# RECOMBINATION INSTABILITY INDUCED CURRENT OSCILLATIONS IN SEMICONDUCTORS

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## 1. Introduction

In the last two decades or so, a remarkable progress has been made in our understanding of spatio-temporal evolution of nonlinear systems which appear in many different fields. Semiconductors are considered to be typical of these nonlinear systems. They are suitable for understanding the nonlinear dynamics because electrical currents, fields and so on can be measured very accurately and the experiments can be performed under precisely controlled conditions. Semiconductors under sufficiently strong excitation conditions will exhibit nonlinear transport properties such as deviation from linear ("Ohmic") current-voltage relations and instabilities leading to current oscillations and/or domain or filament formations.

Field-enhanced trapping is one of the mechanisms which cause instabilities ( so-called "recombination instability") giving rise to slow current oscillations in gold or copper-doped n-Ge and high-resistivity GaAs [1,2]. In gold-doped n-Ge, the gold atoms are distributed as deep impurity levels in the form of doubly or triply charged negative ions. A free electron must penetrate a Coulomb potential barrier of the gold ions for it to be trapped. Therefore the trapping(recombination) coefficient increases with field $E$ while the emission of electrons is effectively field-independent as long as $E$ is well below the threshold for the impact ionization.

## 2. Simulation model

In this report we give the results of our computer simulations for a one-dimensional system of gold-doped n-Ge. The system can be described by the Poisson equation for the electric field $E(x,t)$, the total-current-density equation for $J(x,t)$ and the continuity equations for the free electron density $n$ and the triply-ionized occupied trap density $N^-(x,t)$ as follows:

$$\frac{\partial E(x,t)}{\partial x} = \frac{e}{\epsilon}\{N_d - n(x,t) - 2(N_t - N^-(x,t)) - 3N^-(x,t)\}\ ,\quad J(x,t) = -e\left(n(x,t)\mu E(x,t) - D\frac{\partial n(x,t)}{\partial x}\right)$$

$$\frac{\partial N^-(x,t)}{\partial t} = -\left(\frac{\partial n(x,t)}{\partial t}\right)_g \quad ,\quad \frac{\partial n(x,t)}{\partial t} + \frac{\partial}{\partial x}\left(\frac{J(x,t)}{q}\right) = \left(\frac{\partial n(x,t)}{\partial t}\right)_g$$

$$\left(\frac{\partial n(x,t)}{\partial t}\right)_g = -\alpha_E n(x,t)(N_t - N^-(x,t)) + \beta N^-(x,t) \quad ,\quad \alpha_E = \alpha_0 \exp\left[-\left(\frac{E_{th}}{E(x,t)}\right)^2\right]$$

where $N_d$ is the time-independent donor density, $N_t$ is the time-independent total trap density, $(N_t - N^-(x,t))$ is the doubly-ionized occupied trap density, $D$ is the diffusion constant of electrons, $\alpha_0$ is the recombination coefficient, $\beta$ is the emission coefficient and $E_{th}$ is the threshold field for recombination. In the rhs of the continuity equation for $n$ the first term and the second term express a decrease of $n$ due to recombination by traps and an increase of $n$ due to emission by the optical (and thermal) excitation respectively. We have used the expression for the recombination rate $\alpha_E$ given above which expresses the abrupt decrease in the free electron density with increase of the electric field $E$ in excess of the threshold $E_{th}$. In our computations the coefficients are taken as $\alpha_0 = 3.0 \times 10^{-6}$[cm$^{-3}$/sec] and $E_{th} = 95$[V/cm]. The values of the system parameters which are kept to be fixed during the present computations are taken as the follows: the sample length $L = 3.2 \times 10^{-3}$[cm], $N_d = 5.0 \times 10^{14}$[cm$^{-3}$], $N_t = 2.0 \times 10^{14}$[cm$^{-3}$], $\mu = 5.0 \times 10^3$[cm$^2$/V· sec], $D = 1.0 \times 10$[cm$^2$/sec], $\epsilon = 16\epsilon_0 = 1.42 \times 10^{-12}$[F/cm], $e = 1.6 \times 10^{-19}$[C]. The applied dc bias voltage across the device $\Phi$ is fixed for each calculation. Under these conditions, the computations were performed to pursue spatio-temporal evolution of the system for several chosen values of the control parameters $\Phi$ and $\beta$.

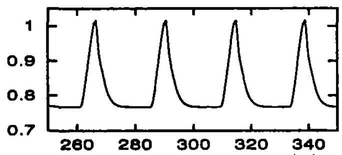
### 3. Results and discussion

We obtained spatio-temporal evolution of the system using a finite-difference method. For suitably chosen values of the model parameters we have found the system becomes electrically unstable and the current oscillations appear which are associated with the formation and the cyclic propagation of the high-field domain. Some examples of our numerical simulations for the case $\Phi$=0.14[V] fixed are shown below.

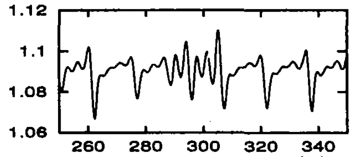
At low values of $\beta$ the system exhibits periodic current oscillations associated with a high-field domain cyclically propagating from the cathode to the anode. This is usually called the transit-time mode [Fig.1]. At intermediate values of $\beta$ the domain cannot sustain the shape of itself so that it is quenched before reaching the anode. This mode is called the quenched mode [Fig.3]. At high values of $\beta$ the system exhibits steady-state behavior. Further, we have found the periodicity of current oscillations is changed and non-periodic oscillations are also observed [Fig.2] at the transition region between the quenched mode and the transit-time mode. Figures show clearly that the current oscillations are closely associated with the motion of the domain and non-periodic oscillations are caused by stochastic quenching of the domains.

Piragas *et al.* reported an experiment on the recombination instability using Cr-doped GaAs where the system exhibits chaotic current oscillations under some conditions, and they tried its explanation using a model of ordinary differential equations [3]. But their model is not sufficient for describing the system in that the spatial structure of the system such as the formation and the propagation of the high-field domain is not taken into account at all. In our model the parameters have been chosen mostly from experimental data so that our results are expected to be observed in real systems. Moreover we can obtain instructive information on the system which is different from that driven under the periodic boundary conditions in that in our case the domains are formed and start to travel at certain specified region of the system.

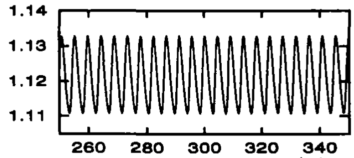
$J$




$t$ Fig.1(a)

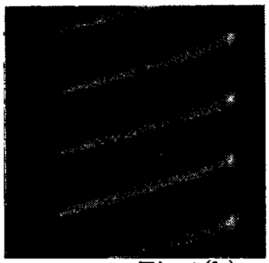



$t$ Fig.2(a)

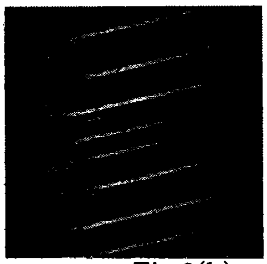



$t$ Fig.3(a)

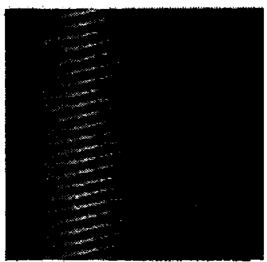
$t$ ↑



$x$ Fig.1(b)



$x$ Fig.2(b)



$x$ Fig.3(b)

Fig.1 The motion for the case $\beta = 4.0 \times 10^5$[sec$^{-1}$].
(a) The total current density at the anode $J(t)$ [in unit of 2.5 A] as a function of time $t$ [in unit of 2.0× $10^{-8}$ sec].
(b) Spatio-temporal evolution of the electric field $E(x,t)$ at the position $x$ and the time $t$. White color means the high electric field.

Fig.2 The same as Fig.1 for the case $\beta = 7.6 \times 10^5$[sec$^{-1}$].

Fig.3 The same as Fig.1 for the case $\beta = 8.4 \times 10^5$[sec$^{-1}$].

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[2] B.K.Ridley and R.G.Pratt: J. Phys. Chem. Solids, **26**(1965)21.
[3] Piragas *et al.*: Sov. Phys. Semicond., **21(3)** (1987) 335.