KINETICS OF PHOTOCONDUCTIVITY IN MACROPOROUS SILICON STRUCTURES

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Relaxation of photoconductivity in macroporous n-silicon structures has been studied. The corresponding effective relaxation time was found to be governed by the barrier mechanism, and the relaxation itself to follow the logarithmic law. The relaxation time of photoconductivity in macroporous silicon turned out by an order of magnitude larger than that in single-crystalline silicon. The temperature dependence of the relaxation time of photoconductivity was found to be governed by the thermoemission mechanism of the current transport in the space-charge region (SCR) at temperatures higher than 150 K, by the recombination mechanism in the temperature range 150–100 K, and by the processes of tunnel current transport at temperatures below 100 K. The probability of tunneling, the lifetime of photocarriers, and the cross-section of their capture are established to be independent of the temperature.

1. Introduction

Macroporous silicon structures, in contrast to micro- and mesoporous ones, are a material with a system of cylindrical air channels arranged in parallel to one another and normally to the substrate surface. Such structures are characterized by a large effective area of the surface, and this circumstance essentially affects the optical, electrophysical, and photo-electrical properties of the material. Macroporous silicon structures are promising for application in the infra-red spectral range owing to their enhanced optical absorption [1], enhanced photoconductivity in the range of fundamental absorption [2], and to the emergence of additional photoconductivity bands [3]. Effects of light absorption enhancement in a two-dimensional photonic macroporous silicon structure, which are by almost two orders of magnitude larger in comparison with those in single-crystalline silicon, have been measured for wavelengths shorter than the optical period of those structures [1]. The angular dependences of photoconductivity and the prevalence of light absorption over light reflection, which macroporous silicon structures demonstrate, were explained by the interaction between the optical modes and the vibrations of oscillators on the macropore surface, as well as by the formation of optical polaritons [2]. The dependences of the electron conductivity, concentration, and mobility on the macropore size and the concentration have been studied on two-layer structures "macroporous silicon–silicon" [4]. Both the microstructure of the macropore surface and the built-in electric field were found to depend on the parameters of the electrochemical process: the initial voltage and the current density [5]. In so doing, the sign of the main maximum in electroreflection spectra and the dependence of its amplitude on the dc voltage correspond to the formation of inversion layers (or Schottky layers) at the macropore surface [6]. Such specimens are characterized by a high photoconductivity, which allows the mechanisms of charge carrier transport and recombination to be determined. In this connection, in this work, the kinetics and the temperature dependence of photoconductivity in macroporous silicon structures have been experimentally studied and theoretically analyzed.

The analysis has been carried out taking into account the mechanism of current transport through a barrier in the SCR at the macropore surface and the mechanism of recombination of photo-induced charge carriers through surface levels. The models of "frozen" or barrier photoconductivity, which have been considered earlier in works [7–9] are mathematically based, as a rule, on a linear model; i.e. the variation of the surface band bending at illumination is supposed to be less than kT/e, and the photoconductivity to depend linearly on the illumination intensity. In this work, we examine the case where the variation of the surface band bending at illumination is larger than kT/e and the photoconductivity nonlinearly depends on the illumination intensity.

According to the results of work [6], photoconductivity in macroporous silicon structures is associated with a reduction of space charge layers at illumination and has the electron character. In this case, there are two reasons why the photoconductivity component related to holes can be neglected. First, the hole mobility is much lower than the electron one, because holes exist only near

the macropore surface. Second, the effective relaxation time of photoconductivity associated with holes is much shorter than that related with electrons, because there is no barrier for holes at the surface.

2. Experimental Dependences of the Photoconductivity Relaxation in Macroporous Silicon Structures

Specimens made up of macroporous silicon and characterized by the n-type of conductivity, the equilibrium electron concentration $n_0 = 10^{15}$ cm^{-3}, the resistance of 4.5 $\Omega \times$ cm, the [100] orientation, and the thickness $H = 400 \div 450$ μm were studied. The method of electrochemical etching at illuminating the back side of a silicon substrate [10,11] was used to form cylindrical macropores of the depth $h_p = 140 \div 150$ μm. The macropores were arranged irregularly (Fig. 1). Their average diameter was $D_p = 2 \div 9$ μm, the average distance between macropores was $a = 4.5 \div 10$ μm and between the macropore edges $a - D_p = 1 \div 2.5$ μm (see the Table).

The ohmic contacts In/single-crystalline n-Si and In/macropore n-Si with a transient resistance of $4 \div 10$ $\Omega \times$ cm^2 were fabricated by thermal deposition of indium in a 4-probe configuration; the distance between the contacts was 4 mm [4]. The electrophysical parameters of macroporous silicon structures were measured at room temperature taking advantage of the four-probe Hall method and in the dc mode. The Table demonstrates that, without being illuminated, macroporous silicon specimens with a small macropore diameter and a large pore-to-pore distance (i.e. when the volume of the silicon matrix is maximal) are characterized by the effective values of resistance ρ_{eff} and current carrier concentration n_{eff} which are close to the corresponding values for a single-crystalline silicon substrate. As the diameter of macropores increases and the distance between them diminishes, the influence of a non-uniform distribution of charge carriers and the enrichment of the near-surface layer (the Schottky layer w, see Fig. 1) by the minority charge carriers grow substantially.

Parameters of macroporous silicon structures

N	H, μm	h_p, μm	D_p, μm	$a - D_p$, μm	ρ_{eff}, $\Omega \times$ cm	n_{eff}, 10^{16}cm^{-3}
1	450	140	2	2.5	4.6	0.23
2	400	150	3	1.5	1.17	2.5
3	400	150	9	1	0.44	1.8
4	450	Si single crystal			3.8	0.22

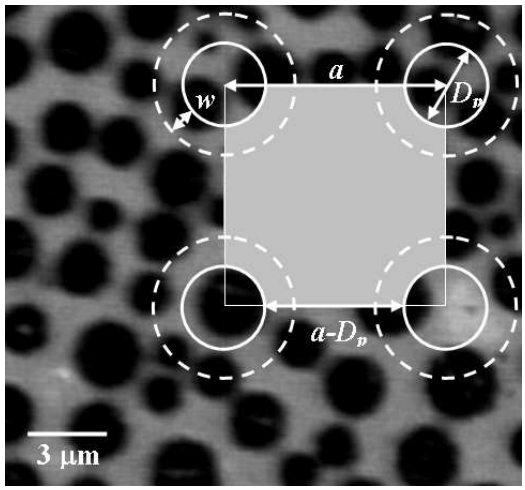

Fig. 1. Microphoto of a macroporous silicon structure with cylindrical macropores. In the inset, the schematic image of a macroporous silicon structure is given: D_p is the macropore diameter, a is the distance between macropores, $a - D_p$ is the distance between the edges of macropores, and w is the Schottky layer thickness

The relaxation of photoconductivity in specimens made up of macroporous and single-crystalline silicon was measured provided that light fell normally to the surface, the contacts were screened, and the nonequilibrium current carriers were pulse-excited making use of a GaAs laser diode with a pulse duration of 40 ns and a wavelength of 0.88 μm. The laser pulse intensity at measurements was 10^{16} photon/(cm$^2 \times$ s).

In Fig. 2, the experimental dependences of the photoconductivity relaxation in macroporous silicon specimen No. 1 (see the Table) at various temperatures are depicted. Note that the photoconductivity kinetics cannot be approximated by an exponential relaxation law. The characteristic relaxation times of photoconductivity in macroporous silicon are of the order of hundreds of microseconds at room temperature and tens of milliseconds at temperatures $T < 200$ K, which is almost an order of magnitude larger than the corresponding value for single-crystalline silicon.

In Fig. 3, the temperature dependences of the effective relaxation time of photoconductivity τ_{eff} in macroporous silicon are exhibited. In the range $T = 200 \div 300$ K, the temperature dependence has an activation character with an activation energy of (0.3 ± 0.01) eV. After the temperature has fallen below 180 K, the value of the parameter τ_{eff} becomes practically independent of the temperature. The temperature

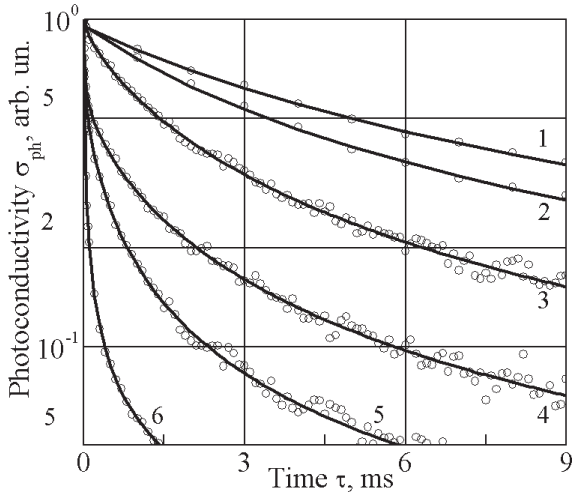

Fig. 2. Experimental (circles) and theoretical (curves) dependences of photoconductivity relaxation in macroporous silicon specimen N 1 at various temperatures: 80 (*1*), 100 (*2*), 160 (*3*), 220 (*4*), 240 (*5*), and 300 K (*6*)

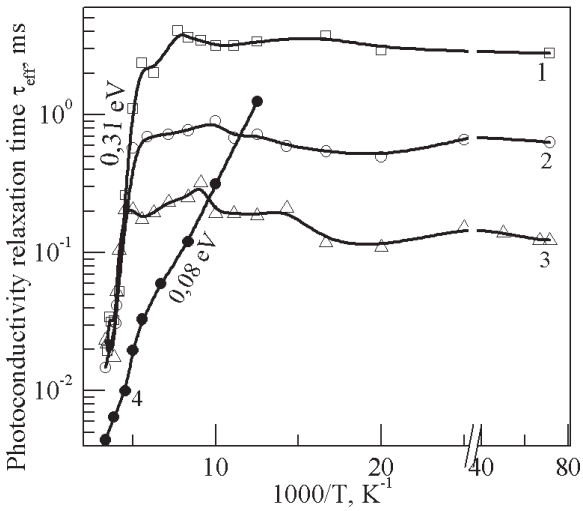

Fig. 3. Temperature dependences of photoconductivity relaxation time in various macroporous silicon specimens: N 1 (*1*), N 2 (*2*), N 3 (*3*), and a single-crystalline one (*4*)

dependence of the relaxation time of photoconductivity in single-crystalline silicon is characterized by a lower activation energy (less that 0.08 eV), and it correlates with the temperature dependence of the capture cross-section for a repulsive center [12].

The previous results of electrophysical researches of the barrier junction [13] "indium–macroporous silicon" not subjected to illumination evidence for the implementation of the thermoemission and tunnel mechanisms of the current transport by charge carriers. The thermoemission mechanism of the current transport has an activation energy of about 0.25 eV and dominates within the temperature interval of 180 – 300 K, which correlates with the data concerning the temperature dependence of the photocarrier lifetime (Fig. 3). Hence, the activation temperature dependence of the photocarrier lifetime in macroporous silicon structures is governed by the potential barrier in the near-surface region of macropores. It is connected with the fact that the barrier interferes with the recombination between photoelectrons in the silicon matrix and holes at the silicon surface. At temperatures $T < 100$ K, the lifetime of photocarriers becomes temperature-independent (Fig. 3). According to the results of work [13], it is in the low temperature interval $T = 77 \div 100$ K that the nonideality factor β for nonlinear current-voltage characteristics grows from 1.5 to 5 as the temperature decreases, which is typical of the tunnel mechanism of current transport.

3. Theoretical Analysis of Photoconductivity Relaxation in Macroporous Silicon Structures

According to the results of the previous section, the relaxation of photoconductivity in two-dimensional macroporous silicon structures has some specific features in comparison with that in single-crystalline silicon specimens. The origin of those features is that, owing to the developed surface of macropores, the majority of light-generated electron-hole pairs are brought into the SCR at the macropore surface, which is a potential well for charge carriers of one sign (holes) and a potential barrier for charge carriers of the opposite sign (electrons). While analyzing the photoconductivity relaxation in macroporous silicon, the fact is to be taken into account that the barrier height depends on the intensity of illumination and changes during the process of photoconductivity relaxation. This phenomenon should result in a non-exponential character of relaxation (Fig. 2) and in the growth of the effective lifetime value in the course of relaxation in comparison with the single-crystalline silicon case (Fig. 3), according to the experimental results.

To simulate the kinetics of photoconductivity, we consider a macroporous silicon structure with cylindrical macropores. The elementary cell of such a structure is presented in the inset in Fig. 1. Light, when falling perpendicularly onto the surface of a macroporous silicon specimen, is absorbed both at the surface and

at the bottom of macropores. In so doing, the main fraction of incident light is absorbed by silicon located between macropores, because the ratio between the photoconductivity components, which correspond to light absorption at the pore surface, σ_1, and at the pore bottom, σ_2, amounts to $\sigma_1/\sigma_2 = 2h/r \approx 80 \div 400$ for specimens under investigation.

In accordance with experimental data [4–6], let us assume that, in the SCR adjacent to the surface of cylindrical pores, there exist equilibrium band bendings which correspond to the strong depletion or inversion of conductivity, and that electrons are the majority charge carriers. Consider first the kinetics of photoconductivity relaxation, without taking into account the recharging of surface levels at illumination and admitting the relaxation processes to be bipolar. Under those assumptions, the law of photoconductivity relaxation, according to the results of work [14], can be determined making allowance for the recombination processes occurring in both the SCR and the neutral regions between macropores:

$$\frac{d(\Delta P + \Delta p(t) d_{\rm por}/2)}{dt} = -\left[S(t) + \frac{d_{\rm por}}{2\tau_B}\right]\Delta p(t), \qquad (1)$$

where $\Delta P(t) = L_{\rm D}\Delta p(t)\exp(-y_s(t))(-y_s(t))^{-0,5}$ at depleting band bendings, and $\Delta P(t) = 2L_{\rm D}\left[(n_0\Delta p(t)\exp(-y_s(t)))^{0.5} - (n_0 p_0\exp(-y_{s0}))^{0.5}\right]$ at inversion ones. The following notations were used in Eq. (1): τ_B is the lifetime of a charge carrier in the bulk of the specimen; $L_{\rm D}$ is the Debye screening length; n_0 and p_0 are the equilibrium concentrations of electrons and holes, respectively, in the semiconducting specimen; y_{s0} is the equilibrium band bending at the interface "macropore surface–silicon"; and $d_{\rm por}$ is the distance between the edges of macropores. For the quantities which depend on the time interval after the illumination having been switched off, we used the following notations: $\Delta P(t)$ is a variation of the Gibbs excess for nonequilibrium holes, $S(t)$ is the effective rate of surface recombination, $\Delta p(t)$ is the excess concentration of electron-hole pairs, and $y_s(t)$ is the dimensionless nonequilibrium band bending at the surface.

Equation (1) is to be supplemented by the equation of integral neutrality:

$$\sqrt{\frac{\Delta p(t)\exp(-y_s(t))}{n_0} - y_s(t)} = \sqrt{\frac{p_0\exp(-y_{s0})}{n_0} - y_{s0}}. \qquad (2)$$

Making use of Eqs. (1) and (2), one can demonstrate that, in the approximation where the depleting band bendings persist both in darkness and at illumination, the instant relaxation time of photoconductivity $\tau_{\rm kin}(t) = \Delta p(t)/(d(\Delta p(t)/dt))$ can be written down as follows:

$$\tau_{\rm kin}(t) = \left(\frac{1}{\tau_B} + \frac{2S(t)}{d_{\rm por}}\right)^{-1}\left(1 + \frac{2}{d_{\rm por}}\cdot\frac{d\Delta P(t)}{d\Delta p(t)}\right), \qquad (3)$$

where

$$d\Delta P(t)/d\Delta p = L_D\exp(-y_S(t))/\sqrt{-y_S(t)}$$

at depleting band bendings, and

$$d\Delta P(t)/d\Delta p(t) = 2L_{\rm D}\sqrt{n_0}[\sqrt{\exp(-y_S(t))/\Delta p(t)} -$$

$$-\sqrt{p_0\exp(-y_{S0})}$$

at inversion ones. Provided that the inequality $\frac{2}{d_{\rm por}}\frac{d\Delta P(t)}{d\Delta p(t)} \gg 1$ holds true, dependence (3) corresponds to the instant relaxation time for the barrier mechanism, when a variation of the barrier height is taken into account. The relaxation time of photoconductivity can substantially grows in this case.

Bearing in mind the results of the previous analysis, consider the effective rate of recombination at the macropore surface, provided that there is a single discrete surface level located near the middle of the energy gap:

$$S(t) \approx (C_p C_n N_t(n_0 + \Delta p(t)))/(C_n n_0\exp(y_{s0} +$$

$$+\Delta y_s(t)) + C_p\Delta p(t)\exp(-y_{s0} - \Delta y_s(t))), \qquad (4)$$

where C_p and C_n are the capture coefficients of holes and electrons, respectively, onto the surface recombination level; and N_t is the concentration of surface recombination levels.

Depending on the initial equilibrium surface band bending and the value of $\Delta p(t)$ in the denominator of formula (4), either the first or second summand can dominate. For instance, the first term dominates, if the depleting and inversion band bendings are large and the quantities $\Delta p(t)$ are rather small, while the second term dominates, provided that the depleting band bendings are not very large, or in the case of inversion bands, if the $\Delta p(t)$-values are large enough. In the former case, the law of photoconductivity relaxation looks like

$$\sigma(t) \approx \sigma(t=0)\ln\left[\left((1 + \frac{t}{\tau_1})\right)^{-1}\right], \qquad (5)$$

where

$$\tau_1 \approx \frac{L_{\rm D} e^{-y_s(t=0)}}{C_n N_t \sqrt{-y_s(t=0)}}.$$

As is seen from Eq. (5), the relaxation of photoconductivity is exponential only at the beginning of the process, when the inequality $t < \tau_1 \exp\left[-\Delta y(t=0)\right]$ is obeyed. If the opposite inequality is valid, i.e. the relaxation times are rather large, the photoconductivity diminishes logarithmically in time. In this case, the law of photoconductivity relaxation reads

$$\sigma(t) = \sigma(t=0)\exp(-t/\tau_2), \tag{6}$$

where

$$\tau_2 \approx \frac{L_D}{C_p N_t \sqrt{-y_s(t=0)}}. \tag{7}$$

The analysis made above is valid only for the case of the thermoemission mechanism of a current flow through the SCR in silicon. At the same time, while studying the regularities of the photoconductivity relaxation in macroporous silicon in a wide range of temperatures and excitation levels, other mechanisms should also be taken into account, in particular, the recombination and tunnel ones. Below, we present the calculation procedure for the kinetics of the photoconductivity relaxation in macroporous silicon, proceeding from the assumption that the photoconductivity is governed by nonequilibrium electrons which partially fill the equilibrium Schottky layer, i.e.

$$\sigma_{\rm ph} = q\mu_n \Delta N, \tag{8}$$

and their Gibbs excess – the concentration of nonequilibrium electrons in terms of $\rm cm^{-2}$ units – is determined by the expression

$$\Delta N = 2L_{\rm D} n_0 (\sqrt{y_0} - \sqrt{y_0 - \Delta y_s(t)}), \tag{9}$$

where $y_0 = -y_{s0}$ in the case of depleting band bendings or $y_0 = 2\ln(n_0/n_i)$ in the case of inversion band bendings at the pore surface.

Let the kinetic equation for finding the law of photoconductivity relaxation be written down in the form

$$\frac{d\Delta N}{dt} = -j_r(t). \tag{10}$$

The quantity $j_r(t)$ is a recombination flux which is determined from the current-voltage characteristics of a Schottky contact (or p–n-junction), provided that the circuit is broken:

$$j_r(t) = \frac{J_s}{q}\left(\exp\left(\frac{\Delta y_s(t)}{\beta}\right) - 1\right), \tag{11}$$

where J_s is the surface density of the saturation current, and β is the coefficient of CVC nonideality.

Substituting Eq. (11) into Eq. (10) and finding the solution of the equation obtained, which satisfies the initial conditions, we obtain that, in the case $\Delta y_s(t) > 1$,

$$\Delta N(t) \approx$$

$$\approx 2L_{\rm D} n_0 (\sqrt{y_0} - \sqrt{y_0 - \Delta y_s(t=0) + \beta \ln(1 + t/\tau_r)}), \tag{12}$$

where

$$\tau_r = \frac{q\beta n_0 L_{\rm D}}{J_s \sqrt{y_0}} \exp\left(-\frac{\Delta y_s(t=0)}{\beta}\right). \tag{13}$$

The magnitude of the effective time of photoconductivity relaxation $\tau_{\rm eff}$, after which the photoconductivity becomes half as high, is determined from the equation

$$\frac{\sqrt{y_0} - \sqrt{y_0 - \Delta y_s(t=0) + \beta \ln(1 + \tau_{\rm eff}/\tau_r)}}{(\sqrt{y_0} - \sqrt{y_0 - \Delta y_s(t=0)})} = \frac{1}{2}. \tag{14}$$

Let us analyze the temperature dependence of the effective time of photoconductivity relaxation $\tau_{\rm eff}$ in macroporous silicon. In so doing, we take into consideration that, in the range of high enough temperatures, where the thermoemission mechanism of current flow dominates, $\beta = 1$ and the temperature dependence of saturation current depends on the band bending at the surface. For instance, provided the inversion band bending at the surface of macroporous silicon, we have $J_s \sim n_i^2 \sim \exp(-E_g/kT)$ for the p–n-junction, and the quantity $\tau_r \sim \exp((E_g - q\Delta\varphi(t=0)/kT)$ grows exponentially as the temperature decreases. Therefore, the value of $\tau_{\rm eff}$ substantially increases with the temperature reduction.

Under conditions that there is no conductivity inversion at the macroporous silicon surface and only the concentration inversion takes place (i.e. $< p_s < n_i$), and that the recombination current is determined by the surface recombination current, one can take advantage of the model of discrete surface level, the position of which is close to the middle of the energy gap [14], in order to find both the saturation current and its

temperature dependence. In this model, a quasi-equilibrium state is established in the exchange between the surface level and the valence band, and the recombination is governed by the capture of an electron from the conduction band onto the surface level. In this case, in accordance with the Shockley–Reed–Hall statistics of recombination,

$$j_r(t) = C_{nt}(N_t - n_t)n_0 \exp(-y_0)\left(\exp\left(\Delta y_s(t)\right) - 1\right), \tag{15}$$

where n_t is the nonequilibrium concentration of electrons at the surface level.

By comparing expressions (11) and (15), we obtain

$$J_s = qC_{nt}(N_t - n_t)n_0 \exp(-y_0). \tag{16}$$

The quantity n_t depends on time. However, in the nonlinear case where $\Delta y_s(t = 0) \gg 1$, the value of $\exp(\Delta y_s(t))$ changes by several orders of magnitude after the illumination has been switched off, whereas the quantity $N_t - n_t$ varies weakly at that. This enables us to replace $n_t(t)$ in Eq. (15) by $n_t(t = 0)$. Ultimately, with an accuracy to the temperature dependence of the preexponent, we obtain

$$\tau_r \sim \quad \exp((-q(\varphi_{s0} + \Delta\varphi(t = 0))/kT). \tag{17}$$

As is evident from Eq. (17), in the concentration inversion range, the value of τ_r grows exponentially as the temperature decreases, but this growth is characterized by a lower activation energy than it was in the case of conductivity inversion, i.e. for a completely formed p-n-junction.

Let us determine the temperature dependence $\tau_{\text{eff}}(T)$ in this case. We assume that $\tau_{\text{eff}}/\tau_r \gg 1$ and

$$\tau_r = \tau_0 \exp((-q(\varphi_{s0} + \Delta\varphi(t = 0))/kT). \tag{18}$$

Substituting expression (18) into Eq. (14) and putting $\beta = 1$, we obtain

$$\tau_{\text{eff}}(T) \approx \tau_0 \exp\left[\frac{1}{4}\left(\sqrt{y_0} + \sqrt{y_0 - \Delta y_s(t = 0)}\right)^2\right]. \tag{19}$$

Therefore, as is seen from Eq. (19), the activation energy τ_{eff} is lower than $-q\varphi_{s0}$ but higher than $-q(\varphi_{s0} + \Delta\varphi_s(t = 0))$ (the φ_{s0}-value is negative, and the value of $\Delta\varphi_s(t = 0)$ is positive).

The situation is not changed essentially in the intermediate temperature region, where the recombination mechanism of the current flow dominates, i.e. when $\beta = 2$ and $J_s \sim n_i \sim \exp(-E_g/2kT)$. In comparison with the cases considered above, only the rate of τ_{eff}-growth becomes slower. Basic modifications occur at low enough temperatures, when the tunnel mechanism of the current flow starts to dominate. In this case, $\beta = \varepsilon_T/kT$, where ε_T is the characteristic energy of tunneling. Therefore, the ratio $\Delta y_s(t = 0)/\beta$ which is equal to $\ln(J_{\text{ph}}/J_s)$, where J_{ph} is the surface density of photo-induced current, does not depend on the temperature, if the quantity J_s is temperature-independent. That is why one should expect that the quantity τ_{eff} would be either independent of or weakly dependent on the temperature in the low-temperature range, where the tunnel mechanism of the current flow dominates.

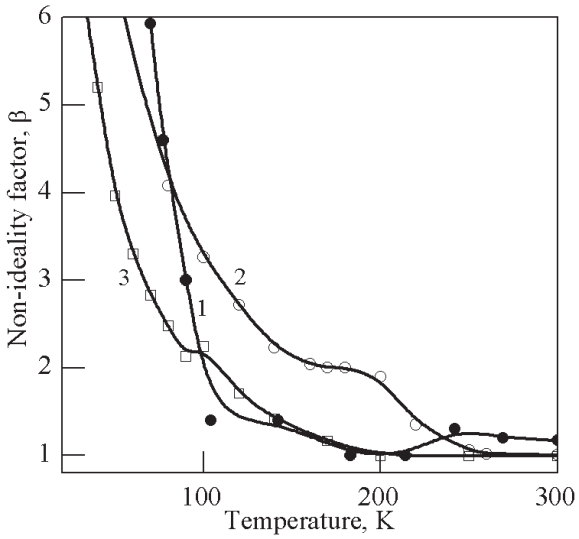

Fig. 4. Temperature dependences of the nonideality factor β: determined from the CVC [7] (*1*) and from the temperature dependence of the photoconductivity relaxation time (Fig. 3) for macroporous silicon specimens N 2 (*2*) and N 3 (*3*)

In Fig. 4, the temperature dependences of the nonideality factor β, which was obtained after the theoretical dependences had been put in agreement with experimental data (Fig. 3), are depicted. The figure demonstrates that the dependence concerned includes a section with $\beta = 1$ (the thermoemission mechanism of the current transport) in the temperature interval from 300 to 200 K, a section with $\beta = 2$, which corresponds to the recombination mechanism, in the temperature interval from 170 to 100 K, and a section with a varying β that strongly depends on the temperature, which corresponds to the tunnel mechanism [15] (at temperatures lower than 100 K).

By fitting the theoretical dependences of the photoconductivity relaxation to experimental ones

(Fig. 2), the magnitudes of the surface potential in darkness, y_0, and at illumination, $y_0 - \Delta y_s(t = 0)$, were determined. In particular, the dimensionless y_0-value at $T = 300$ K is approximately equal to 12, which corresponds to the equilibrium surface band bending of about 0.31 eV. The temperature dependence of the photoconductivity relaxation time τ_{eff} has an activation character with the activation energy $E_a = 0.3 \pm 0.01$ eV. According to the results of electrophysical researches, in macroporous silicon structures with a barrier contact, the thermoemission mechanism of the charge carrier transport in the direction from silicon to silicon oxide is implemented in the temperature interval $180 - 300$ K. The thermoemission mechanism is characterized by an activation energy of 0.25 eV, which agrees with the data concerning the temperature dependence of the photocarrier lifetime and the results of calculation of the equilibrium surface band bending. Really, in the inversion concentration region, the lifetime of photocarriers grows as the temperature decreases, following the exponential dependence with a lower activation energy than the corresponding value in the case of the conductivity inversion, i.e. a completely formed p-n-junction: $q\varphi_{s0} > E_a > q(\varphi_{s0} - \Delta\varphi_s(t = 0))$. The ratio $(y_0 - \Delta y_s(t = 0))/y_0$ changes at that from 0.4 at room temperature to 0.78 at a temperature lower than 180 K. At low temperatures, when the surface and the silicon matrix exchange the injected charge carriers by engaging the tunnel mechanism of exchange, the lifetime of photocarriers, the probability of tunneling, and the cross-section of photocarrier capture do not depend on the temperature.

4. Conclusions

1. The kinetics of the photoconductivity in macroporous silicon has been found experimentally to have a non-exponential law of relaxation. The characteristic times of the photoconductivity relaxation in macroporous silicon comprise – by the order of magnitude – hundreds of microseconds at room temperature and tens of milliseconds at $T < 100$ K. In the range $T = 200 \div 300$ K, the temperature dependence of the photoconductivity relaxation time has an activation character with an activation energy of 0.3 ± 0.01 eV and does not depend on the temperature at $T < 100$ K.

2. The character of the photoconductivity relaxation in macroporous silicon has been analyzed theoretically, depending on the mechanism of the current flow through the near-surface space charge region. The effective time of the photoconductivity relaxation in macroporous silicon structures was found to be governed by the barrier mechanism, and the relaxation itself follows a logarithmic law.

3. At temperatures higher than 150 K, the temperature dependence of the photoconductivity relaxation time is governed by the thermoemission mechanism of the current flow through the near-surface space charge region. In the temperature range $150 - 100$ K, it is governed by the recombination mechanism, and, at temperatures lower than 100 K, by the tunnel processes of current flow. In the last case, the probability of tunneling, the photocarrier lifetime, and cross-section of photocarrier capture do not depend on the temperature.

4. By comparing the theoretical and experimental dependences for the photoconductivity relaxation, the values of the surface potential in darkness, y_0, and at illumination, $y_0 - \Delta y_s(t = 0)$, have been determined. The dimensionless y_0-value is about 12 at room temperature, which corresponds to the equilibrium surface band bending of about 0.31 eV and agrees with the data on the temperature dependence of the photocarrier lifetime.

1. L.A. Karachevtseva, O.A. Lytvynenko, E.A. Malovichko, and E.J. Stronska, Semicond. Phys. Quant. Electron. Optoelectron. **4**, N 4, 347 (2001).
2. L.A. Karachevtseva, N.I. Karas', V.F. Onischenko, and F.F. Sizov, Int. J. Nanotech. **3**, 76 (2006).
3. L. Karachevtseva, A. Glushko, M. Karas, and V. Onischenko, Proc. SPIE **5733**, 297 (2005).
4. L.A. Karachevtseva, O.A. Lytvynenko, E.A. Malovichko, V.D. Sobolev, and O.L. Stronska, Semicond. Phys. Quant. Electron. Optoelectron. **4**, N 1, 40 (2001).
5. R.Yu. Holiney, L.A. Matveeva, E.F. Venger, L.A. Karachevtseva, and O.A. Lytvynenko, Appl. Surf. Sci. **172**, 214 (2001).
6. V.I. Ivanov, L.A. Karachevtseva, N.I. Karas, O.O. Lytvynenko, K.A. Parshin, and A.V. Sachenko, Semicond. Phys. Quant. Electron. Optoelectron. **10**, N 4, 72 (2007).
7. A.V. Zuev, A.V. Sachenko, and K.B. Tolpygo, Ukr. Fiz. Zh. **10**, 1176 (1965).
8. M.K. Sheinkman, I.V. Markevich, and V.A. Khvostov, Fiz. Tekh. Poluprovodn. **5**, 1585 (1971).
9. N.L. Dmitruk, V.I. Lyashenko, O.Yu. Borkovskaya, and O.I. Maeva, Fiz. Tekh. Poluprovodn. **9**, 2261 (1975).
10. V. Lehmann and H. Foll, J. Electrochem. Soc. **137**, 653 (1990).
11. V. Lehmann, J. Electrochem. Soc. **140**, 2836 (1993).
12. K.D. Glinchuk and N.M. Litovchenko, Poluprovodn. Tekhn. Mikroelektr. **28**, 3 (1978).
13. L. Karachevtseva, V. Onishchenko, A. Sukach, and V. Teterkin, Proc. SPIE **6127**, 232 (2006).
14. A.V. Sachenko and O.V. Snitko, *Photoeffects in Near-Surface Layers of Semiconductors* (Kyiv, Naukova Dumka, 1984) (in Russian).

15. S.M. Sze, *Physics of Semiconductor Devices,* 2nd ed. (Wiley, New York, 1981).

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КІНЕТИКА ФОТОПРОВІДНОСТІ В СТРУКТУРАХ МАКРОПОРИСТОГО КРЕМНІЮ

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Р е з ю м е

Досліджено релаксацію фотопровідності макропористого кремнію n-типу провідності. Встановлено, що ефективний час релаксації фотопровідності структур макропористого кремнію визначається бар'єрним механізмом, а релаксація відбувається за логарифмічним законом. Характерні часи релаксації фотопровідності макропористого кремнію на порядок величини перевищують час релаксації фотопровідності монокристалічного кремнію. При температурах, більших за 150 К, температурна залежність часу релаксації фотопровідності визначається термоемісійним механізмом проходження струму в області просторового заряду, в діапазоні температур 150–100 К – рекомбінаційним механізмом, а при температурах, менших за 100 К – тунельними процесами струмопротікання. При цьому імовірність тунелювання, час життя фотоносіїв та переріз захоплення фотоносіїв не залежать від температури.