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Self-organization dynamics of charge carrier concentration in semiconductors due to the charge injection

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Abstract. The *purpose* of this study is to investigate the phenomenon of self-organization of the dynamics of charge carriers in semiconductor structures. Investigate the basic model, give a numerical estimate for given parameters and propose its modification. Determine the dependence of the evaluation results on the control parameter. Consider the dynamics when the control parameter depends on time. Carry out theoretical analysis, numerical simulation and build graphs. *Methods.* In this paper, we investigate the possibilities and limitations of the basic model of generation-recombination dynamics in semiconductors, proposed earlier by other researchers. A modification of this model was proposed and considered. *Results.* Various types of charge carrier concentration dynamics are demonstrated.Theoretical analysis of the model was carried out. Numerical simulation has shown that for certain values of the control parameter, stable states are observed. Numerical estimates of the control parameter were obtained, phase portraits of the nonlinear equation were constructed, and the behavior of the dynamical system was considered when the control parameter is periodic. The extended model showed a qualitatively new behavior in comparison with the basic one. *Conclusion.* It is shown that charge dynamics in semiconductor structures can exhibit different behaviors. The patterns and estimates obtained are consistent with those obtained earlier. The results obtained can be verified experimentally and will be useful in the development of photo- and beta-voltaic devices.

Keywords: semiconductors, self-organization, nonlinearity, nonlinear systems, phase portraits, photo- and beta-voltaic generators.

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Introduction

A semiconductor crystal is a complex system in which electrical instabilities are observed (current breakdown, switching between conductive and non-conductive states, or spontaneous fluctuations in current or voltage). Similar phenomena occur when a semiconductor is transferred to a nonequilibrium state.

In this paper, the dynamics of charge carriers in semiconductor structures under external injection are investigated. Photons (photocell), beta particles (beta element) [1] can act as an external influence. The model used has been considered before [2–4], but to an insufficient extent. Previous researchers did not study the model in the case of the dependence of the control parameter on time. The [4] study examined dynamics in semiconductors, but under the influence of a strong magnetic field. The shock ionization coefficient was considered as a constant.

The results of the study of such models are applicable for modeling photo- and beta-voltaic devices. In the future, additional parameters can be taken into account to expand the model.

The purpose of this study is to determine stable states and verify the dependence of the results of the assessment of the concentration of charge carriers on the parameters: the coefficient of shock ionization, recombination, concentration of donors and acceptors; to consider the dynamics under conditions of periodic dependence of the control parameter.

1. Methods

1.1. The basic kinetic equation. Let's consider the basic model of electron dynamics in a nonequilibrium semiconductor. It was proposed in [3] and reviewed in [5]. In it, the authors neglect the thermal ionization of traps and Auger recombination. This corresponds to a semiconductor at low temperatures. The neglect of Auger recombination is motivated by the fact that it leads to a simplification of the model. Taking into account this process does not qualitatively affect the [3] model. The crystal lattice of a semiconductor contains various defects and impurities that create local energy levels in the band gap. Therefore, the main process of recombination is recombination through traps. The surface of the semiconductor is considered ideal, therefore, surface recombination is also not taken into account.

$$\frac{dn}{dt} = n[XN_D - T_{\mathrm{r}}(N_t - N_D) - n(X + T_{\mathrm{r}})], \tag{1}$$

where T_{r} is the recombination rate constant of the trap zone, X is impact ionization coefficient, N_D are concentration of donors, N_t are concentration of traps, n are concentration of charge carriers, in this case electrons. X is a control parameter and the nature of the phase portrait and the behavior of the system depend on it.

The critical value of the control parameter:

$$X_{\mathrm{crit}} = (Nt/Nd - 1)T_{\mathrm{r}}.$$

The equation always has a solution $n = 0$ (Fig. 1), which is stable at $X < X_{\mathrm{crit}}$. For $X > X_{\mathrm{crit}}$, a stable solution arises in the positive half-plane (Fig. 2).

$$n = \frac{XN_D - T_{\mathrm{r}}(N_t - N_D)}{X + T_{\mathrm{r}}}.$$

In Fig. 1 shows the dependence of the electron concentration on X, which varies continuously from 0 to $2X_{\mathrm{crit}}$. This allows you to observe a change in the behavior of the system when the

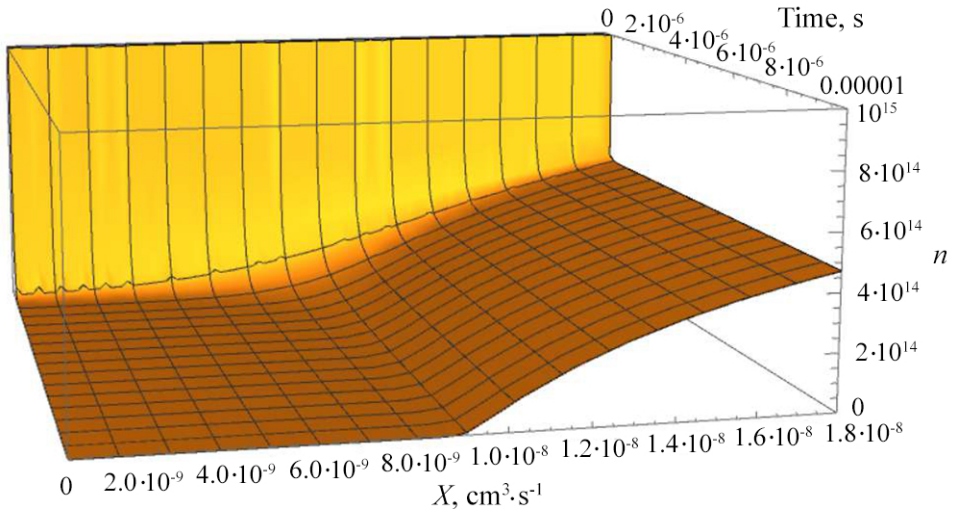

Fig. 1. Dependence of the stationary electron concentration n on the impact ionization coefficient X (color online)

control parameter reaches a critical value. In this case, the equilibrium concentration becomes different from zero.

In Fig. 2 one-dimensional phase portraits of equation (1) are depicted at different values of the control parameter. A transcritical bifurcation occurs, in which a solution that previously lay in a non-physical region of space (Fig. 2, *a*) passes into the physical region (Fig. 2, *b*). That is, there is a nonequilibrium phase transition of the second kind from a nonconducting state to a conductive one.

The following values were used in numerical modeling: $T_{\text{r}} = 10^{-9}$ cm^{3}s^{-1}, $N_D = 10^{15}$ cm^{-3}, $N_t = 10^{16}$ cm^{-3}. This is typical for silicon at a trap depth of 0.54 eV below the conduction band [3]. Тогда $X_{\text{crit}} = 9 \cdot 10^{-9}$ cm^{3}s^{-1}.

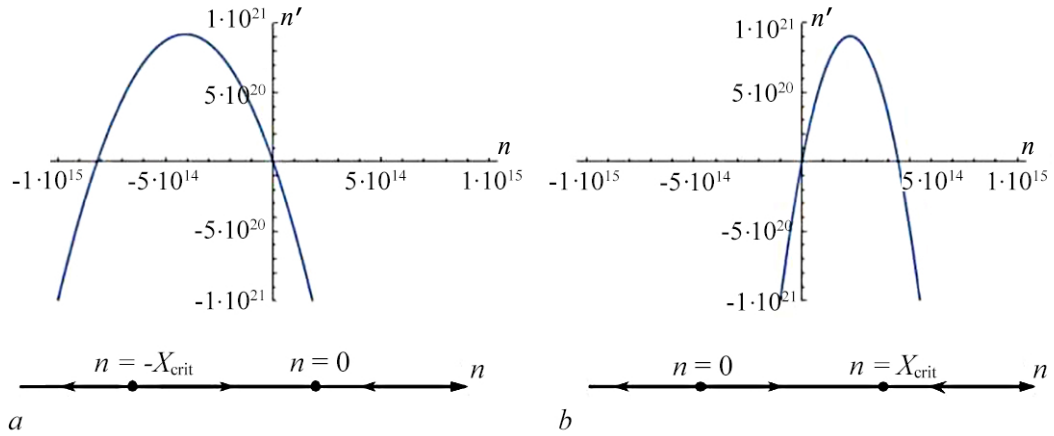

Fig. 2. Phase portraits of the equation (1) for $X = 0.5X_{\text{crit}}$ (a), $X = 1.9X_{\text{crit}}$ (b)

1.2. An augmented model with a function $X(t)$. Previously, the control parameter X was considered as a time-independent constant. Now let's consider the case of its functional dependence on time t. The shock ionization coefficient X is strongly related to the value of the

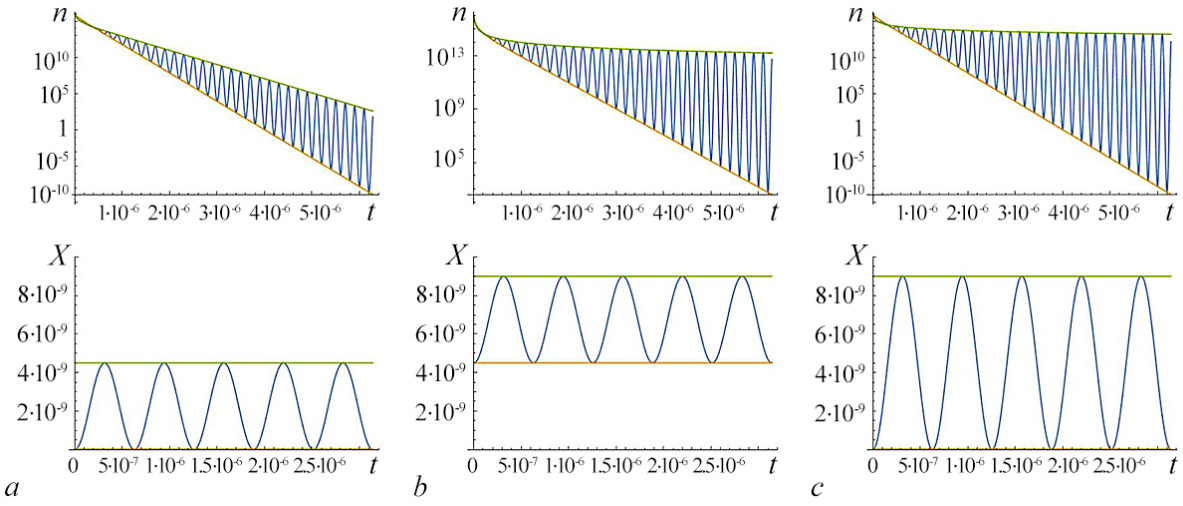

Fig. 3. Above — semi-logarithmic graphs of the dependence of concentration n on time t, below — impact ionization coefficient $X(t)$ for $X_1 = 0.5X_{\text{crit}}, X_2 = 0$ (a), $X_1 = 0.5X_{\text{crit}}, X_2 = 0.5X_{\text{crit}}$ (b), $X_1 = 1.001X_{\text{crit}}, X_2 = 0$ (c)

applied electric field E. Therefore, in practice, the functional task X is carried out through the control of E [6]. In this paper, the following expression is proposed as a function of $X(t)$:

$$X(t) = X_1 \left(0.5 - 0.5 \sin\left(10^7 \pi t + \frac{\pi}{2}\right)\right) + X_2, \tag{2}$$

where X_1 is responsible for the periodic part of the function, and X_2 is responsible for the time-independent stationary part. At the same time, $10^7\pi$ is the angular frequency of vibrations, and $\pi/2$ is the initial phase. The type of dependence on time is motivated by the desire to consider the model under conditions of harmonic oscillations. The value of the coefficient 10^7, which is the frequency, is explained by the fact that the transition to an equilibrium state occurs in microseconds. With a small frequency of change of $X(t)$, the contribution of oscillations will be extremely small.

The periodicity effect is well manifested in modeling (Fig. 3). The green bar is the upper bounding line corresponding to X_1+X_2. The orange stripe is the lower bounding line corresponding to X_2. When the stationary part is zero and the periodic part is less than X_{crit} (Fig. 3, a), there is a general trend to reduce the concentration to zero. If $X_1+X_2 = X_{\text{crit}}$ (Fig. 3, b), then the upper limit line tends to a stable state, and the lower one tends to zero. That is, during the oscillation period, the system manages to reach a conducting stationary state from the non-conducting state $n = 0$. If $X_1 = X_{\text{crit}}$ and $X_2 = 0$ (Fig. 3, c), then the general behavior will be similar to the second case, but the time to reach the upper trend line of the steady state line will be longer.

2. Results

A graph of the stationary electron concentration from the shock ionization coefficient was constructed. Equation (1) of the basic model is analyzed and phase portraits are constructed. An extended model (2) was proposed, according to which graphs were also constructed. The dynamics obtained by the extended method of Fig. 3, correlate well with the results of the main model Fig. 1, while having qualitative features.

Conclusion

This model allows us to consider various concentration dynamics. Despite its simplicity, its analysis yields results worthy of consideration. At the frequency values that were considered, the method showed sufficient sensitivity to the value of X everywhere.

In the future, it is planned to expand the model and take into account such effects as recombination, thermal ionization, the influence of crystal lattice defects, and others. This will expand the applicability of the model to a wider range of real structures and compare theoretical data with experimental ones.

It is planned to use the results in modeling photo- and beta-voltaic devices [1].

As a result, the following advantages of the method can be formulated:

- Ease of analysis.
- Has a wide possibility of modification. The ability to take into account additional effects.
- The possibility of experimental verification.

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