fig. 1

mobile charge carriers in the base exceeds the equilibrium concentration of majority carriers p_p and tends to the saturation when the concentration of nonequilibrium holes in the emitter becomes commensurable or begins to exceed n_n. As a result, the maximum ratio of the S_0 values at high and low injection levels do not exceed n_n/p_p.

Plotted in Fig. 5, the effective SRV S_0 represents the surface recombination occurring within non-metallized regions of the SC frontal surface. In a more general case, the S_0 values should be derived by use of the expression, in which the degeneration of charge carriers, bulk recombination in the n^+-emitter, and top contact grid are taken into account [11]:

$$S_0 \approx S_0^0(1 + \Delta_0) \tag{7}$$

$$S_0^0 = \nu_p \frac{p_p}{N_c} e^{\Delta E_g^{(n^+)} - Z_n} \left[\left(S_{pm} \mathrm{ch}\left(\frac{x_n}{L_p}\right) + \right.\right.$$

$$\left. + \nu_p \ \mathrm{sh}\left(\frac{x_n}{L_p}\right)\right) m \Big/ \left(S_{pm} \ \mathrm{sh}\left(\frac{x_n}{L_p}\right) + \nu_p \ \mathrm{ch}\left(\frac{x_n}{L_p}\right)\right) +$$

$$+ \left(S_{\mathrm{eff}} \ \mathrm{ch}\left(\frac{x_n}{L_p}\right) + \nu_p \ \mathrm{sh}\left(\frac{x_n}{L_p}\right)\right) \times$$

$$\left. \times (1 - m) \Big/ \left(S_{\mathrm{eff}} \ \mathrm{sh}\left(\frac{x_n}{L_p}\right) + \nu_p \ \mathrm{ch}\left(\frac{x_n}{L_p}\right)\right)\right]. \tag{8}$$

Here, $\Delta_0 = \Delta n(x_n + w_p)/p_p, \nu_p = D_p/L_p$ is the diffusion velocity, D_p is the hole diffusion coefficient in the n^+-region, N_c is the effective density of states in the conduction band of silicon, $\Delta E_g^{(n^+)}$ is a narrowing of the silicon forbidden band in the n^+-region due to the impurity doping (in kT units), m is the ratio of metallized to non-metallized regions of the frontal SC surface, $S_{pm} = V_{pT}/4$, V_{pT} is the thermal velocity of holes, S_{eff} is the effective SRV at the insulator—semiconductor interface reduced to the plane $x = w_n$, and Z_n is determined from the equation

$$n_n = N_c F_{1/2}(Z_n), \tag{9}$$

where $F_{1/2}(Z_n)$ is the Fermi—Dirac integral of the order of 1/2.

The account of recombination processes at the rear SC surface can be made similarly to that considered above for S_0. In particular, if the rear surface is completely metallized, the following equations for the effective SRV reduced to the plane $x = x_n + x_p - w_d$ are valid [11]:

$$S_d \approx S_d^0(1 + \Delta_d), \tag{10}$$

$$S_d^0 = \nu_n \frac{p_p}{N_v} \exp(\Delta E_g^{(p^+)} - Z_p) \times$$

$$\times \frac{S_{nm} \mathrm{ch}(w_d/L_n) + \nu_n \mathrm{sh}(w_d/L_n)}{S_{nm} \mathrm{sh}(w_d/L_n) + \nu_n \mathrm{ch}(w_d/L_n)}. \tag{11}$$

Here, w_d is the width of the rear p^+-p-junction, $\Delta_d = \Delta n_d/p_p$, Δn_d is the excess electron concentration at $x = x_n + x_p - w_d$, $S_{nm} = V_{nT}/4$ is the "true" SRV at the metal-semiconductor interface, $\nu_n = D_n^+/L_n^+$ is the diffusion velocity, D_n^+ is the diffusion coefficient, L_n^+ is the diffusion length of electrons in the p^+-region, N_v is the effective density of states in the silicon valence band, $\Delta E_g^{(p^+)}$ is a doping-induced narrowing of the forbidden band in the p^+-region (in kT units), and Z_p is determined from the equation

$$p_p = N_v F_{1/2}(Z_p). \qquad (12)$$

As is known, at relatively high diffusion length values $L_n > d$, the following expression can be used for the determination of the effective lifetime τ_{eff} in the silicon SC:

$$\tau_{\text{eff}} = (\frac{1}{\tau_\nu} + \frac{S_0 + S_d}{d})^{-1} = (\frac{1}{\tau_\nu} + \frac{S^*(\Delta_0)}{d})^{-1}. \qquad (13)$$

Here, $d = x_n + x_p$ is the SC thickness, S^* is the sum of effective recombination velocities at the frontal, rear and side surfaces of SC reduced to the quasi-neutral base region, and τ_ν is the bulk lifetime. As follows from (13), the surface recombination processes should affect τ_{eff} if the inequality $S^*(\Delta_0)\tau_\nu/d \geq 1$ is valid.

As follows from the analysis performed, at low impurity concentrations in the emitter (Fig. 5, curve *1*) or in the case of thermally oxidized p-base surface of the interdigitated SC [7], the surface recombination processes can essentially decrease τ_{eff} in a wide range of Δn, especially at the low Δn values. At the same time in commonly used silicon SCs with a high enough emitter doping concentration ($n_n > 10^{18}$ cm^{-3}), the effect of the density and polarity of surface charge on the surface recombination processes is weakened due to a decrease of S_0^* at low Δ_0. Nevertheless, as $S^*(\Delta_0)$ is changed linearly with Δ_0,

$$S^*(\Delta_0) \approx S_0^*(1 + \Delta_0), \qquad (14)$$

the surface recombination losses at high Δ_0 can be significant. For example, if the effect of the surface recombination on τ_{eff} at $S_0^* = 1$ cm/s and $\Delta_0 = 1$ becomes appreciable only at $\tau_\nu = 10^{-2}$ s, then, at $S_0^* = 1$ cm/s and $\Delta_0 = 10^2$, this effect becomes noticeable already at $\tau_\nu = 10^{-4}$ s.

3. Conclusions

A self-consistent approach to the analysis of surface recombination losses at various photo-excitation levels in high-efficiency silicon solar cells with interdigitated or commonly used contact metallization design is proposed. Within the framework of this approach, a special attention is paid to the effect of the density and polarity of the surface charge formed at the insulator–semiconductor interface on the effective surface recombination velocity S_{eff}. The parameters of surface recombination centers, as well as the concentrations of doping impurities and excess charge carriers in the emitter and base regions were also taken into consideration. It is shown that the passivation of a rather weakly doped emitter or a base region by a dielectric film containing a built-in charge of the same polarity as the polarity of majority charge carriers in the substrate can result in a catastrophically high increase of surface recombination losses due to the formation of the surface space charge region depleted by mobile charge carriers. At the same time, the formation of the accumulation or inversion layers at the surface essentially reduces the effective surface recombination velocity S_{eff} at low injection levels. The slope of the $S_{\text{eff}}(\Delta n)$ curves can be both positive and negative depending on the density and polarity of a surface charge. However, S_{eff} ceases to depend on the injection level and the SC design in the region of very high injection levels and is defined only by the parameters of surface recombination centers.

1. *Sachenko A.V., Snitko O.V.* Photoeffects in Semiconductor Surface Layers. — Kyiv: Naukova Dumka, 1984 (in Russian).
2. *Litovchenko V.G., Gorban' A.P.* Fundamentals of the Physics of Microelecronic Metal–Insulator–Semiconductor Systems. — Kyiv: Naukova Dumka, 1978 (in Russian).
3. *Fahrenbruch A.L., Bube R.H.* Fundamentals of Solar Cells. Photovoltaic Solar Energy Conversion. — New York, 1983.
4. *Green M.A.* Solar cells: Operating Principles, Technology and System Application. — Englewood Cliffs: Prentice-Hall, 1982.
5. *Schwartz R.J.* // Solar Cells. — 1982. — **6**, N1.— P. 17—21.
6. *Altermatt P.P., Heiser G., Dai X. et. al.* // J. Appl. Phys. — 1996. — **80**, N6. — P. 3574—3586.
7. *Swanson R.M.* // Solar Cells. — 1986. — **17**, N1. — P. 85—118.
8. *Glunz S.V., Sproul A.B., Warta W., Wettling W.* // J.Appl.Phys. — 1994. — **75**, N3. — P. 1611—1615.
9. *Kampwerth H., Rein S., Glunz S.* // Proc. 19th Europ. Photovoltaic Solar Energy Conf., June 7—11, 2004. — Paris, 2004. — P. 733—737.
10. *Yablonovitch E., Allara D.L., Chang C.C. et al.* // Phys. Rev. Lett. — 1986. — **57**, N2. — P. 249—252.
11. *Gorban A.P., Kostylyov V.P., Sachenko A.V., Chernenko V.V.* // Proc. 17th Europ. Photovoltaic Solar Energy Conf., October 22—26, 2001, Munich. — Vol. 1. — P. 234—237.

ВПЛИВ КОНЦЕНТРАЦІЇ НАДЛИШКОВИХ НОСІЇВ ЗАРЯДУ НА ЕФЕКТИВНУ ШВИДКІСТЬ ПОВЕРХНЕВОЇ РЕКОМБІНАЦІЇ В КРЕМНІЄВИХ ФОТОЧУТЛИВИХ СТРУКТУРАХ

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Резюме

В рамках самоузгодженого підходу проаналізовано закономірності впливу на поверхневі рекомбінаційні втрати величини і знака поверхневого заряду, параметрів рекомбінаційних центрів межі поділу діелектрик—напівпровідник, концентрації легуючих домішок в емітері і в базовій області сонячного елемента (СЕ), а також рівня ін'єкції в базі і в емітері. Показано, що пасивація поверхні діелектричним шаром, що містить вбудований заряд того ж знака, що й основні носії заряду в прилеглому напівпровідниковому шарі, може привести до катастрофічного збільшення поверхневих рекомбінаційних втрат. В той же час в разі утворення приповерхневих шарів збагачення чи інверсії поверхневі рекомбінаційні втрати при малих рівнях ін'єкції істотно знижуються. В залежності від величини і знака поверхневого заряду характер залежності ефективної швидкості поверхневої рекомбінації від рівня ін'єкції нерівноважних носіїв заряду може бути як спадним, так і зростаючим. В області максимально великих рівнів ін'єкції ефективна швидкість поверхневої рекомбінації перестає залежати від рівня ін'єкції і конструктивного виконання СЕ і визначається винятково параметрами поверхневих рекомбінаційних центрів.