Modelling of voltage changes in the n-p junction in the pulse mode

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Abstract. The article presents the results of modeling the effect of the effective lifetime in the space charge region (SCR) of the n+p junction on the impulse characteristics of silicon structures. The model is based on solving the fundamental system of differential equations for the transport of charge carriers in inhomogeneous semiconductors. The calculated time dependences of the voltage change in the SCR for a pulse voltage change on the n+p-p+p+ structure correspond to the experimental data.

1. Introduction
Recombination processes determine the switching time of semiconductor devices in the pulse mode. In silicon, the recombination of nonequilibrium charge carriers occurs mainly through impurity centers. Methods for measuring the decay of photoconductivity are used for measure the lifetime of nonequilibrium charge carriers taking into account the influence of surface recombination [1, 2]. Non-contact measurements of the lifetime of non-basic charge carriers using photoconductivity recorded by microwave radiation are used to control the results of technological influence [3]. The influence of structural defects on the lifetime of non-basic charge carriers in a two-sided polycrystalline silicon solar cell was studied using pulsed illumination [4].

In order to exclude the time dependence of the photocurrent and photoconductivity used in the methodology of [1–4], the voltage change in the pulsed mode was measured in unlit silicon n+p-p+p+ structures irradiated with low-energy protons in the work [5]. The measurements were carried out using bipolar rectangular voltage pulses with a constant amplitude \( U_m = 10 \) mV. The measurement conditions [5] allowed to conclude that the value of the switching time is determined by the effective lifetime in the region of the spatial charge (SCR) of the n+p-junction of the studied structures.

The aim of the work is to analyze the transport of charge carriers in a semiconductor structure with an n+p junction under conditions of a pulsed voltage change with a small amplitude at the contacts.

2. Analysis of the transport of the charge carrier
The fundamental system of differential equations (FSDE) (1) for the transport of charge carriers in semiconductors with homo-junctions was proposed by Shockley [6] and generalized for complex semiconductor structures in [7, 8]. In FSDE (1) \( n \) and \( p \) – concentrations of electrons and holes, respectively, \( N_e \) – effective density of electronic states in the area of the bottom of the conduction band, \( E_c \) – position of the bottom of the conduction band, \( q \) – elementary charge, \( \phi \) – the potential of the
internal electric field, \( N_f \) – effective density of electronic states in the area of the vertex of the valence band, \( E_v \) – position of the top of the valence band, \( \vec{j}_n \) – electron flux density, \( \mu_n \) – mobility of the electrons, \( D_n \) – electron diffusion coefficient, \( \vec{j}_p \) – the density of the hole flow, \( \mu_p \) – mobility of the holes, \( D_p \) – hole diffusion coefficient, \( G \) – volume generation rate of electron-hole pairs, \( R \) – the rate of volume recombination of electron-hole pairs, \( N_D^+ \) – concentration of ionized donors, \( N_A^- \) – concentration of ionized acceptors, \( \varepsilon \) – dielectric constant, \( e_0 \) – dielectric constant.

\[
\begin{align*}
\vec{j}_n &= -\mu_n n \left( -\vec{\nabla} \varphi + \frac{1}{q} \vec{\nabla} E_v \right) - D_n \vec{\nabla} n + D_n n \vec{\nabla} \ln N_e, \\
\vec{j}_p &= \mu_p p \left( -\vec{\nabla} \varphi + \frac{1}{q} \vec{\nabla} E_v \right) - D_p \vec{\nabla} p + D_p p \vec{\nabla} \ln N_h, \\
\frac{\partial n}{\partial t} + (\vec{\nabla}, \vec{j}_n) &= G - R, \\
\frac{\partial p}{\partial t} + (\vec{\nabla}, \vec{j}_p) &= G - R, \\
\Delta \varphi &= -\frac{q}{\varepsilon e_0} \left( p - n + N_D^+ - N_A^- \right)
\end{align*}
\]

The condition of smallness of the voltage amplitude at the contacts means

\[ qU_m / kT < 1, \]

where \( k \) – Boltzmann constant, \( T \) – absolute temperature. Under the conditions of measuring the work [5], the inequality (2) is fulfilled. In this case, the mode of low injection of charge carriers in the emitter of the \( n^+ \) type of conductivity and the base of the \( p \) type of conductivity is realized, in addition, there is no light generation of electrons and holes \( G = 0 \). In this case, the FSDE (1) is simplified so that the solution for the concentration of nonequilibrium electrons and holes can be found in the form \( n = n_0 + \Delta n, p = p_0 + \Delta p \), where the equilibrium concentrations of electrons \( n_0 \) and holes \( p_0 \) are the solution of the system (1) under the conditions \( \vec{j}_n = 0, \vec{j}_p = 0, \)

\[
\begin{align*}
\Delta n(x,t) &= \sum_i \left[ A_{n_i}(x) - B_{n_i}(x) \cdot \exp \left( -\frac{t - t_0}{\tau_i} \right) \right], \text{ at } t_0 \leq t \leq t_m, \\
\Delta p(x,t) &= \sum_i \left[ A_{p_i}(x) - B_{p_i}(x) \cdot \exp \left( -\frac{t - t_0}{\tau_i} \right) \right], \text{ at } t_0 \leq t \leq t_m,
\end{align*}
\]

where \( t_m - t_0 = (2f)^{-1} \), \( f \) – frequency of bipolar pulses. We will find the functions \( A_{n_i}(x), B_{n_i}(x), A_{p_i}(x), B_{p_i}(x) \) by solving the simplified equations in quasi-neutral \( p \), \( n^+ \) regions and SCR by the method of separating variables. Solutions have is quite complex, so they are not included in the text of the article. The summation index \( i \) numbers the various processes of relaxation of the concentration of charge carriers to stationary values.

The measurement procedure with the duration of bipolar voltage pulses \( (2f)^{-1} \) and the discretization time of the measured signal \( \Delta t \) identifies a range of values of relaxation parameters: \( \tau_i \in (2\Delta t, (4f)^{-1}) \). It performs filtration of relaxation processes. The SCR make the main contribution to the voltage drop \( U \) on \( n^+ - p - p^+ \) structure [9]. Due to the measurements using a pulse voltage under the condition (2) it was found that the structure implements the processes of voltage relaxation with the parameters of the effective lifetime \( \tau_i \) corresponding to the processes in the SCR:
This conclusion justifies the experimental results of the work [5]. When modeling the transport of charge carriers in a semiconductor structure with n+-p junction under conditions of a pulsed voltage change in formulas (3, 4), it is sufficient to take into account the relaxation processes with the parameters $\tau \in (2\Delta t, (4f)^{-1})$.

3. Results and discussion

On the figure 1 and figure 2 are shown calculated dependencies of voltage drop in SCR on time for different values of the relaxation time $\tau$ with a bipolar voltage change with an amplitude of $U_m = 10 \text{ mV}$ on the contacts of n+-p-p+ structure. Pulse frequency is $f = 200 \text{ kHz}$ for figure 1 and $f = 1 \text{ MHz}$ for figure 2.

Response function $U(t)$ it manages to reach stationary values $\pm 10 \text{ mV}$ during the duration of each pulse $T_{1/2} = 2.5 \mu s$ at the relaxation time $\tau = 0.25 \mu s$ and $\tau = 0.5 \mu s$ (figure 1). Reducing the pulse duration time changes the nature of the response function. The response function does not reach stationary values when $T_{1/2} = 0.5 \mu s$ and it gets a sawtooth appearance when $\tau = 0.25 \mu s$ and $\tau = 0.5 \mu s$ (figure 2). The results of these calculations fully correspond to the experimental data of [5].
An increase in the pulse frequency changes the shape of the pulse characteristic. At a frequency of 10 MHz and the same parameters $\tau = 0.25 \ \mu s$ and $\tau = 0.5 \ \mu s$ the pulses have a triangular shape of a smaller amplitude with the same duration of the leading and trailing edges (figure 3).

![Figure 3](image1)

**Figure 3.** Dependence of the voltage drop in the SCR on time at the frequency $f = 10$ MHz: $1 - \tau = 0.25 \ \mu s$, $2 - \tau = 0.5 \ \mu s$.

![Figure 4](image2)

**Figure 4.** Dependence of the voltage drop in the SCR on time at the frequency $f = 10$ MHz: $1 - \tau = 0.025 \ \mu s$, $2 - \tau = 0.05 \ \mu s$.

![Figure 5](image3)

**Figure 5.** Dependence of the voltage drop in the SCR on time at the frequency $f = 10$ MHz: $1 - \tau = 0.005 \ \mu s$, $2 - \tau = 0.01 \ \mu s$.

Reducing the values of $\tau$ at $f = 10$ MHz restores the shape of the pulses: a reduction of 10 times gives the impulse characteristics shown in figure 4, and 50 times – the pulse characteristics shown in figure 5.
4. Conclusion
Proton irradiation technologies make it possible to modify the structure of semiconductor devices in a controlled manner, introduce recombination centers, reduce the effective lifetime of charge carriers in hidden layers, and create layers with hydrogen-containing centers [10]. As a result of implantation of hydrogen ions, an inhomogeneous disturbed layer is formed, the characteristics of which require study [11, 12]. Changing the lifetime of charge carriers in the local volume of semiconductor structures irradiated with protons makes it possible to improve the totality of static and frequency characteristics of devices [13].

The presented results of modeling the transient characteristics of semiconductor structures justify the methodology for determining the effective lifetime of electrons and holes in the SCR of the $n^+ - p$ junction are demonstrate the influence of the effective lifetime on the shape of pulse and frequency characteristics.

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