JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 11 No 5, 05005(8pp) (2019)
ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 11 № 5, 05005(8cc) (2019)

Analytical Estimation of Recombination Current of Sharp Asymmetric *p-n* Junction

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(Received 24 May 2019; revised manuscript received 21 October 2019; published online 25 October 2019)

When simulating an asymmetric *p-n* junction, the high-alloyed region in the approximation of small currents does not affect the distribution of carriers in the low-alloyed region, in which the entire volume charge is concentrated. In this paper, an analytical estimate of the recombination current through traps in the space charge region and in the quasi-neutral region was made. To obtain an analytical representation, an approximation of the linearity of the potential distribution in the vicinity of the maximum recombination cross section is used. A method is proposed to analytically estimate the integral of the specific volume recombination rate over a region of the space charge that cannot be taken through elementary functions. The possibility of increasing the accuracy of the analytical estimate of the recombination current through traps in the space charge region was confirmed. The differential ideality coefficient is determined and its dynamics is analyzed depending on the voltage at the junction. Comparative analysis of the following recombination current estimates was made: the recombination current in the space charge region by elementary estimate, the diffusion current from the low-alloyed quasi-neutral region, the recombination current through traps in the quasi-neutral region, the current in the case of a linear approximation of the potential in the region of maximum recombination through the analytical integral, the real recombination current. An analysis of the error in the calculation of the recombination current from the doping level of the low-doped region and the applied voltage is presented. From the above data it can be seen that the error estimate for calculating the current through the analytical integral does not exceed 10 %, which is quite enough for its use in simulating the recombination current of most power semiconductor devices.

Keywords: Recombination through traps, Current of recombination, Coefficient of ideality, Differential coefficient of ideality, Photoelectric converter, Errors of calculation.

DOI: 10.21272/jnep.11(5).05005 PACS number: 73.40.Lq

1. INTRODUCTION

When simulating photoelectric converters (PEC), the problem of estimating the recombination current in the space charge region of the *p-n* junction is often encountered. The currently existing numerical estimates of the recombination current are distinguished by a low computation rate, which is not always acceptable due to the need for multidimensional parametric optimization of the PEC [1-3]. The simplest analytical estimates [4] do not provide a sufficiently accurate calculation of the recombination current through the energy levels of nonradiative recombination traps in semiconductor p-n junctions and an adequate steepness of the volt-ampere characteristic (IVC) of the PEC in the full range of voltage variation applied to the space charge region.

When analyzing the various options for estimating the current of recombination, the following cases were identified that make it possible to apply an adequate simplification of the estimate, without large errors:

– the recombination levels are located close to the middle of the forbidden zone, which gives the right to equate the recombination coefficients for electrons and holes [5];

– recombination currents are calculated for the asymmetric p-n junction, which means that the space charge region is located entirely in the high-resistance low-alloy region;

– the currents flowing through the p-n junction are so small that the Fermi quasi-levels are practically not perturbed by the flowing currents, and the Fermi quasi-levels are taken at the boundary of the space charge region (SCR) and the quasi-neutral region (QNR) [4].

When calculating the asymmetric p-n junction, the high-alloyed region in the approximation of small currents does not affect the distribution of carriers in the low-alloyed region, in which the entire volume charge is concentrated. The distribution of concentrations is determined entirely by the applied voltage.

The effect of the high-alloyed region is manifested only when the voltage approaches the contact potential difference of the semiconductor junction. In this case, the boundary conditions for minority carriers cease to be valid in the approximation of small currents [4] and the perturbation of concentration profiles by the flowing currents must be taken into account.

Thus, in the approximation of small currents when calculating the concentration profiles, this makes it possible to obtain a solution to the problem of estimating the recombination current, considering only the low-doped region without joining solutions with the high-doped region (equality of concentrations and their derivatives), applying a simplified boundary condition, for minority carriers:

$$p_n = p_{n0} \cdot \boldsymbol{exp}\left(\frac{U}{\varphi_t}\right),$$

where p_n, p_{n0} are the concentrations of nonequilibrium and equilibrium minority carriers at the SCR boundary, respectively, ϕ_t is the temperature potential.

In the approximation of small currents, the variation of voltage on the SCR of the transition is limited by the contact potential difference, from which the doubled temperature potential is subtracted, since the action of currents is always manifested above this voltage. Even more stringent voltage limits are imposed by the Schottky approximation. In this case, the voltage variation is limited by the collapse of the SCR, depending on the concentration of donors in the low-alloyed region. A transition when this voltage is exceeded, of course, does not disappear, but the space charge region is absent, and the diffusion approximation ceases to be valid:

$$U_{sh} = 2\cdot\varphi_t\cdot(\ln(N_d/n_i)+\ln(\delta)),$$

where δ is the accuracy of determining the charge in the SCR.

Accounting for the high-alloyed region of the anisotypic *p-n* junction is possible through the contact potential difference (CPD). A more detailed analysis of the voltage variation at the semiconductor junction in the context of the error analysis for estimating the boundary conditions of small currents requires separate consideration.

2. GENERALIZATION OF MODELS OF SHARP ASYMMETRIC SEMICONDUCTOR CONTACTS

Let us consider analytical estimates for two applications: the calculation of the characteristics of a sharp asymmetric semiconductor *p-n* junction and the contact of a metal with a donor semiconductor. We introduce the following characteristics:

$$\Delta\varphi_{ipDob} = \frac{\Phi_M-\chi_i}{q_e}-\frac{\Delta E_g}{2\cdot q_e}-\varphi_t\cdot\ln(\frac{N_c}{N_v}),$$

$$\Delta\varphi_{ni} = \varphi_t\cdot(\frac{1}{2}\cdot(\frac{\Delta E_g}{k_b\cdot T}+\ln(\frac{N_c}{N_v}))-\ln(\frac{N_c}{N_{id}})),$$

$$\varphi_{Dob\_n} = \Delta\varphi_{ipDob}+\Delta\varphi_{ni}\ ,\ \varphi_k = \varphi_{Dob\_n}-U,$$

where $\Delta\varphi_{ipDob}$ is the additional CPD of a heavily doped semiconductor or a metal in the state of thermodynamic equilibrium (TDE) relative to nondoped semiconductor, Φ_M is the work function of a metal or an acceptor semiconductor, $\Delta\phi_{ni}$ is a CPD of a donor semiconductor relative to nondoped semiconductor in the state of TDE, U is a positive voltage applied to the SCR of a semiconductor junction reducing the CPD, φ_k is a CPD across the SCR of a semiconductor junction.

3. DESCRIPTION OF THE SPACE CHARGE REGION MODEL AND THE INITIAL ESTIMATE OF THE RECOMBINATION CURRENT THROUGH THE TRAPS

When estimating the recombination current, for definiteness, consider the SCR in the donor semiconductor. For a sharp asymmetric *p-n* junction, we will have expressions for the junction width and electric field strength:

$$E`_{xp} = -\frac{q_e\cdot N_a}{\varepsilon\cdot\varepsilon_0},\ E`_{xn} = -\frac{q_e\cdot N_d}{\varepsilon\cdot\varepsilon_0},\ \tau = -E`_{xn}/E`_{xp},$$

$$\delta_{n\_пред} = \sqrt{\frac{2\cdot(\varphi_{pn}-U)}{E`_{xn}}},\ \delta_n = \frac{\delta_{n\_пред}}{\sqrt{1+\tau}},\ \Delta\varphi_n = \frac{\varphi_{pn}-U}{1+\tau},$$

where N_a, N_d are the concentration of donors and acceptors, ε is the dielectric constant, ϕ_{pn} is the CPD, U is a positive voltage applied to the semiconductor junction.

Taking into account the effect of mobile carriers on the charge density distribution profile [10], it should be noted that the electric field at the transition boundary does not decrease to zero, but extends into the QNR.

The profiles of the electric field and potential will have the form [4-6]:

$$E_n(x) = -E`_{xn}\cdot(x-\delta_n),$$

$$\Delta\varphi_n(x) = \varphi_n(x)-\varphi_n(\delta_n),$$

$$\Delta\phi_n(x) = -E`_{xn}\cdot\frac{(x-\delta_n)^2}{2},$$

where $\delta_n = \sqrt{\frac{2\cdot(\varphi_{pn}-U)}{E`_{xn}}}$ is the thickness of the SCR, $E_n(x)$ is the profile of the electric field strength in the SCR, $\Delta\varphi_n(x)$ is the increment of the potential in the SCR measured from the boundary of the QNR.

The distribution profiles of the concentrations of electrons and holes in the SCR in the approximation of the smallness of the transition currents will have the form:

$$n(x) = n_0\cdot\exp(-\frac{(x-\delta_n)^2}{L_E}),$$

$$p(x) = p_0\cdot\exp(\frac{U}{\phi_t})\cdot\exp(-\frac{(x-\delta_n)^2}{L_E}),$$

where $L_E = \sqrt{\frac{2\cdot\varphi_t}{E`_{xn}}}$ is the characteristic length of the SCR, n_0, p_0 are the unperturbed concentrations in the depth of the semiconductor, respectively, of electrons and holes.

The estimation of the rate of bulk recombination through the trap was made in the approximation of the prevalence of recombination through one sort of recombination centers [5]. The concentration of free carriers n_L, p_L in the zones when the Fermi level coincides with the level of the trap and the speed of the recombination R_{lov} are:

$$n_L = N_c\cdot\exp(\frac{En_L}{k_b\cdot T})\ ,\ P_L = N_v\cdot\exp(\frac{Ep_L}{k_b\cdot T}),$$

$$R_{lov} = \frac{\gamma_n\cdot\gamma_p\cdot N_L\cdot(n\cdot p-n_0\cdot p_0)}{\gamma_n\cdot(n+n_L)+\gamma_p\cdot(p+p_L)},$$

where v_n, v_p are the average thermal velocities, $\gamma_n = \sigma_n v_n$, $\gamma_p = \sigma_p v_p$, are the coefficients of non-radiative recombination, σ_n, σ_p are the effective cross sections of the processes of non-radiative recombination, N_L is the concentration of traps in the semiconductor.

Considering the approximate equality of recombination coefficients, we make the simplification of the formulas for the rate of bulk recombination:

$$\upsilon = \sqrt{\upsilon_n \cdot \upsilon_p}\ ,\ \ \sigma = \sqrt{\sigma_n \cdot \sigma_p}\ ,$$
$$\nu = \sigma \cdot \upsilon\ ,\ \ \nu = \sqrt{\nu_n \cdot \nu_p}\ ,$$
$$R_{lov} = \frac{\gamma \cdot N_L \cdot (n \cdot p - n_0 \cdot p_0)}{n + n_L + p + p_L}\ .$$

An elementary estimate of the recombination current in the SCR will have the form], but taking into account the fact that the width of the SCR depends on the voltage, the exponent is replaced by a hyperbolic sine, to determine the IVC in the low voltage region, we obtain:

$$j_{rec\_oce} = \frac{2 \cdot q_e \cdot \gamma \cdot N_L \cdot n_i^2 \cdot \delta_n}{n_{n0} \cdot e^{-\frac{\varphi_{pn} - \Delta\varphi_s}{2 \cdot \varphi_t}} + p_{n0} \cdot e^{\frac{\varphi_{pn} - \Delta\varphi_s}{2 \cdot \varphi_t}}} \cdot sh\left(\frac{U}{2 \cdot \varphi_t}\right)\ .$$

Usually, for a symmetric transition, an estimate of the maximum recombination in the middle of the potential jump is chosen. Taking into account the above, the estimated potential for a sharp asymmetric transition needs to be taken on a quarter-vertical of the potential jump of the SCR from the side of the weakly doped QNR (Fig. 1).

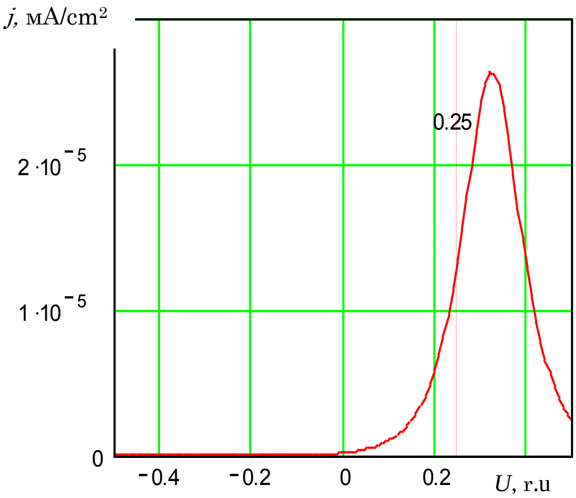

Fig. 1 – Recombination current density (mA/cm²) depending on the applied voltage (relative units in CPD fractions) through the levels of traps located in the middle of the forbidden zone and justification of the choice of a fixed potential cross section of the integral recombination estimate in the SCR

4. MAXIMUM RECOMBINATION CROSS SECTION AND IMPROVED ANALYTICAL EVALUATION OF THE RECOMBINATION CURRENT

Analyzing the true recombination profile, it should be noted that it has a maximum recombination cross section in the SCR [7]. Moreover, as the voltage increases, the coordinate of the maximum recombination profile has a minimum, and then slightly increases (Fig. 2).

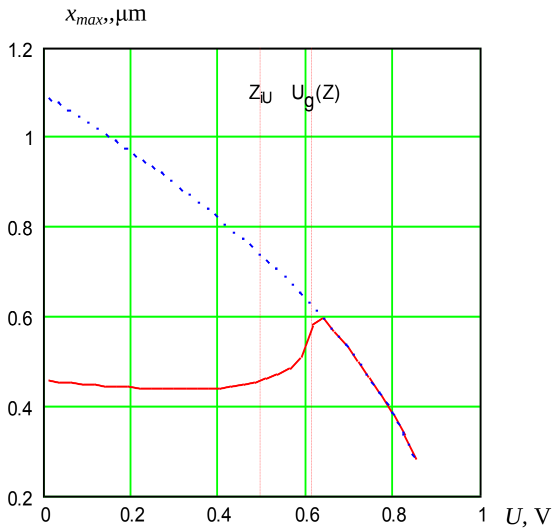

Fig. 2 – Dynamics of the cross section of the maximum recombination with voltage variation on the SCR of the transition (----- is the SCR width, – – is the coordinate of the maximum recombination)

$$x_{max} = \delta_n - \sqrt{\frac{\varphi_t}{E`_{xn}} \cdot \left(ln\left(\frac{n_{n0}}{p_{no}}\right) - \frac{U}{\varphi_t}\right)}\ ,$$
$$x_{max} = \delta_n - \sqrt{\frac{\varepsilon \cdot \varepsilon_0}{q_e \cdot N_{id}} \cdot \left(2 \cdot ln\left(\frac{N_{id}}{n_i}\right) - U\right)}\ ,$$

where x_{max} is the coordinate of the maximum recombination section, $\delta_n = \sqrt{\frac{2 \cdot \varepsilon \cdot \varepsilon_0}{q_e \cdot N_{id}} \cdot (\Delta\varphi_{ipDob} + \Delta\varphi_{ni} - U)}$ is the SCR width.

However, the cross section of the maximum recombination is in the SCR only up to the boundary voltage U_g, and then the cross section of the maximum recombination passes into the low-alloy QNR of the semiconductor

$$U_g = \varphi_t \cdot ln\left(\frac{n_{n0}}{p_{no}}\right)\ .$$

In fact, the boundary voltage is the collapse voltage with equal concentrations of dopants and mobile carriers (100 % error in determining the depleted region) [10], that is, Schottky approximation on the profile of the electric potential ceases to be valid.

Analytical expression of the recombination current through elementary functions is impossible. Therefore, to obtain an analytical representation, an approximation of the linear distribution of the potential in the vicinity of the maximum recombination cross section is used (Fig. 3):

$$E_{max} = E_n(x_{max})\ ,\ \ \Delta\varphi_{max} = \Delta\varphi(x_{max})\ ,$$
$$\Delta\varphi_{n\_apr}(x) = \Delta\varphi_{max} - E_{max} \cdot (x - x_{max})\ .$$

The true and approximation recombination profiles, in the approximation of linearity of the potential in the vicinity of the maximum recombination cross section, will look like that shown in Fig. 4.

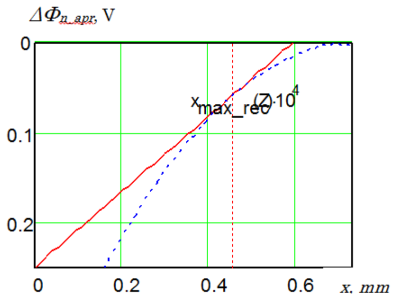

Fig. 3 – Linear approximation of the distribution of the SCR potential in the vicinity of the cross section for maximum recombination (— linear approximation, - - - real distribution)

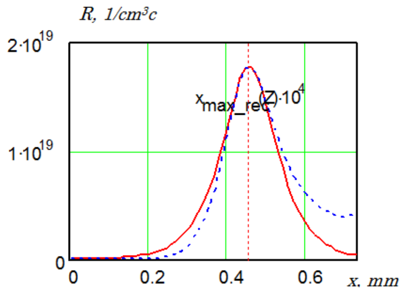

Fig. 4 – Dependence of the rate of volume recombination on the coordinate in the SCR (— linear approximation ΔΦn_apr, - - - real distribution)

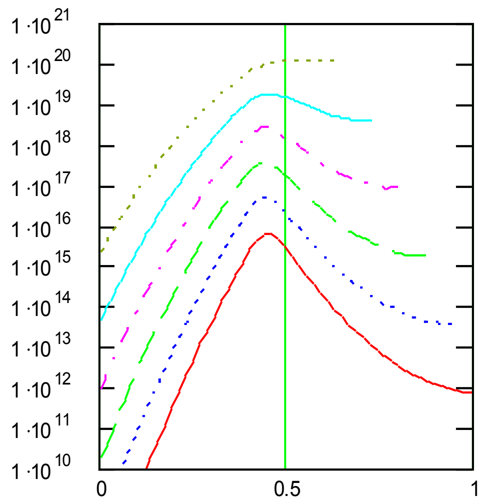

Fig. 5 – Changes in the velocity profile of the bulk recombination in the SCR at voltages $U = 0.1...0.6$ V, (bottom to top)

The dynamics of the change in the recombination profile with voltage is shown in Fig. 5. From a comparative analysis of the recombination profiles, it can be seen that in the depth of a semiconductor, the use of approximation leads to an underestimation of the recombination rate, with the maximum recombination cross section approaching the SCR-QNR boundary, the electric field strength decreases to zero. In fact, the strength of the electric field does not decrease to zero, gradually passing into the QNR.

Thus, the limit of application of the approximation is determined by the integral error of the approximation of the potential of the SCR, within the limits of a change in the recombination profile from the maximum to values that contribute within the error limits of the recombination integral.

5. NUMERICAL EXPERIMENT

The numerical experiment was performed on the hyper-space of scalar parameters, the characteristics of which are given in Table 1.

Table 1 – Characteristics of the parameters of the model

Designation	Minimum	Support	Maximum	Points	Unit
U	0.01	0.5	0.85	33	B
N_d	10^{15}	10^{15}	10^{18}	13	1/cm³
N_L	10^{10}	10^{12}	10^{15}	13	1/cm³
E_r	– 0.28	– 0.56	– 0.84	33	eV
dn	0.01	0.03	0.03	7	S

Non-radiative recombination coefficient through recombination centers for Si adopted $\gamma = 3.3 \cdot 10^{-7}$ cm³/s. The formulas for the approximation coefficients will be:

$$k > 0 \ , \ k = -\frac{E_{max}}{\varphi_t} \ , \ a = \gamma \cdot N_L \cdot n_i^2 \cdot (e^{U/\varphi_t} - 1) \ ,$$

$$b = n_{n0} \cdot e^{\frac{\varphi_{max} + E_{max} \cdot x_{max}}{\varphi_t}} \ , \ c = p_{no} \cdot e^{\frac{U}{\varphi_t}} \cdot e^{-\frac{\varphi_{max} + E_{max} \cdot x_{max}}{\varphi_t}} \ ,$$

$$d = n_L + p_L \ ,$$

where k, a, b, c, d are the auxiliary coefficients of the analytical estimates of the current recombination in the SCR.

The general form of the approximation profile in the approximation of the linearity of the potential in the vicinity of the recombination maximum will be:

$$R_{lov\_apr}(x) = \frac{a}{b \cdot e^{k \cdot x} + c \cdot e^{-k \cdot x} + d} \ .$$

The analysis of the magnitudes of the terms of the denominator of the formula R_{lov_apr} in the context of substantiating the two-region simplified approximation is shown in Fig. 6 (it gives a small error in the field of average voltages on the SCR):

$$j_{app} = \frac{q_e \cdot a}{k} \cdot \left(\frac{e^{k \cdot x_{max}}}{c} + \frac{e^{-k \cdot x_{max}}}{b} \right) .$$

The antiderivative approximation of the analytical calculation of the recombination current in the SCR region is:

$$I_{ana} = \int \frac{a}{b \cdot e^{k \cdot x} + c \cdot e^{-k \cdot x} + d} dx \ ,$$

$$I_{ana} = \frac{2 \cdot a \cdot \arctan\left(\frac{2 \cdot b \cdot e^{k \cdot x} + d}{\sqrt{4 \cdot c \cdot b - d^2}} \right)}{k \cdot \sqrt{4 \cdot c \cdot b - d^2}} \ .$$

It should be noted that the integral estimate of the recombination current in the SCR is valid only at a sufficiently low concentration of non-radiative recombination traps, and is limited by the positivity of the root primitive expression.

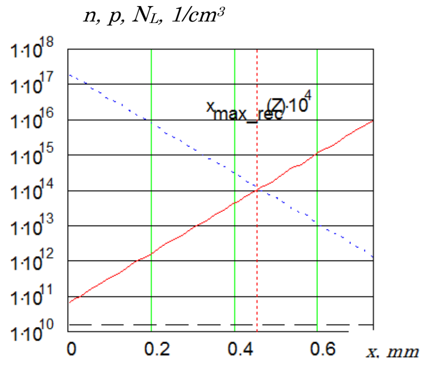

Fig. 6 – Distribution of concentrations of mobile carriers and traps in the SCR (- electrons, - - - holes, – – traps)

The estimate of the recombination current in the low-alloyed QNR will be:

$$j_{rno} = \frac{q_e \cdot d_{kno} \cdot \gamma \cdot N_L \cdot n_i^2 \cdot (e^{U/\varphi_t} - 1)}{n_{n0} + n_L + p_{no} \cdot e^{U/\varphi_t} + p_L},$$

wehere d_{kno} is the thickness of the QNR.

The lower estimate of the recombination current in the QNR is approximated, when the thickness of the QNR is much less than the diffusion length of the minority carriers. In reality, the recombination current in the QNR of PEC will be greater due to the excess concentration of minority carriers over the concentration at the boundary of the spatial charge region.

To analyze the IVC, we introduce the integral ideality coefficient of the IVC from the expression [5]:

$$j = j_s \cdot (\exp(\frac{U}{m_I \cdot \varphi_t}) - 1),$$

where j_s is the saturation current.

For a more detailed analysis of the IVC, we define the differential ideality coefficient of the IVC:

$$m = (\frac{j}{\frac{\partial j}{\partial U}}) \cdot \frac{1}{\phi_t \cdot (1 - \exp(-\frac{U}{\phi_t}))}.$$

The change in the differential ideality coefficient for the recombination profile calculated from the integral of the Schottky concentration profiles is shown in Fig. 7. Connection of integral and differential ideality coefficient is written as:

$$m_I = \frac{1}{U_f - U_s} \cdot \int_{U_s}^{U_f} m(U) dU,$$

where U_s, U_f are the initial and final values of the voltage interval, in which the average coefficient of integral ideality is identified.

By virtue of the above, the differential ideality coefficient m can serve as a diagnostic indicator of the mechanism of prevailing recombination in the semiconductor transition. The dependence of m on the junction voltage is shown in Fig. 7.

The results of the analytical estimates are presented in Fig. 8. From the results of the numerical experiment it can be seen that for a typical thickness (100-300 μm) of the PEC, at typical voltages (0.4-0.6 V), the recombination current in the SCR is much less than the recombination current on traps in the QNR. From this it follows that for solar cells with typical thicknesses, the recombination current in the SCR can be neglected.

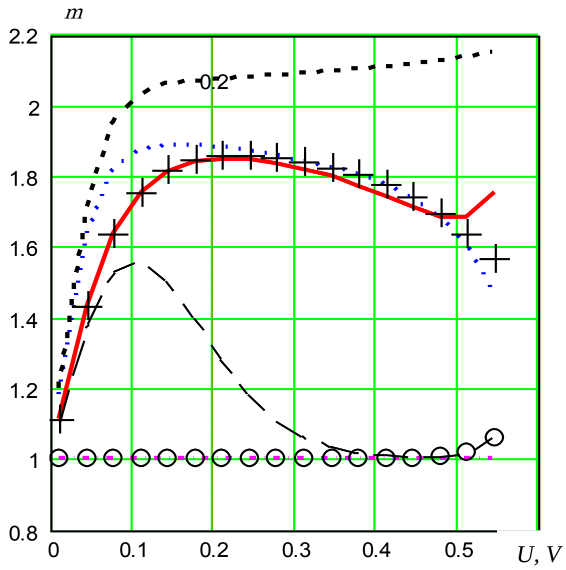

Fig. 7 – Calculations of the ideality coefficient for the two-region approximation (...), the integral recombination current (—), taking into account the recombination maximum by a quarter of the potential jump (-), the QNR dark current (-.-), the PEC current in the QNR (ooo), total current PEC (– –)

From a comparison of elementary estimates with approximate estimates, it is obvious that they behave like functions with exponential multiplier, which corresponds to the approximation parameter of the experimental data of the I-V characteristic with the ideality coefficient $m = 1...2$. The experimental ideality coefficient, in contrast to the approximation parameter, has a constant value. If the recombination current is accurately taken into account, there are two subregions of voltage variation for the value of this parameter (see Fig. 7, Fig. 8):

– a subregion, in which the recombination in the SCR prevails with the ideality coefficient $m = 1...2$;

– a subregion, in which the recombination in the QNR with a coefficient of ideality $m = 0.5...2$ prevails.

It should be noted that in the last subregion, the recombination will depend on the thickness of the QNR, the recombination rate at the rear contact, and the profile of the generation function in the semiconductor. The value of the ideality coefficient less than unity is possible for active PEC regimes, in which the diffusion length is less than the PEC thickness.

6. ANALYSIS OF THE ERRORS OF THE ANALYTICAL ESTIMATES OF THE CURRENT RECOMBINATION

The error analysis of the recombination current calculation from the doping level of the low-doped area and the applied voltage on the SCR is shown in Fig. 9, Fig. 10 and Fig. 11.

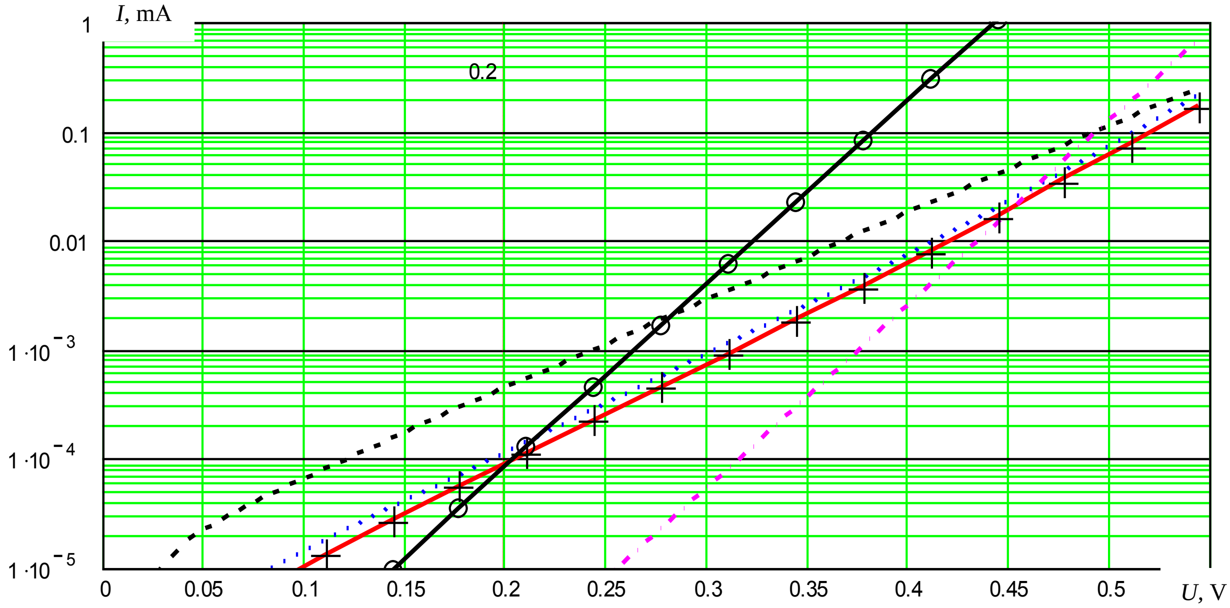

Fig. 8 – Comparative analysis of recombination current estimates: --- an elementary estimate of the recombination current in the SCR, -.- diffusion current from low-alloyed QNR, ooo recombination through QNR traps, +++ linear approximation of the potential in the region of maximum recombination via an analytical integral, ... linear approximation of the potential in the region of maximum recombination, —— the real recombination current

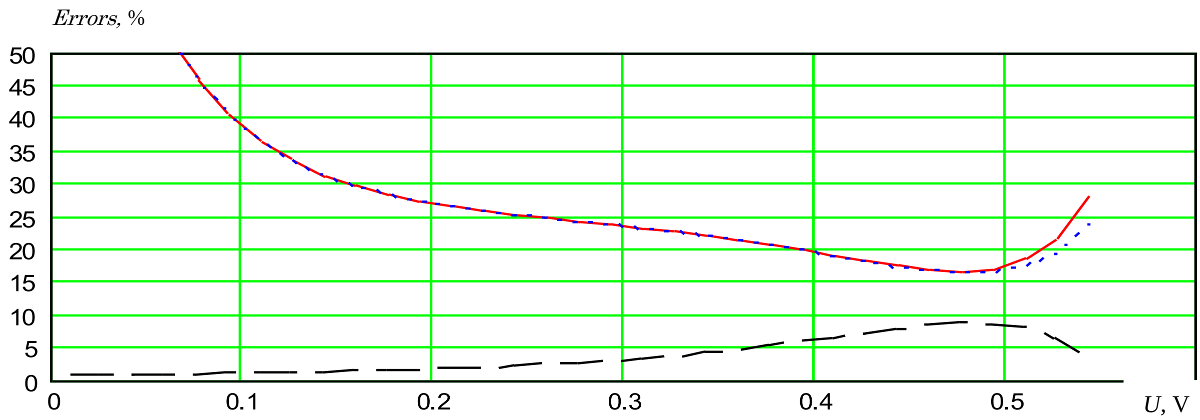

Fig. 9 – Comparative analysis of errors of recombination current estimates in SCR: — recombination in the approximation of fast exponents decay, — recombination through simplified integrals over a finite region, - - estimate through an analytical integral

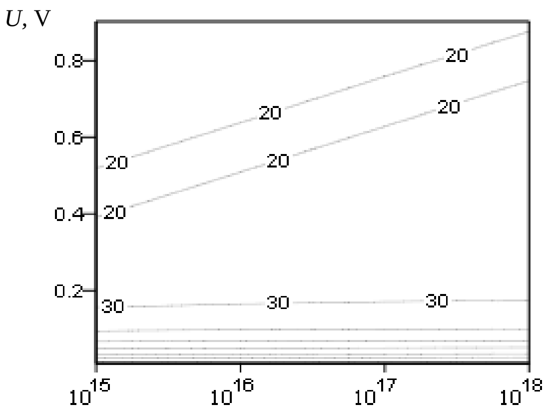

Fig. 10 – The relative error (in percent) of the two-zone approximation of the recombination current in the SCR at different voltages on the SCR and doping levels

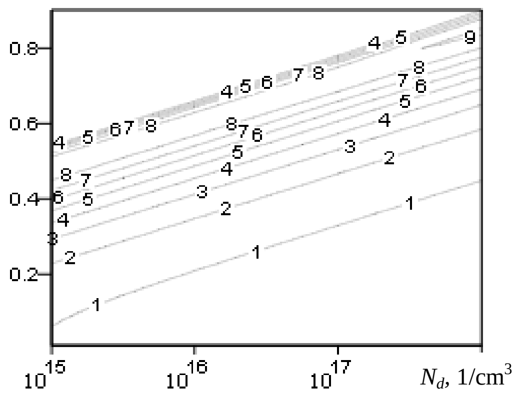

Fig. 11 – The relative error (in percent) of the approximation of the recombination current in the SCR when calculated through the analytical integral at different voltages on the SCR and doping levels

From the presented data it is clear that the estimate of the error in calculating the current through the analytical integral does not exceed 10 %, which is quite enough for its use in simulating the recombination current of most semiconductor devices.

The incomplete filling of the graphs is due to the dependence of the collapse voltage [6] on the doping level of the base transition region.

7. CONCLUSIONS

In this paper, we proposed analytical estimates of the integral of the specific volume recombination rate over a SCR that cannot be taken through elementary functions, and confirmed the possibility of refining the analytical estimate of the recombination current through traps in the space charge region. With such an assessment, the maximum error decreases in some cases by more than 50 times compared with the standard estimate (Fig. 9, Fig. 10, Fig. 11). In this case, the error increases when the cross section (coordinate) of the maximum recombination approaches the boundary of the SCR-QNR region.

In the process of searching for a refining analytical assessment, it was revealed that the increase in its error when the maximum recombination cross section passes from the SCR to the QNR is due to the error of the Schottky model, especially when the SCR disappears [6]. It can be reduced by appropriate definitions at voltages of the disappearance of the SCR according to the Schottky model [6], but at the same time other factors play a primary role:

– it is necessary to take into account the distribution of mobile carriers in the SCR with both signs;

– currents flowing through the semiconductor junction;

– dependence of mobile carrier concentrations on non-equilibrium Fermi quasi-levels.

But, even neglecting these refinements, the reduced analytical estimate of the recombination current will make it possible to more accurately estimate the magnitudes of the recombination currents of semiconductor junctions in the simulation of power semiconductor devices.

Also in this paper, the differential coefficient of ideality was introduced into consideration and its connection with the integral (ordinary) ideality coefficient [5-7, 9]. The wider possibilities of the differential coefficient of ideality are shown in the context of the diagnosis of the prevailing recombination mechanisms. The sensitivity of the differential ideality coefficient for detecting the prevailing semiconductor junction recombination mechanism depending on the applied voltage was clearly shown (a sharp jump in Fig. 7). The behavior of the differential ideality coefficient was studied for several variants of the recombination current in the SCR.

The disadvantages of the differential ideality coefficient were also identified due to its dependence on the rate of change of the equivalent thickness of the SCR from the applied voltage, especially in the area of the voltage of the SCR. For an adequate assessment, it is necessary to decompose the differential coefficient of ideality into factors responsible separately for the recombination mechanism and the effective thickness of the recombination, but due to the wideness of this topic, this issue requires a separate consideration.

From the analysis of the results obtained in this work (Fig. 7 and Fig. 8), it should be noted that even the lower estimate of the recombination current in the QNR in a solar cell with a typical base thickness of 0.01 cm is much higher than in SCR. Therefore, for solar cells, it is necessary to take into account the recombination current through the lifetime in the QNR, for typical voltages and illumination of solar cells [2, 3].

The resulting analytical assessments will be widely used in the following applications:

– simulation of the IVC of semiconductor heterojunctions or metal-semiconductor junctions [1],

– study of the processes of non-radiative recombination of semiconductors,

– improved analysis of the structure of semiconductor junctions by the differential ideality coefficient [6].

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Аналітична оцінка струму рекомбінації різкого асиметричного p-n переходу

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При моделюванні асиметричного p-n переходу високолегована область в наближенні малих струмів не впливає на розподіл носіїв в низьколегованої області, в якій зосереджений весь об'ємний заряд. У даній роботі проведена аналітична оцінка струму рекомбінації через пастки в області просторового заряду і в квазинейтральной області. Для отримання аналітичного уявлення застосовується наближення лінійності розподілу потенціалу в околиці перетину максимальної рекомбінації. Запропоновано методику аналітичної оцінки інтеграла питомої об'ємної швидкості рекомбінації по області просторового заряду, що не береться через елементарні функції. Підтверджено можливість підвищення точності аналітичної оцінки рекомбінаційного струму через пастки в області просторового заряду. Визначено диференційний коефіцієнт ідеальності і проаналізована його динаміка в залежності від напруги на переході. Виконано порівняльний аналіз наступних оцінок струму рекомбінації: струм рекомбінації в області просторового заряду за елементарної оцінки, дифузний струм з низьколегованої квазинейтральної області, струм рекомбінації через пастки в квазинейтральної області, струм у разі лінійної апроксимації потенціалу в області максимальної рекомбінації через аналітичний інтеграл, реальний струм рекомбінації. Наведено аналіз похибки розрахунку струму рекомбінації від рівня легування слаболегірованних області і прикладеної напруги. З наведених даних видно, що оцінка похибки розрахунку струму через аналітичний інтеграл не перевищує 10 % що цілком достатньо для її застосування при моделюванні струму рекомбінації більшості силових напівпровідникових приладів.

Ключові слова: Рекомбінація через пастки, Струм рекомбінації, Коефіцієнт ідеальності, Диференційний коефіцієнт ідеальності, Фотоперетворювач, Похибка розрахунку.