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# Current Oscillations in Imperative Semiconductors with Two Types of Medium Carriers

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***Abstract:*** *A theory of current oscillations in impurity semiconductors with two types of charge carriers is constructed, when the equilibrium ratios of the concentrations of electrons and holes are determined by the ratio of the characteristic frequencies of electrons and holes. Analytical formulas for the external electric field and for the frequency arising inside the impurity semiconductor are obtained. The growth increment of arising waves has been determined. When a current oscillates in a circuit, a semiconductor impedance is calculated. It is indicated that when a capacitive character appears in a circuit, the value of which is equal to the ohmic resistance in the circuit, the frequency of current oscillation mainly depends on the frequency of electron capture. The electric field during the radiation of a sample mainly depends on the frequency of the capture of electrons by impurity centers.*

***Keywords****: Frequency, increment, oscillations, capture, recombination, generation.*

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## I. Introduction

The impurity centers in semiconductors, which are able to be in several charged states in the presence of an external field, excite the growing recombination waves. For example, gold atoms in germanium can, besides the neutral state, be once, twice and three times negatively charged centers. These impurity centers create several energy levels in the forbidden band. Free charge carriers can capture (or emit) these levels. As a result of recombination and generation of free charge carriers e, the concentration of electrons in the conduction band is the concentration of holes in the valence band and the electrical conductivity of the semiconductor varies greatly. Under various experimental conditions, these impurity centers are more or less active; therefore, recombination and generation mainly occurs with a certain number of impurity centers. For example, in the experiment [1] (the results of which will be used by us later), the active centers were once and twice negatively charged center of gold in germanium. When gold is in the presence of an electric field, free carriers receive the electric field energy order, $eE_0l$ (e is the elementary charge, $E_0$ is the intensity, l is the mean free path of charge carriers). Therefore, electrons can overcome the Coulomb barrier of a single negatively charged center and become trapped. As a result of thermal transfer, electrons can be generated from impurity centers to conduction bands. The number of holes increases due to the capture of electrons by impurity centers from the valence band and decreases due to the capture of electrons from impurity centers by holes. Such different probabilities of generation and recombination of charge carriers leads to a change in the conductivity of the semiconductor.

In [2–7], the equations of the kinetics of electrons and holes in these impurity semiconductors are described in detail and the theory of internal (ie, the excited wave propagates only inside the sample and current oscillations in the external circuit $J'= 0$) and external (i.e . $J'\neq 0$) instabilities. In these studies, current oscillations were investigated in several situations (i.e., when the semiconductor contacts are ohmic, or charge carriers are injected through the semiconductor contacts).

In this theoretical work, we will prove that when the concentrations of electrons and holes have certain values, internal and external oscillations are excited in a semiconductor with a singly and twice negatively impurity centers for a certain value of the external electric field and determine the corresponding frequencies of these oscillations.

## II. Basic equations of the problem

The kinetics equations of electrons and holes in the above semiconductors are described in detail in [2–7] and therefore we do not write them out.

The continuity equations of electrons and holes have the form [2-7]:

$$\frac{\partial n'}{\partial t}+divj'_{-}=\nu_{-}n'_{-}-\frac{\nu'_{-}}{\nu-i\omega}\left[+\nu_{+}n'_{1}+\nu_{-}n'+\left(\nu_{+}^{E}\ n_{1+}\beta_{1}^{\gamma}+\nu_{-}n\beta^{\gamma}\right)\frac{e\left(\mu_{+}n'_{1}+\mu n'\right)}{\sigma+\sigma_{1}}\right]+\nu_{-}n_{-}\beta_{-}^{\gamma}\frac{e\left(\mu_{+}n'_{+}+\mu n'\right)}{\sigma+\sigma_{1}} \quad (1)$$

$\frac{\partial n_+'}{\partial t} + divj_+' = -\nu_+ n_+' + \frac{\nu_+'}{\nu - i\omega}[\nu_+ n_1' + \nu_- n' + (\nu_+^E\ n_{1+}\beta_1^\gamma + \nu_- n\beta^\gamma)\ \frac{e(\mu_+ n_1' + \mu n')}{\sigma + \sigma_1}]$- $\nu_+^E\ n_{1+}\beta_1^\gamma\ \frac{e(\mu_+ n_1' + \mu n')}{\sigma + \sigma_1}$ (2)

$$\overrightarrow{j_-'} = -\frac{\sigma_-}{e}\overrightarrow{E'} - \frac{\sigma_-}{e}\beta_- \overrightarrow{E_0}\frac{\overrightarrow{E_0}\overrightarrow{E'}}{E_0^2} - \overrightarrow{\vartheta_-} n'$$

$$\overrightarrow{j_+'} = \frac{\sigma_+}{e}\overrightarrow{E'} + \frac{\sigma_+}{e}\beta_+ \overrightarrow{E_0}\frac{\overrightarrow{E_0}\overrightarrow{E'}}{E_0^2} + \overrightarrow{\vartheta_+} n'$$

$\beta_\pm = 2\frac{d\ln\mu_\pm}{d\ln E_0^2}$; $\quad \overrightarrow{\vartheta_\pm} = \mu_\pm \overrightarrow{E_0}, \quad n_\pm = n_\pm + n_\pm', \quad \vec{E} = \overrightarrow{E_0} + \overrightarrow{E'}$

$$n_\pm' \ll n_\pm^0$$

$E' \ll E_0$ , $T \ll eE_0 l$ (T=$k_0 T_0$, $T_0$ – lattice temperature).

$$\beta_\pm^\gamma = 2\frac{d\ln\gamma_\pm(E_0)}{d\ln E_0^2}$$

$\vartheta_- = \gamma_-(E_0)N_0$ - electron capture frequency , $\vartheta_+ = \gamma_+(0)N_-$ - hole grabbing frequency, $\nu_+^E = \gamma_+(0)N_0$ - the frequency of emission of holes.$n_{1-} = \frac{n_-^0 N_0}{N_-^0}$ , $n_{1+} = \frac{n_+^0 N_-^0}{N_0}$, $N_0 = N_+ N_-$total concentration of deep traps, N-once negatively charged centers, $N_-$-double negatively charged centers , N ≫N_ $\mu_\pm$- hole and electron mobility.

$\sigma = \sigma_+ + \sigma_- =$ e $(n_+^0\mu_+ + n^0\mu)$; $\sigma_1 =$ e $(n_+^0\mu_+\beta_+ + n^0\mu\beta_-)$

$\nu = \nu_+' + \nu_-' = \gamma_+(0)n_+^0 + \gamma_+(E_0)n_{1+} + \gamma_-(E_0)n^0 + \gamma_-(0)n_{1-}$combined frequency of capture and emission of electrons and holes by non-equilibrium traps $(N_0, N_-^0) \gg (n_\pm^0)$.

## III. Theory

From (1-2) it is easy to prove that with

$$\nu_+ n_+^0 = \nu_- n^0 (3)$$

(1) and (2) have

$$\frac{\partial n'}{\partial t} divj_-' = \nu_- n';\ \frac{\partial n_+'}{\partial t} + divj_+' = -\nu_+ n_+' \quad (4)$$

From $J' = e(j_+' - j_-')$=0 (5); we get

$$E' = -\frac{\vartheta_+ n_+' + \vartheta_- n_-'}{n_+\mu_+(1+\beta_+) + n_-\mu_-(1+\beta_-)} \quad (6)$$

Substituting (6) into (4), we can easily obtain the following dispersion equation for determining the frequency of oscillation inside the sample

$\omega^2 + \left(\frac{k\,\vartheta_+\sigma_{1-} - k\vartheta_-\sigma_{1+}}{\sigma} + i\nu_-\right)\omega - 2k^2\vartheta_-\vartheta_+\frac{\sigma_{1-}-\sigma_{1+}}{\sigma^2} + \nu_-\nu_+ + ik\frac{\vartheta_-\nu_+\sigma_{1+} + \vartheta_+\nu_-\sigma_{1-}}{\sigma}$=0 (7), $\sigma_{1\pm} = en_\pm\mu_\pm(1 + \beta\pm$

From solution (7) with (3) and $\nu_- > \nu_+$we get:

$$x_{1,2} = -\frac{E_0}{2E_1} - \frac{i}{2} \pm \sqrt{\frac{{E_0}^2}{4{E_1}^2} + i\frac{E_0}{2E_1} - \frac{1}{4} + \frac{{E_0}^2}{{E_2}^{2-}} - \frac{\nu_+}{\nu_-} - i\frac{E_0}{E_3}} \quad (8)$$

x= $\frac{\omega}{\nu_-}$ ; k$\frac{\mu_+\sigma_{1-} - \mu\sigma_{1+}}{\sigma\nu_-} = \frac{1}{E_1}$; ${E_2}^2 = \frac{\sigma^2}{2\sigma_{1+}\sigma_{1-}}\frac{{\nu_-}^2}{k^2\mu\mu_+}E_3 = \frac{\sigma{\nu_-}^2}{k(\mu_-\sigma_{1+}\nu_+ + \mu_+\sigma_{1-}\nu_-)}$

From (8) at$E_0 = E_1$ and $E_1 = E_2\left(\frac{\nu_+}{\nu_-}\right)^{1/2}$ easy we get

$$x_1 = -\frac{3}{2} + \frac{i}{2};\ x_2 = \frac{1}{2} - \frac{3i}{2}x_1\ (10)$$

From (9) and (10) can be seen that only the wave with x can increase with a fraction with an increment

$$\omega_0 = -\frac{3}{2\nu_-}\ (11)$$

$$\omega_1 = \frac{\nu_-}{2} \quad (12)$$

In obtaining (11) and (12), we assumed that $\overrightarrow{E'}\overrightarrow{E_0} = E'E_0$, that is, oscillations occur in the longitudinal direction. If $\overrightarrow{E'}\overrightarrow{E_0} = 0$ m. oscillations occur in the transverse direction then all obtained formulas remain valid only at $\beta_\pm^\mu$ .

From (11) and (12) it can be seen that the oscillation frequency $\omega_0$ is larger than the oscillation increment $\omega_0$>$\omega_1$.. However, a wave with a frequent $\omega_0$ and an increment of $\omega_1$cannot grow without stopping. To determine the wave growth time, it is necessary to find the oscillation amplitudes as a function of time, i.e.

$$E' = E'(t)e^{i(kx-\omega t)} n_\pm' = n_\pm(t)e^{i(kx-\omega t)}$$

To determine $E^{'}(t)$and $n_{\pm}(t)$, we need to construct a nonlinear theory. In one experimental case, a nonlinear theory was constructed by us in [8].

## IV. External instability

With internal instability, the frequency of oscillation and the wave vector were determined as follows
$\omega = \omega_0 + i\omega_1,\ k = k_0 = \frac{2\pi}{L}$
(L-size of the crystal). When current oscillations occur the circuit i.e$\mathcal{J}^{'} \neq 0$ the oscillation frequency and the free vector are defined as follows

$$\omega = \omega_0,\ \ k = k_0 + ik^{'}\ (14)$$

To determine the frequency of current oscillation $\omega_0$ with external instability, it is necessary to calculate the crystal impedance

$$Z = \frac{1}{\mathcal{J}'}\int_0^L E(x)dx$$

We first define the wave vector from the dispersion equation (7).
From (7)

$$\frac{k^2}{k_1^2} - (\frac{1}{k_2} + \frac{i}{k_3})\,k - \frac{\omega^2}{\nu_-^{\ 2}} - \frac{\nu_+}{\nu_-} - i\,\frac{\omega}{\nu_-} = 0 \qquad (16)\ .$$

$$k_1^2 = \frac{\sigma^2 \nu_-^{\ 2}}{2\,\vartheta_- \vartheta_+ \sigma_{1-} \sigma_{1+}}\ k_2 = \frac{\sigma \nu_-}{\vartheta_+ \sigma_{1-}}\ k_3 = \frac{\sigma \nu_-^{\ 2}}{\vartheta_- \nu_+ \sigma_{1+} + \vartheta_+ \nu_- \sigma_{1-}}$$

From (16) we get :

$$k^{1,2} = \frac{k_1^2}{2}\left(\frac{1}{k_2} + \frac{i}{k_3}\right) \pm k_1\sqrt{\frac{k_1^2}{4}\left(\frac{1}{k_2} + \frac{i}{k_3}\right)^2 + \frac{\omega^2}{\nu_-^{\ 2}} + \frac{\nu_+}{\nu_-} + i\,\frac{\omega}{\nu_-}} = \frac{k_1^2}{2}\left(\frac{1}{k_2} + \frac{i}{k_3}\right) \pm k_1\sqrt{a + ib} = \frac{k_1^2}{2}\left(\frac{1}{k_2} + \frac{i}{k_3}\right) \pm (x + iy) \qquad (17)$$

Opening the square root of (17) we easily get $k^{'}$ and $k^2$

$$\omega = \frac{\nu_-}{2\sqrt{2}}\frac{k_1}{k_3} \qquad (18)$$

Define $E^{'}$from $\mathcal{J}^{'} = (j_+^{'} - j_-^{'})$

$$E^{'} = \frac{\mathcal{J}^{'}}{\sigma} - \frac{e\vartheta_+}{\sigma_{1+}\sigma_{1-}}n_+^{'} - \frac{e\vartheta_-}{\sigma_{1+}\sigma_{1-}}n_-^{'}(19)$$

$n_+^{'}$ and$\mathrm{n}^{'}$we have to determine from the boundary conditions. Sample contacts are injecting and therefore

$$n_{\pm}^{'} = \delta_{\pm}\,\mathcal{J}^{'}(20).$$

$$n_+^{'} = \mathrm{C}_1 e^{ik_1x} + \mathrm{C}_2 e^{ik_2x},\ \mathrm{n}^{'} = \mathrm{C}_1^{\ -} e^{ik_1x} + \mathrm{C}_2^{\ -} e^{ik_2x}(21).$$

Substituting (21) into (20) it is easy to define constants $\mathrm{C}_1^{\ \pm}$ и $\mathrm{C}_2^{\ \pm}$ .

$$\mathrm{C}_1^{\ +} = \frac{\delta_+^{\ 0} + \delta_+^{\ L}}{1 - e^{ik_1L}}\,\mathcal{J}';\ \mathrm{C}_2^{\ +} = \frac{\delta_+^{\ L} - \delta_+^{\ 0}e^{ik_1L}}{1 - e^{ik_1L}};\ \mathrm{C}_1^{\ -} = \frac{\delta_-^{\ 0} - \delta_-^{\ L}}{1 - e^{ik_1L}}\,\mathcal{J}';\ \mathrm{C}_2^{\ -} = \frac{\delta_-^{\ L} - \delta_-^{\ 0}e^{ik_1L}}{1 - e^{ik_1L}}\ (22).$$

Substituting (19) with (22) into (15), we obtain:

$$\frac{Z}{Z_0} = 1 - \frac{1}{ik_1L}\frac{\sigma}{\sigma_1}[\mathrm{e}\vartheta_+(\delta_+^{\ L} - \delta_+^{\ 0}e^{ik_1L}) + \mathrm{e}\vartheta_-(\delta_-^{\ L} - \delta_-^{\ 0}e^{ik_1L})]\ (23).$$

$ik_1L = i\frac{k_1^2}{k_2}L - \frac{k_1^2}{k_3}L;\ Z_0 = \frac{L}{\sigma S}$; (S- sample cross section).

$ik_1L = i\frac{\sigma\nu_- L}{2\sigma_{1+}\mu}\frac{1}{E_0} - \frac{\sigma\nu_+ L}{\sigma_{1-}\mu}\frac{1}{E_0} = i\frac{E_1}{E_0} - \frac{E_2}{E_0};\ E_0 \gg E_1, E_2$ .

$$\frac{E_1}{E_2} = \frac{1}{2}\frac{\mu}{\mu_+} \gg 1$$

$$E_1 = \frac{\sigma\nu_- L}{2\sigma_{1+}\mu_-};\ E_2 = \frac{\sigma\nu_+ L}{2\sigma_{1-}\mu};$$

$$e^{ik_1L} - 1 = \cos\frac{E_2}{E_0} - i\sin\frac{E_2}{E_0}\ (24)\ .$$

Substituting (24) into (23) and selecting $\frac{ReZ}{Z_0}$ and $\frac{ImZ}{Z_0}$ we get:

$$Re\,\frac{Z}{Z_0} = 1 + (e\vartheta\delta)_L(\frac{E_2}{E_1} + \sin\frac{E_2}{E_1}) - (e\vartheta\delta)_0(\frac{E_2}{E_1} + 1/2) \qquad (25).$$

$$\mathrm{Im}\,\frac{Z}{Z_0} = (e\vartheta\delta)_L(\frac{E_2}{E_1} + \sin\frac{E_2}{E_0}) - (e\vartheta\delta)_0[\frac{E_0}{E_1} + \frac{\sin\frac{E_2}{E_0}}{2(1 - \cos\frac{E_2}{E_1})}] \qquad (26).$$

$$(e\vartheta\delta)_L = \frac{\sigma}{\sigma_1}(e\vartheta_+\delta_+^{\ L} + e\vartheta_-\delta_-^{\ L});\ \ (e\vartheta\delta)_0 = \frac{\sigma}{\sigma_1}(e\vartheta_+\delta_+^{\ L} + e\vartheta_-\delta_-^{\ L});$$

When external instability (i.e. $\mathcal{J}^{'} \neq 0$)
$\frac{ReZ}{Z_0}0,$ and $\frac{ImZ}{Z_0}$can have any character. From (24) and (25) we obtain the following equations for the determination of the electric field.

$$Re\frac{Z}{Z_0}+\frac{R}{Z_0}=0 \qquad \mathrm{Im}\frac{Z}{Z_0}=\frac{R_1}{Z_0}=0 \quad (27).$$

R-ohmic resistance in the circuit, and $R_1$, depending on the sign, Im$Z$ resistance of inductive or capacitive nature. Defining $\cos\frac{E_2}{E_1}$ from (24) supplying in (26) we find $\sin\frac{E_2}{E_1}$

Then from$sin^2\frac{E_2}{E_1}+cos^2\frac{E_2}{E_1}=1$ we will get

$E_0=E_{0_1}\frac{2R_1}{Z_0}$ и $\frac{Z_0}{2R_1}+\frac{R}{Z_0}$=2, $R=R_1=Z_0$

Thus, in impurity semiconductors, when $n_+\nu_+=n_-\nu_-$, internal and external instability occurs and the specified semiconductor, in the presence of external instability, becomes a source of energy radiation, the field value is determined by the formula

$E_0=E_1\frac{2R_1}{Z_0}$; $R_1>0$.

The frequency of current oscillations is determined by the formula

$$\omega=\frac{\nu_-}{2\sqrt{2}}\frac{k_1}{k_3}$$

## V. Discussion

Thus, in the above impurity semiconductors, under the influence of an external electric field, oscillations occur inside the crystal. The wave growth conditions are determined by specific analytical expressions. These waves propagate through the electric field. The frequency and wave increment are expressed in terms of the electron capture frequency. When the current begins to oscillate in the circuit (that is, the radiation of the sample begins) of the electric field, the frequency of the oscillation changes significantly. The analytical formulas found for the frequency of oscillation and the external electric field are quite feasible experimentally.

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