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Suppression of Surface Recombination in Highly-Efficient Silicon Solar Cells.

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ABSTRACT

The efficiency of the silicon solar cells significantly is limited by the high surface recombination velocity (SRV). Because of it their dark currents are elevated, and open-circuit voltages, short-circuit currents and efficiencies are reduced. SRV is very high because it is increasing sharply with the increasing of the doping near the semiconductor-insulator interface, and near-surface layers of the solar cells are heavy doping. The carried-out physical analysis revealed that effective recombination velocity in a solar cell can be considerably reduced by replacing continuous high-concentration layers with the lattice of the small heavily-doped regions the distance between which is much greater than their size. It is shown that at the optimum ratio between the size of these regions and the distance between them there is a possibility of considerable increase of the operating voltage and the efficiency of the solar cell.

Keywords: silicon solar cells, surface recombination velocity, semiconductor-insulator interface, insular solar cell

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INTRODUCTION

The efficiency of modern solar cells on the mono-Si is limited, first of all, by the strong carrier recombination near the surface of the semiconductor. Its main consequence is the increased dark current, which is significantly reducing the open-circuit voltage V_{OC} . In addition, it reduces the carrier collection factor, and together with it the short-circuit current I_{sc}. Recently, thanks to the success in combating with the surface recombination at the metal-semiconductor interface the efficiency of such solar cells made by the industry [1,2], was seriously improved and especially studied in the experimental researches [3,4].

But now the surface recombination on the semiconductor-insulator interface and, above all, due to its increased dark current interferes the further raising of the efficiency of the solar cells. The main cause of the dark current increasing is high surface recombination velocity (SRV) on the boundary of the heavily doped semiconductor-dielectric. SRV when the doping level 10^{16} cm^{-3} is ~ 10 cm/s and even lower, but with ~10^{20} cm^{-3} SRV may far exceed 10^4 cm/s [2,5,6]. This factor appears to be fundamental [7], as at the high concentration SRV relies heavily on the level of doping and weakly on the surface treatment, whereas at concentrations of ~ 10^{18} cm^{-3} and lower the dependence on surface treatment is strong. And because even in the best silicon solar cells the doping, at least, near the surface adjoining p-n junction becomes strong in order to avoid the considerable resistance in series, and SRV is very high there, and insomuch as the potential barrier existing there can't lower dark current adequately [2].

The article proposes an explanation of the reasons for SRV growth with the doping level increase at the surface of the semiconductor and it describes a physical approach that can significantly reduce SRV, and the dark current. It is referred to heavily doping not a continuous near-surface layer, but small regions, "islands", i.e. replace the continuous p-n junction by the lattice of the small local p-n junctions. Thus, of course, the collection of the minority carriers worsens, and photocurrent decreases. But there are optimal parameters of islands where the dark current is reduced greatly, and the photocurrent is reduced faintly (or not at all), which increases the efficiency of the solar cell.

The article compares the physical processes and the photocurrent flow characteristics and dark current in the conventional and in the proposed insular solar cells and the effects of the concentration dependence of SRV at the semiconductor-dielectric interface.

METHODOLOGY

Photocurrent and dark current in conventional solar cell.

First, let's consider the flow of photocurrent and dark current in the conventional solar cell. These results contain the description of the influence of SRV to its characteristics and are used in the Section 3.2 where the link is found between photocurrents in the case of continuous p-n junction and in the event of its replacement by the lattice of small local p-n junctions.

The analysis of the processes in normal and insular solar cells is carried out by the example of the substrate (base) of p-type (of course the results are applicable to n-type) at low-level injection, where the processes are described by the continuity equation for electrons

$$D\Delta n-\left(n-n_{p0}\right)/\tau=-G(z). \qquad (1)$$

Here n is their concentration, n_{p0} is its equilibrium value, D is diffusion coefficient, τ is life time and $G(z)$ is rate of their generation by the incident radiation, depending only on z coordinate. In Eq. 1 it is assumed that the flux density of electrons $\mathbf{j}$ is determined by their diffusion: $\mathbf{j}=-D\nabla n$.

First, we consider a conventional solar cell with p-type base, lying between the planes z = 0 and z = d. In the plane z = 0 there are n^+-layer and p-n junction, and in the plane z = d there is p^+-layer. Their thickness is assumed to be negligibly small as compared with d and diffusion length $L = \sqrt{D\tau}$. In this case, the photocurrent is calculated by solving Eq. 1 with boundary conditions

a) $n|_{z=0} = 0$, b) $-D\partial n/\partial z|_{z=d} = s_d n|_{z=d}$. (2)

Eq. 2a takes into account that the velocity of electrons generated in the base increases rapidly in the field of p-n transition, wherefore their concentration at the junction becomes much less than the depth of the base (but far exceeds n_{p0}). Eq. 2b expresses the electron flow at $z = d$ through effective surface recombination velocity (ESRV) s_d , which takes into account both Auger-recombination in the conventional p^+ -layer at this boundary and surface recombination at the boundary of this layer with metal.

The solar cell will be highly effective, if the losses for recombination in it are small, for what the following conditions have to be satisfied

a) $d/L << 1$, b) $s_d << D/d$. (3)

Under these conditions, the main flow of electrons from base is directed to p-n junction due to diffusion with a typical velocity D/d which considerably exceeds the velocity of their recombination in the base, d/τ , and at the second boundary, s_d . It turned out that, taking into account the first-order corrections on small parameters, determined by the Eqs. 3, the expression for the photocurrent density through p-n junction is given by:

$$i_L \approx \left(1 - \alpha \frac{d^2}{L^2} - \beta \frac{s_d d}{D}\right)\int_0^d d\xi G(\xi), \quad (4)$$

where α and β are numerical parameters of order 1. The same result can be obtained from the solution of Eq. 1 with boundary conditions Eqs. 2. In particular it follows that when a homogeneous carrier generation: $\alpha = 1/3$ and $\beta = 1/2$. Estimations and available data [2] show that in the industrial manufactured devices [1,6], the main contribution in recombination losses makes a back metal-semiconductor contact. So when $d = 0.02$ cm, $D \approx 30$ cm^2/s and $s_d = 400$ cm/s – $s_d d/D \approx 0.25$, and when $s_d = 150$ cm/s – $s_d d/D = 0.1$, i.e., these losses are not very small. But in the solar cells with tunnel back contact where recombination is very small [4] losses of photocurrent at recombination are much less: $d^2/L^2 \sim 0.01$ and $s_d d/D \sim 0.01$. Note that the Eq. 4 shows that without taking into account the small corrections, the photocurrent does not depend on near what surface relative to the light, front or back the p-n junction is located.

For calculation of dark current it is necessary to solve the Eq. 1, having removed from it the term $G(z)$, and to use alterable boundary conditions Eqs. 2:

$$\text{a) } n|_{z=0} = n_{p0} \exp(eV/T),$$
$$\text{b) } -D\partial n/\partial z_{z=d} = s_d \left(n|_{z=d} - n_{p0}\right). \quad (5)$$

Here T is temperature in energy units, n_{p0} is equilibrium electrons concentration in the base, which is equal to $n_{p0} = n_i^2 / N_a$, where n_i is carrier intrinsic concentration and N_a is acceptor concentration in the base.

In highly effective solar cells, where Eqs. 3 are satisfied, the dark electron concentration is almost homogeneous in the base, because the rate of their diffusion significantly exceeds the rates of their recombination in the bulk and at the contact. For this reason even small inhomogeneity of the concentration would be enough for the diffusion to generate a flow of carriers going to recombination. Hence, in view of condition Eq. 5a we obtain

$$n(z) \approx \left(n_i^2 / N_a\right) \exp\left(eV/T\right). \qquad (6)$$

Using the Eqs. 1, 5, 6, we obtain an expression for the current density of the dark recombination of electrons

$$\begin{aligned} i_{nd} &= -e\left[\int_0^d dz \frac{n(z) - n_{p0}}{\tau} + s_d \left(n\big|_{z=d} - n_{p0} \right)\right] \approx \\ &- e\left(\frac{d}{\tau} + s_d\right)\frac{n_i^2}{N_a}\left(\exp\left(eV/T\right) - 1\right) \end{aligned} \qquad (7)$$

From the Eq. 7 it follows that in the highly effective solar cells the saturation current density i_s is the sum of the saturation current density of the base $i_{sb} \approx e n_i^2 d / N_a \tau$ and saturation current density of the back contact $i_{sbc} \approx e n_i^2 s_d / N_a$.

But it did not include the recombination of holes on the front surface of the semiconductor, in adjacent to it n[+] layer and the inside of p-n junction, i.e. at z=0. Next, we denote the density of the dark current of the holes i_{pd} and define ESRV s_{0p} through the saturation current density of the front contact i_{sfc} : $i_{sfc} = e n_i^2 s_{0p} / N_a$. Then for the total dark current density and total saturation current density the expressions take the form:

$$\begin{aligned} i_d &= i_{nd} + i_{pd} = \\ &- e\left(d/\tau + s_d + s_{0p}\right)\left(n_i^2 / N_a\right)\left(\exp\left(eV/T\right) - 1\right)' \end{aligned} \qquad (8)$$

$$\begin{aligned} i_s &= i_{sfc} + i_{sb} + i_{sbc} = \\ e&\left(d/\tau + s_d + s_{0p}\right)\left(n_i^2 / N_a\right) = e s_{eff}\left(n_i^2 / N_a\right). \end{aligned} \qquad (9)$$

Eq. 9 introduced an effective recombination velocity s_{eff} , which, along with the saturation current density is a characteristic of the dark current of the solar cell.

The efficiency of modern solar cells is limited, first of all, by high ESRVs s_d and s_{0p} , wherefore the saturation current density increases (Eq. 9) and the photocurrent density decreases (Eq. 4). They are high because SRVs are very high on the front and back surfaces of the semiconductor, s_f and s_b . And although the potential barriers highly decrease the flow of minority carriers to these surfaces, wherefore $s_{0p} << s_f$,

$s_d << s_b$ it appears not sufficient. So ESRV is usually the highest on the edge with metal, where SRV s_b reaches 10^7 cm/s and even though p^+ layer near this border greatly reduces ESRV s_d in comparison with s_b, nevertheless, on the surface coated with metal $s_d = 400$ cm/s [2], which is equivalent to a high saturation current density $i_{sbc} \approx 5*10^{-13}\ A/cm^2$. And also the photocurrent considerably decreases (see discussion of Eq. 4) with such a high ESRV.

RESULTS

SRV at the semiconductor-insulator interface

To reduce ESRV s_d the dielectric is deposited instead of metal on the back surface and above it a metal contacting with p^+-layer only in narrow slots [2]. Then the main recombination goes at the boundary with the dielectric, s_d decreases up to ~ 150 cm/s, and the efficiency of the solar cell increases significantly. But this reduction s_d was not as strong as might be expected, since at the boundary the semiconductor-dielectric SRV appeared very high: s_b ~ 45000 cm/s [2].

The matter is that SRV greatly increases with growth of doping of silicon at the boundary with dielectric (oxide). As experiment shows [8,9,10], with moderate doping of silicon (at a impurity density ~10^{15}-10^{16} cm^{-3} and lower) SRV usually lies in the range of ~1-100 cm/s and at the same time it strongly depends on the surface treatment. With increasing of doping SRV grows from 100 cm/s at doping level 10^{18} cm^{-3} to $4*10^4$ cm/s $2*10^{20}$ cm^{-3} [11]. There is also evidence [9 that at the concentration of phosphorus at the surface of ~ 7.5* 10^{18} cm^{-3} SRV depends on passivation method and varies in the range from 200 to 1000 cm/s, and with the concentration increase up to ~ $2*10^{20}$ cm^{-3} SRV reaches 2-3*10^4 cm/s and then weakly depends on the passivation method. At change of near-surface concentration of boron from $6*10^{18}$ cm^{-3} to $8*10^{19}$ cm^{-3} SRV increases by two orders [12]. It is also known [5], that at the concentration of phosphorus $1.5*10^{18}$ cm^{-3} SRV is ~ 300 cm/s at the surface orientation [100] and increases more than 2 times, if the surface is textured, but at the concentration of ~ $5*10^{19}$ cm^{-3} SRV reaches ~ $2*10^4$ cm/s and weakly depends on the type of surface.

This SRV behavior is naturally explained on the basis of the concept about the fluctuation surface states [5]. These states arise in the semiconductor near the boundary with dielectric in the potential relief created by random distribution of the charged centers which are built in dielectric. The theory of fast and slow surface states [7,12,13], describes a variety of observed properties of the structures Si: SiO_2 (among them: the spectrum characteristics of the surface-state density, SRV, statistics of the occurrence of slow surface traps and their properties, characteristics of random telegraph signals) at the densities of positively and negatively charged centers built-in the dielectric, Σ_+ and Σ_- , which are typical for these structures $\Sigma_+ \sim \Sigma_- \sim 10^{12} cm^{-2}$ [15].

The electrons and holes are bound in this relief, respectively, to the positively and negatively charged fluctuations of densities of the centers from their average values. Therefore, these states represent attracting centers of capture and generation for electrons and holes. The greater the charge of the fluctuation, the less probability of its formation and the greater the binding energy of the captured carrier. Therefore, the density of these states decreases in depth of the band gap. For the recombination of electrons and holes they need to tunnel between such states, and for the tunneling to be effective, the sum of binding energies of the electron and hole states should be close to the width of the band gap of silicon. Therefore at $\Sigma_+ \sim \Sigma_- \sim 10^{12} cm^{-2}$ such localized electron and hole states are separated by distances, much larger typical length of tunneling, which in silicon has order $\sim 10^{-7} cm$. As a result the tunneling time between them is high, and SRV is small even if the surface-state density is quite high.

Namely the properties of such tunnel-coupled localized states explain the experimentally observed regularities of the surface recombination. So the higher the densities is Σ_+ and Σ_-, the higher the recombination rate, and this dependence has to be very strong, as even relatively small increases in those densities, and with it a weak reducing of the distances between the tunnel-bound localized electron and hole states will lead to a great reduction in the tunneling time, since the typical tunneling length is short. As long as these densities depend on the method of passivation, so it strongly affects the SRV [16]. The densities of the charged centers depend on the orientation of the interface and are minimal at the surface [100], where for this reason the surface-state density is minimal [15,17]. This explains the increase of SRV on the textured surfaces in comparison with the surface [100] under weak doping [5].

All this is true for low impurity concentration at the surface of the semiconductor N_S, when the average distance between impurities in a semiconductor is small compared to the average distance between the charges built in the dielectric, i.e. when $N_S < \Sigma^{3/2} \sim 10^{18} cm^{-3}$. In this case the volume doping weakly affects the surface-state density and SRV. With strong semiconductor doping, for example, by donors, such that $N_S >> 10^{18} cm^{-3}$, the density of localized states for electrons at the surface created by clusters of donors will be much greater than the density of surface states created by fluctuations in the density of charged centers, built in a dielectric [7]. Besides the distances between the tunnel-bound states of electrons and holes are greatly reduced and no longer depend on distances between charges, built in a dielectric. This leads to a very strong reduction of the tunneling time and to a corresponding increase in SRV and eliminates the sharp dependence of SRV from the orientation of the semiconductor surface.

From this explanation it follows that the strong growth of SRV with increasing of the doping level at the concentrations greater than 10^{18} cm^{-3}, there is an inherent property of the silicon-silicon dioxide boundary, and therefore heavily doped surface layers reduce the efficiency of solar cells. And such layers, as a rule, are presented on both surfaces of the solar cell as low-resistance back contact [2] and low-resistance top layer of p-n junction.

The authors of the work [4] on experimental samples managed to solve the critical issue of the low-impedance contact with the metal with low SRV of minority carriers through the creation of a tunnel oxide passivated contact (TOPCon). But the problem of getting low SRV at the interface dielectric-low-resistivity layer of the p-n junction is not solved yet.

Insular solar cell

Now let consider how to change the results of Section 2, when replacing n^+-layer by n^+-islands placed with the periods a and b along X and Y axes. The surface of the island (thus the boundary of the p-n junction) assume hemisphere of small radius $r_0 << a, b$.

To calculate the photocurrent in such a solar cell it is necessary to find a photocurrent collected from the area $A = ab$ by the island with the center at the point $r = 0$, where $r = \sqrt{x^2 + y^2 + z^2}$. It is determined by Eq. 1 with the condition on p^+-contact Eq. 2b. But the boundary condition Eq. 2a in the present geometry has to be replaced by two conditions:

$$\text{a) at } r = r_0 - n\big|_{r=r_0} = 0, \qquad \text{b) at } z = 0,$$

$$r > r_0 - D\partial n/\partial z\big|_{z=0} = s_{0n} n\big|_{z=0}. \qquad (10)$$

Eq. 10a as well as Eq. 2a reflects the sharp decrease of the carrier concentration of minority carriers at the boundary of p-n junction in comparison with their concentration in the depth of the base. Eq. 10b determines the flow of electrons at the front surface of the semiconductor when ESRV is s_{0n}. In addition, when solving 3d- equation Eq. 1, it is necessary to use the additional boundary conditions

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a) $\partial n/\partial x|_{x=a/2,-a/2} = 0$,
b) $\partial n/\partial y|_{y=b/2,-b/2} = 0$, (11)

which reflect the absence of the normal flow of electrons at the lateral surfaces.

Next, we consider that the radius r_0 is small, diffusion length L is large, and SRVs are small:

a) $r_0 << a, b, d << L$,
b) $s_d, s_{0n} << D/d$, (12)

and show that in this case the saturation current of the solar cell can be drastically reduced while maintaining the high conversion efficiency of light.

Under Eqs. 12 the electron concentration is almost uniform throughout the base (this concentration is denoted as $\tilde{n}$), excepting small regions of the radius of a few r_0 around n$^+$-islands. In such region Eq. 1 becomes spherically symmetric, because the generation and recombination of electrons weakly affect their flow, and takes the form

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial n}{\partial r}\right) = 0. \quad (13)$$

Its solution at $r \ge r_0$ that satisfies Eq. 10a and is consistent with the expression for the concentration in the base takes the form

$$n(r) = \tilde{n}(1 - r_0/r), \quad (14)$$

From Eq. 14 it follows that the flow of electrons through p-n junction, J_{n^+}, is equal to:

$$J_{n^+} = -2\pi r_0^2 D\,\partial n(r)/\partial r|_{r=r_0} = -2\pi D r_0 \tilde{n}. \quad (15)$$

In the considered element with the area of A the flows of electrons going to the recombination are equal to: in its volume – $J_b = -Ad\tilde{n}/\tau$, on its surfaces – $J_0 = -As_{0n}\tilde{n}$ and $J_d = -As_d\tilde{n}$. And since the inflow of the electrons to the base is equal to their outflow, this permits to find the concentration $\tilde{n}$ and then the photocurrent, flowing to n$^+$-island:

$$I_{n^+} = -eJ_{n^+} = Ai_L/\left[1 + A(s_d + s_{0n} + d/\tau)/2\pi D r_0\right]. \quad (16)$$

Here i_L is the density of the photocurrent of the conventional solar cell (see Eq. 4). This implies that insular solar cell to be highly effective under Eq. 12 if the radius of the island is in the range

$$A(d/\tau + s_{0n} + s_d)/2\pi D << r_0 << a, b, d. \quad (17)$$

For the determination of the dark current for this geometry one has to solve Eq. 1 with $G(z) = 0$ and the boundary conditions from the previous section, with the only difference being that, when applying a voltage V boundary condition on the surface of n$^+$-island Eq. 10a should be replaced as follows:

at $r = r_0$ – $n|_{r=r_0} = n_{p0}\exp(eV/T)$. (10c)

In an efficient solar cell, where Eqs. 12 are true, recombination is weak, and the concentration of injected carriers is determined by Eq. 6. That is why the dark current flowing through n[+]-island, I_{di}, is equal (compare with Eq. 8)

$$I_{di} \approx -eA\left(d/\tau + s_{0n} + s_d + 2\pi r_0^2 s_{0pM}/A\right)n_{p0}\left(\exp(eV/T)-1\right), \quad (18)$$

where s_{0pM} is ESRV of the holes at the surface of the n[+]-island, determined primarily by their recombination at the interface with the metal. Here, taken into account that electrons recombine almost along the entire front surface of the solar cell, and holes recombine only inside n[+]-islands. This dramatically reduces contribution of their recombination in this geometry, in spite of its very high velocity.

Comparison of characteristics of insular and conventional solar cells

Below we analyze the possibilities of increasing the efficiency of conventional solar cell when replacing in it the continuous p-n junction by the lattice of small local p-n junctions. Note that earlier this analysis [7] was limited by the specific situation of the back contact with a very high SRV, which is typical for the metal-semiconductor interface [1].

Compare the features of the conventional and insular elements with the same area S. Using Eqs. 4, 8, 16, and 18, we obtain the following expressions for the currents of conventional and insular solar cells, *I* and I_I:

$$I = Si_L - eS\left(d/\tau + s_{0p} + s_d\right)n_{p0}\left(\exp(eV/T)-1\right), \quad (19)$$

$$I_I = Si_L \Big/ \left(1 + \frac{A}{2\pi r_0 D}\left(\frac{d}{\tau} + s_{0n} + s_d\right)\right) - eS\left(\frac{d}{\tau} + s_{0n} + s_d + \frac{2\pi r_0^2}{A}s_{0pM}\right)n_{p0}\left(e^{\frac{eV}{T}} - 1\right). \quad (20)$$

From Eqs. 19, (20), neglecting corrections of the order of i_s/i_L we find that the short circuit currents $I_{sc} = Si_L$ and I_{Isc}, open-circuit voltages $V_{oc} \approx (T/e)\ln\left[i_L/\left(e\left(d/\tau + s_d + s_{0p}\right)n_{p0}\right)\right]$ and V_{Ioc} are connected by the following relations:

$$I_{Isc} = I_{sc}/\left[1 + A\left(d/\tau + s_{0n} + s_{dI}\right)/2\pi r_0 D\right], \quad (21)$$

$$V_{Ioc} = V_{oc} + \frac{T}{e}\ln\left[\frac{1}{1 + A\left(d/\tau + s_{0n} + s_d\right)/2\pi r_0 D}\frac{d/\tau + s_d + s_{0p}}{d/\tau + s_d + s_{0n} + 2\pi r_0^2 s_{0pM}/A}\right]. \quad (22)$$

From Eqs. 19-22 it follows that the power $P = IV$, produced by these solar cells, reach maximums P_m and $P_{I,m}$ at voltages V_m and $V_{I,m}$, and currents I_m and $I_{I,m}$, defined by the expressions:

a) $V_m + (T/e)\ln(1 + eV_m/T) = V_{oc}$,
b) $V_{I,m} + (T/e)\ln(1 + eV_{I,m}/T) = V_{Ioc}$, (23)
a) $I_m = I_{sc}/(1 + T/eV_m)$,

b) $I_{I,m} = I_{Isc} / \left(1 + T/eV_{I,m}\right)$. (24)

From the results of the previously performed optimization of parameters of the insular solar cell, it follows that optimal values of the radius of the island $r_{0,opt}$, area A_{opt}, operating voltage V_{opt}, current I_{opt} and power $P_{opt} = V_{opt} I_{opt}$ are bound by the following parametric relations [7]:

$$r_{0,opt} = \frac{u^2}{1-u} \frac{2DT\left(eV_{opt} + T\right)}{s_{0pM}\left(eV_{opt} - T\right)^2}, \quad (25)$$

$$A_{opt} = \frac{u^3}{1-u} \frac{8\pi D^2 T^2 \left(eV_{opt} + T\right)}{s_{0pM}\left(d/\tau + s_d + s_{0n}\right)\left(eV_{opt} - T\right)^3}, \quad (26)$$

$$\frac{V_{opt} - V_m}{T/e} + \ln\left(1 + \frac{V_{opt} - V_m}{V_m + T/e}\right) = \ln\left(\frac{d/\tau + s_d + s_{0p}}{d/\tau + s_d + s_{0n}} \frac{1}{1 + \frac{2uT}{eV_{opt} - T}} \frac{1}{1 + \frac{u}{1-u}\frac{eV_{opt} + T}{eV_{opt} - T}}\right), \quad (27)$$

$$I_{opt} = I_{sc} \Big/ \left(1 + \frac{T}{eV_{opt}}\right)\left(1 + \frac{2u}{eV_{opt}/T - 1}\right), \quad (28)$$

where u is an arbitrary parameter, which varies within a range from 0 to 1 ($0 \le u < 1$). Thus, if we, for example, chose the radius of the island, thereby we set the value u, and hence the area, operating voltage, current and power, which correspond to this radius.

From Eqs. 27, 28 it follows that the values V_{opt} and I_{opt}, and with them the power P_{opt} increase with decreasing u. And this decreases the optimal radius of the island, $r_{0,opt}$ and the optimal area of the cell per one island, A_{opt}. If $u = 0$, then $r_{0,opt} = 0$ and $A_{opt} = 0$, and the value P_{opt} reaches its maximum, $P_{\lim}$:

$$P_{\lim} = V_{\lim} I_{sc} \Big/ \left(1 + \frac{T}{eV_{\lim}}\right) = P_m \frac{V_{\lim}}{V_m}\left(1 + \frac{T}{eV_m}\right) \Big/ \left(1 + \frac{T}{eV_{\lim}}\right), \quad (29)$$

where the maximum optimum voltage $V_{\lim}$ is the solution of the equation

$$\frac{V_{\lim} - V_m}{T/e} + \ln\left(1 + \frac{V_{\lim} - V_m}{V_m + T/e}\right) = \ln\left(\frac{d/\tau + s_d + s_{0p}}{d/\tau + s_d + s_{0n}}\right) \equiv B. \quad (30)$$

Thus, from Eqs. 29, 30 it follows that the maximum power and with it the efficiency of the insular solar cell exceed the corresponding characteristics of the conventional solar cell, as soon as the following condition is satisfied

$$s_{0n} < s_{0p}, \quad (31)$$

i.e., if SRV of the minority carriers at the interface dielectric-semiconductor (not heavily doped) is less than ESRV s_{0p} caused by recombination on the surface adjacent to the heavily doped layer of the p-n junction, Auger-recombination in this layer and recombination at the metal contacts to this layer. Eq. 31, as it was discussed in Section 3, is always performed by wide margins.

Now let's discuss how much one can improve the efficiency of the solar cell in real devices. Typical values of ESRV s_{0p} at the interface highly-doped semiconductor-dielectric are about 100 cm/s, whereas the typical values of SRV s_{0n} are as a rule in the range of 1-10 cm/s. It is clear that improvement of characteristics increases with decreasing the sum $d/\tau + s_d$. Its lowest known value is ~ 10 cm/s, which is derived from the values [4], $i_{sb} = 9*10^{-15}\ A/cm^2$, $i_{sbc} = 1.3*10^{-14}\ A/cm^2$, $n_i = 8.3*10^9\ cm^{-3}$ [18], $N_D = 5*10^{15} cm^{-3}$, $\tau = 3.4*10^{-3} s$ [19], $d = 2*10^{-2} cm$. Through the evaluation with these values it is easy to get that in all cases $B \le 2$, therefore with good margin the following condition is carried out

$$TB/eV_m << 1. \qquad (32)$$

Then the approximate expression for the maximum power, which follows from Eqs. 29, 30, can be written as:

$$\frac{P_{\lim}}{P_m} \approx 1 + \frac{TB}{eV_m} \quad . \qquad (33)$$

For example, at $B = 2$ and $V_m = 0.6$ V the right side of Eq. 33 is ~ 1.08. That is in this case the efficiency of, say, 23% can be in the limit increased to ~25%.

This limiting expression corresponds to a zero radius of the island. Using Eq. 33 together with Eqs. 25-28, we can derive an approximate expression for the optimal power at small, but finite radius (at $u << 1$, see Eq. 25). It has a form

$$\frac{P_{opt}}{P_m} \approx 1 + \frac{T}{eV_m}(B - 3u). \qquad (35)$$

From Eq. 25 with the following parameters: $r_{0,opt} = 5*10^{-4}$ cm, $s_{0pM} = 400$ cm/s, $D = 30$ cm^2/s we obtain: $u \approx 0.237$. Then the right side of Eq. 33 at $B = 2$ and $V_m = 0.6$ V is equal to ~ 1.054. That is with this radius of the island the efficiency, say, 23% can be increased to 24.2%.

Finally, we note that from Eqs. 25, 26 one can derive the following equation

$$\begin{aligned} &2\pi r_{0,opt}^2 s_{0pM} / [A(d/\tau + s_d + s_{0n})] = \\ &u(1 + T/eV_{opt}) / [(1-u)(1 - T/eV_{opt})]. \end{aligned}$$

Its left side is the ratio of the recombination current within n^+-island (mainly near the metal surface) to recombination current outside of the island: in the volume of, on front and back surfaces of the semiconductor. Therefore, from the right side of this equality it follows that at $u < 0.5$ the contribution of recombination outside of the n^+-island surpasses the contribution of recombination within it.

Above the boundary of p-n junction is assumed to be hemisphere that is not critical. When replacing a spherical boundary of p-n junction by the ellipsoidal one (and, in particular, by flat) the found higher the optimal characteristics V_{opt}, I_{opt} and P_{opt} remain the same under a moderate change of the optimal radius $r_{0,opt}$ and square A_{opt} [7].

DISCUSSION

Since in this paper we consider how much the characteristics of a conventional solar cell can be improved by replacing the continuous p-n junction by the lattice of p-n junctions with small radius, thus, it implicitly takes into account the impact of a number of parasitic factors, such as the resistance in series and recombination in the space-charge region of the p-n junction, reducing the fill factor and the efficiency of the solar cell. The calculated values of the efficiency of the insular solar cell is likely a somewhat underestimated since such cell has the improved photoresponse in short-wavelength part of the spectrum (as long as n^+-layer is absent, and SRV on a front surface is low). Therefore real photoresponse of such solar cell can even exceed photoresponse of a conventional cell although in our calculations was always considered less of it. In addition, the paper does not consider possible additional reduction of the dark current caused by the fact that replacement of n^+-layer by small n^+-junctions virtually eliminates the contribution to the dark current of the recombination in the space charge region. It should be noted that a further improvement in the characteristics of the insular solar cell in comparison with the estimate given in Section 5, is possible with decreasing the distance d between its surfaces.

Also note that in the approximation used in the paper the solar cell efficiency depends only on the product of $A = ab$, where a and b are the repetition periods of the islands along axes X and Y. Characteristics of real devices can be improved, if we choose the distance between the islands along the buses, a, smaller than the distance in the perpendicular direction, b, as in this case the front surface will be open in maximum to the light at the minimum technologically permissible width of metallic buses.

CONCLUSION

The results of this work will be used to develop highly efficient solar cells on mono-Si. Strong surface recombination at the interface heavily doped semiconductor-dielectric affects the characteristics of many devices. Therefore the creation of the quantitative theory describing dependence of SRV on doping level of semiconductors is obviously important direction of the future researches. Another important area for future research is to study the influence of the heavily doped contact regions of MOSFETs (metal-oxide-semiconductor field effect transistors) of submicron size on the statistics of occurrence of the slow fluctuation traps and on characteristics of the random telegraph signals produced by these traps [20].

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