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NON-LINEAR FLUCTUATIONS OF CONCENTRATION OF CHARGE CARRIERS AND AN ELECTRIC FIELD IN SEMICONDUCTORS

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Abstract- It has been proven that due to generation and recombination of charge carriers at the presence of an external constant electric field concentration fluctuations of charge carriers and electric field occur in semiconductors with deep traps. For the first time a Van-der-Paul type equation was obtained in these semiconductors for the alternating electric field. From the solution of the obtained equation both the amplitude and oscillation frequency were determined in the first approximation by the method of N.N. Bogolyubov and Yu.A. Mitropolsky. It was shown that the frequency of oscillations in the first approximation is more important than in the zero approximation. The amplitude of oscillations tend to a finite value at very high time value $t \to \infty$. This proves that there is a steady dynamic mode. A graph indicating the dependence of amplitude on time was developed. The values of the electric field and the constants of generation and recombination of charge carriers were determined.

Keywords: Traps, Frequency, Amplitude, Oscillations, Generation, Recombination.

I. INTRODUCTION

The study of oscillatory processes is essential for the most diverse areas of physics and engineering. Electromagnetic oscillations in electronics and optics, sound and ultrasonic vibrations, all of these processes are combined through methods of mathematical physics in one common doctrine of oscillations. It is necessary to note that with the development of science and technology the role of the studies about oscillations is also rapidly increasing. The origins of the modern theory of oscillations can be clearly seen in the classical mechanics of the times Galileo, Huygens and the Newton's task of the motion of the pendulum. In the works of Lagrange has already the formed theory of small oscillations. In the further development it was called the theory of linear oscillations, i.e. fluctuations characterized by linear differential equations with constant coefficients both with homogeneous and free members being the known functions of time.

In the works of A.N. Krylov and his students the differential equations have successfully applied to the problems of artillery, ship rocking and also to the theory of gyroscope. The main concept of oscillation theory, specific frequency, damping decrement, and resonance achieved the widest popularity.

Due to the fact that the theory of linear oscillations developed in detail and its mathematical apparatus operates almost automatically, researchers strive to learn their oscillatory processes as far as possible to subsume under the linear scheme, discarding often without proper substantiation of nonlinear terms. Wherein sometimes completely overlooked one aspect that such a "linear" interpretation can lead to serious errors not only quantitative, but also a fundamentally qualitative nature. The fact is that the usual expansion in powers of the small parameter leads for the unknown quantities characterizing movement, to the approximate formulas, where along with members harmonically depending on time, there are still so-called secular terms such as

$$t^m \sin\alpha t\ ,\ t^m \cos\alpha t \tag{1}$$

For example, the movement described by the equation

$$\frac{dx}{dt} = -\varepsilon x \tag{2}$$

with a small positive parameter ε has a solution

$$x = ce^{-t\varepsilon} \tag{3}$$

If we apply the decomposition method, we get

$$x = c\left(1 - \varepsilon t + \frac{\varepsilon^2 t^2}{2} + ...\right) \tag{4}$$

This formula becomes applicable only until $t << \frac{1}{\varepsilon}$ and during this time x will not manage to change appreciably.

The Van-der-Paul method of expansion of equation

$$\frac{d^2x}{dt^2} + \omega_0^2 x = \varepsilon f\left(x, \frac{dx}{dt}\right) \tag{5}$$

can lead to secular members in form of (1).

After 20 second of the last century new methods of the oscillation systems' research have been developed. They are described in detail in the book of N.N. Bogolyubov and Yu.A. Mitropolsky titled as "Asymptotic methods in the theory of nonlinear oscillations".

The solution of the Van-der-Paul Equation (5) in the method of N.N. Bogolyubov and Yu.A. Mitropolsky seems in the following expansion form

$$x = a\cos\psi + \varepsilon U_1(a,\psi) + \varepsilon^2 U_2(a,\psi) + ... = a\cos\psi + \sum_{i=1}^{n} \varepsilon^n U_n(a,\psi) \quad (6)$$

where, $\psi = \omega t + \theta$, ε is positive small parameter and $U_i(a,\psi)$ is periodic function of the angle with 2π period, and the values a, ψ are determined as time functions according to the following differential equations:

$$\frac{da}{dt} = \sum_{i=1}^{n} \varepsilon^n A_n, \quad \frac{d\psi}{dt} = \omega_0 + \sum_{i=1}^{n} \varepsilon^n B_n \quad (7)$$

It is required that at small ε the Equation (6) would give a sufficiently accurate representation of solution of Equation (5) for a sufficiently long period of time. Periodical functions $U_n(a,\psi)$ satisfy the following conditions:

$$\int_0^{2\pi} U_1(a,\psi)\cos\psi d\psi = 0, \quad \int_0^{2\pi} U_2(a,\psi)\cos\psi d\psi = 0, \quad \int_0^{2\pi} U_1(a,\psi)\sin\psi d\psi = 0, \quad \int_0^{2\pi} U_2(a,\psi)\sin\psi d\psi = 0 \quad (8)$$

After expansion of the Van-der-Paul Equation (5) in powers of the small parameter ε we get [1]:

$$A_1(a) = -\frac{1}{2\pi\omega}\int_0^{2\pi} f\left(x, \frac{dx}{dt}\right)\cos\psi d\psi, \quad B_1(a) = -\frac{1}{2\pi a\omega}\int_0^{2\pi} f\left(x, \frac{dx}{dt}\right)\cos\psi d\psi \quad (9)$$

Substituting (9) in (7) we obtain the differential equation for determining the oscillation amplitude and frequency fluctuations in the first and second approximations. This mathematical method eliminates the secular terms of form (1).

We will for the first time apply this asymptotic method of solution to the impurity semiconductors. First of all, it is necessary to obtain an equation of Van-der-Paul type (5) for semiconductors.

II. MODEL OF IMPURITY SEMICONDUCTOR AND THE BASIC EQUATIONS OF PROBLEM

Some impurities in semiconductor create the canters capable of finding in several charged states (mono-, di-, etc. positively or negatively charged). For example, gold atoms in germanium can except neutral state be once positively charged and singly, doubly and triply negatively charged centers. The atoms of copper, other than the neutral state can be singly, doubly and triply negatively charged centers.

Thus impurity centers correspond to several energy levels in the forbidden zone. These energy levels are located at different distances from the bottom of the conduction band in the forbidden zone of semiconductor. These levels are called deep traps depending on the removal from their valence band. The deep traps are able to capture electrons or holes depending on their charge states. As a result of such capture the concentration of electrons in the conduction band and the concentration of holes in the valence band are changed, and consequently the conductivity of semiconductor varies.

The deep traps can be more or less active under different experimental conditions. Singly and doubly negatively charged gold centers in germanium were active traps during the experiments conducted [2]. In the presence of an electric field, the electrons (and holes) receive an energy of $eE_0\ell$ from the electric field (where e is a positive charge, E_0 is the value of the electric field and ℓ is electron mean free path). Due to this energy the electrons can overcome the Coulomb barrier of a singly charged center and be captured (i.e., recombined with the center). Furthermore, due to the warm transfer the electrons can be generated from the traps to the conduction band. The number of holes is also changing as a result of electron capture by deep traps. Further we will be referring to a semiconductor with carriers of both signs, i.e. electrons and holes with concentrations n_- and n_+, respectively. In addition, the semiconductor has negatively charged deep traps with a concentration of $N_0 >> n_-, n_+$.

From N_0, N is the concentration of singly negatively charged traps, N_- is the concentration of doubly negatively charged traps.

$$N_0 = N + N_- \quad (10)$$

The linear theory of oscillations in the abovementioned semiconductors was discussed and presented in the early publications of the authors [3-6]. In these works, the system of equations is described in detail and we will write them without detailed analysis.

III. EXPERIMENTAL PROCEDURE

The continuity equation for electrons and holes n_- and n_+ in a semiconductor with above types of traps will be:

$$\left.\begin{array}{l}
\frac{\partial n_-}{\partial t} + \text{div} j_- = \gamma_-(0) n_{1-} N_- - \gamma_-(E) n_- N = \left(\frac{\partial n_-}{\partial t}\right) \\
\frac{\partial n_+}{\partial t} + \text{div} j_+ = \gamma_+(0) n_{1+} N_- - \gamma_+(0) n_+ N_- = \left(\frac{\partial n_+}{\partial t}\right)_{rek.} \\
j_+ = n_+\mu_+ E - D_+ \nabla n_+ ; \ j_- = n_-\mu_- E - D_- \nabla n_- \\
n_{1-} = \frac{n_-^0 N_0}{N_-^0} ; n_{1+} = \frac{n_+^0 N_-^0}{N_-^0} \\
\frac{\partial N_-}{\partial t} = \left(\frac{\partial n_+}{\partial t}\right)_{rek.} - \left(\frac{\partial n_-}{\partial t}\right)_{rek.} ; \ \text{div} J = 0, J - j_+ - j_-
\end{array}\right\} \quad (11)$$

Signs "0" mean the equilibrium values of the corresponding quantities. We will bring the system of Equations (11) to (5), i.e. we need to get from (11) a non-linear equation for one of unknown values n_-, n_+, E, N_-.

When linearization (11) $n_{\pm}=n_{\pm}^{0}+\Delta n'_{\pm}$, $E=E_0+E'$, $N_{-}=N_{-}^{0}+N'_{-}$, the variables $\Delta n'$, E' and N'_{-} are considered much less than the equilibrium values $n_{\pm}^{0}$, E_0 and N_{-}^{0}. However, when we need to build a theory of nonlinear oscillations the variables $\Delta n'_{\pm}$, E' and N'_{-} can be compared to their equilibrium values. Then, from the equation $\operatorname{div}J=0$, $J=J_0$=const, we obtain:

$$\begin{aligned}&U_{+}(E')=U_{+}^{0}+\mu'_{+}E_0+\mu'_{+}E'\\&\upsilon_{-}(E')=\upsilon_{-}^{0}+\mu'_{-}E_0+\mu'_{-}E'\\&\varphi(E')=\left(\mu'_{+}n_{+}^{0}+\mu'_{-}n_{-}^{0}\right)E_0+\\&+\left(\mu'_{+}n_{+}^{0}+n_{+}^{0}\mu_{+}^{0}+n_{-}^{0}\mu_{-}^{0}+\mu'_{-}n_{-}^{0}\right)E'\end{aligned}\tag{12}$$

$$D_{\pm}\nabla n_{\pm}<<n_{\pm}\mu_{\pm}E\ ,\ \frac{T}{eE}\frac{\nabla n_{\pm}}{n_{\pm}}<<1\tag{13}$$

$$n'_{+}=-\frac{\upsilon_{-}(E')}{\upsilon_{+}(E')}n'_{-}-\frac{\varphi(E')}{\upsilon_{+}(E')}\tag{14}$$

Taking into account (12), (13) and (14), from (11) we obtain:

$$\frac{\partial n'_{-}}{\partial t}-\frac{\partial}{\partial x}\left(\mu_{-}n_{-}E\right)=\nu_1N'_{-}-\nu_{-}n_{-}\tag{15}$$

$$-\frac{\nu}{\partial t}\cdot\frac{\upsilon_{-}n'_{-}+\varphi}{\upsilon_{+}}-\frac{\nu}{\partial x}\left(\mu_{+}E\cdot\frac{\upsilon_{-}n'_{-}+\varphi}{\upsilon_{+}}\right)=\nu_{+}n_{1+}-\nu_2\frac{\left(n_{+}^{0}+n'_{+}\right)}{n_{1+}}N_{-}\tag{16}$$

$$\frac{\partial N_{-}}{\partial t}=\nu_{+}n_{1+}+\nu_{-}n_{-}\tag{17}$$

where, $\nu_{\pm},\nu_{1,2}$ are the characteristic frequencies of the electron and hole capture and

$\nu_{-}=\gamma_{-}(E)N_0$, $\nu_{+}=\gamma_{+}(E)N_0$

$\nu_1=\gamma_{-}(0)n_{1-}$, $\nu_2=\gamma_{+}(0)n_{1+}$

From (15), (16) and (17) we can easily obtain the following equation in operator form:

$$\begin{aligned}&\left[\frac{\partial^2}{\partial t^2}-\mu_{-}E\frac{\partial^2}{\partial x\partial t}+\nu_{-}\frac{\partial}{\partial t}-\frac{\partial\nu_{-}}{\partial t}-\nu_{-}\nu_1\right]n'_{-}=\\&=\nu_1\nu_{+}n_{1+}+n_0\frac{\partial^2(\mu_{-}E)}{\partial x\partial n}-n_0\frac{\partial\nu_{-}}{\partial t}\end{aligned}\tag{18}$$

$$\begin{aligned}&\begin{bmatrix}\upsilon_{+}\dfrac{\partial\upsilon_{-}}{\partial t}-\upsilon_{-}\dfrac{\partial\upsilon_{+}}{\partial t}+\upsilon_{-}\upsilon_{+}\dfrac{\partial}{\partial t}-2\upsilon_{+}\mu_{+}E\dfrac{\partial\upsilon_{-}}{\partial x}-\\-2\upsilon_{+}\upsilon_{-}\mu_{+}E\dfrac{\partial}{\partial x}-2\upsilon_{-}\mu_{+}E\dfrac{\partial\upsilon_{+}}{\partial x}-3\upsilon_{-}\upsilon_{+}\nu_{-}\end{bmatrix}n'_{-}=\\&=\upsilon_{+}^{2}\left(\nu_{+}n_{1+}+n_{-}^{o}\nu_{-}\right)-\upsilon_{+}\frac{\partial\varphi}{\partial t}+\varphi\frac{\partial\upsilon_{+}}{\partial t}+\nu_{-}\upsilon_{+}\varphi+\\&+2\mu_{+}E\upsilon_{+}\frac{\partial\varphi}{\partial x}+2\mu_{+}E\varphi\frac{\partial\upsilon_{+}}{\partial x}+3\nu_{-}\varphi\upsilon_{+}\end{aligned}\tag{19}$$

Let's write (18) and (19) in the following form:

$$\hat{\Omega}_1n'_{-}=A\ ,\ \hat{\Omega}_2n'_{-}=B\tag{20}$$

and from (20):

$$\hat{\Omega}_1A=\hat{\Omega}_2B\tag{21}$$

Designating $y=\dfrac{E'}{E_0}$ after opening (21), we obtain:

$$\begin{aligned}&\frac{1}{\varepsilon}\left(\frac{\partial^2y}{\partial t^2}+\omega_0^2y\right)=6\nu_1\nu_{+}\left(y^2+\beta_{+}^{\gamma}y^2+\beta_{-}^{\gamma}y^3\right)+\\&+\frac{\nu_1\nu_{+}}{\nu_{-}}\frac{\partial y}{\partial t}\times\begin{pmatrix}3+10y+14y^2+6\beta_{+}^{\gamma}y^2+2\beta_{+}^{\gamma}+11y^3+\\+9\beta_{+}^{\gamma}y^2+2y^4+7\beta_{+}^{\gamma}y^4+2\beta_{+}^{\gamma}y^5\end{pmatrix}+\\&+\frac{\nu_1\nu_{+}\upsilon_{-}}{\nu_{-}}\frac{\partial y}{\partial x}\begin{bmatrix}6+6y+12y^2+14y^3+12y^4+4y^5-\\-\dfrac{1}{\varepsilon}\dfrac{\nu_{-}}{\nu_{+}}\left(1+7y+12y^2+7y^3+5y^5\right)\end{bmatrix}-\\&-\frac{4\nu_1\nu_{-}}{\varepsilon}\left(\frac{y^2}{2}+\beta_{-}^{\gamma}y^2+\frac{\beta_{-}^{\gamma}}{2}y^3+\frac{y^4}{2}\right)+\frac{\upsilon_{-}}{\varepsilon}\beta_{-}^{\gamma}\\&-\frac{\partial y}{\partial x}\frac{\partial y}{\partial t}\left(2+10y+23y^2+28y^2+25y^4+8y^5\right)+\\&+\frac{\mu_{+}}{\mu_{-}}\nu_{-}\beta_{-}^{\gamma}\frac{\partial y}{\partial t}\left(\frac{n_{-}}{n_{+}}+\frac{\nu_{+}}{\nu_{-}}\right)\left(1+2y+3y^2+2y^3+y^4\right)+\\&+4\nu_{-}\beta_{-}^{\gamma}\frac{\partial y}{\partial t}\left(y+3/2y^2+3/2y^3+1/2y^4\right)+\\&+\frac{\partial^2y}{\partial t^2}\left[y+\frac{1}{\varepsilon}\left(y^2+y^3+2y^4\right)\right]+\left(\frac{\partial y}{\partial t}\right)^2\left(1+\frac{2y^3}{\varepsilon}\right)=\\&=f\left(y_1\frac{dy}{dt},\frac{y}{dx}\right)\end{aligned}\tag{22}$$

$$\begin{aligned}&\frac{da}{dt}=\frac{\varepsilon}{2\pi\omega}\int_0^{2\pi}f\left(y,\frac{dy}{dt},\frac{dy}{dx}\right)\sin\psi d\psi\ ,\ \varepsilon=\frac{en_{1+}\mu_{-}}{\sigma}\\&\omega_0^2=\nu_{-}\nu_{+}\begin{bmatrix}4-3\varepsilon\left(2+\beta_{+}^{\gamma}\right)+\\+\dfrac{\mu_{+}}{\mu_{-}}\beta_{+}^{\gamma}+\dfrac{n_{-}\mu_{+}}{n_{1+}\mu_{-}}\beta_{-}^{\gamma}+\beta_{-}^{\gamma}-\dfrac{4\nu_{-}}{\nu_{+}}\dfrac{1}{\varepsilon}\end{bmatrix}\end{aligned}\tag{23}$$

After integration of (23), we obtain:

$$\frac{da}{dt}=\frac{\nu_1\nu_{+}\varepsilon}{2\nu_{-}}\left\{\begin{bmatrix}\dfrac{3}{4}\left(14+6\beta_{+}^{\gamma}\right)+\\+\dfrac{\nu_{-}^{2}}{\nu_1\nu_{+}}\dfrac{\mu_{+}}{\mu_{-}}\left(\dfrac{n_{-}}{n_{+}}+\dfrac{\nu_{+}}{\nu_{-}}\right)\end{bmatrix}a-\frac{9\nu_{-}}{\omega}a^3\right\}\tag{24}$$

When receiving (24), the values of both the electric field E_0 and the constant β_{-}^{γ} were determined by the following formulas:

$$E_0=\frac{3\nu_{+}\varepsilon}{\mu_{-}};\beta_{-}^{\gamma}=\frac{\nu_1\nu_{+}}{\nu_{-}^{2}}\left(\frac{1}{3}+7\beta_{+}^{\gamma}\right)\tag{25}$$

Designating $\Omega=\dfrac{\nu_1\nu_{+}}{\nu_{-}}$;

$$\delta=\frac{3}{4}\left(14+6\beta_{+}^{\gamma}\right)+\frac{\nu_{-}^{2}}{\nu_1\nu_{+}}\frac{\mu_{+}}{\mu_{-}}\left(\frac{n_{-}}{n_{+}}+\frac{\nu_{+}}{\nu_{-}}\right)$$

from (24) we obtain $\upsilon=\dfrac{\omega\delta}{9\nu_{-}}$;

$$\frac{da}{dt}=\frac{\Omega\delta\varepsilon}{2}a\left(1-\frac{9\nu_{-}}{\omega\delta}a^2\right)=\frac{\Omega\delta\varepsilon}{2}a\left(1-\frac{1}{\upsilon}a^2\right)\tag{26}$$

Let's write (26) in the following form:

$$\frac{da^2}{dt}=\frac{1}{\tau}a^2\left(1-\frac{1}{\varphi}a^2\right)$$

$$\tau=\frac{4}{\delta\varepsilon....}$$

$$\frac{da^2}{a^2\left(1-\frac{1}{\varphi}a^2\right)}=\frac{dt}{\tau} \quad (27)$$

$$\frac{da^2}{a^2}+\frac{da^2}{\varphi-a^2}=\frac{dt}{\tau}$$

$$\ell na^2-\ell n\left(\varphi-a^2\right)=\ell na_0^2-\ell n\left(\varphi-a_0^2\right)=\frac{t}{\tau}$$

$$a=\frac{a_0e^{\frac{t}{2\tau}}}{\left[1+\frac{a_0^2}{\varphi}\left(e^{\frac{t}{\tau}}-1\right)\right]^{1/2}} \quad (28)$$

$$E'=E_0\frac{a_0e^{\frac{t}{2\tau}}}{\left[1+\frac{a_0^2}{\varphi}\left(e^{\frac{t}{\tau}}-1\right)\right]^{1/2}} \quad (29)$$

Considering Equation (29), if the initial value of the amplitude is zero then the amplitude will be equal to zero for t, and we obtain $E'=0$, i.e. trivial solution of the Van-der-Paul equation.

This trivial solution is obviously corresponding to the static mode, i.e. the absence of oscillations in the sample. However, based on this formula, it is easy to notice that the static mode is unstable. Indeed, matter how small has not been an initial value of the amplitude, it will still increase monotonically, approaching the limit value equal to $\varphi^{1/2}$.

From (29) we also observe that if $a_0=\varphi^{1/2}$ then $a=\varphi^{1/2}$ for all $t\geq 0$. It corresponds to the dynamic mode

$$E'=E_0\varphi^{1/2}\cos\left(\omega_0 t+\theta\right) \quad (30)$$

IV. RESULTS AND DISCUSSION

Thus, the obtained dynamic mode has strong stability, whichever be the value $a_0\neq 0$ all the same $a(t)\to\varphi^{1/2}$ at $t\to\infty$. The conservative system has no dissipation or energy source, once excited vibrations can neither grow nor attenuate, and their amplitude is equal to its initial value.

The semiconductor discussed in this paper has energy dissipation and its source, the electric field, E_0. Therefore, the amplitude of the oscillations will increase if the quantity of energy obtained through the charge carriers from electric field is greater than the amount of energy dissipated by the dissipative forces. If the quantity of energy obtained from the electric field is less than the quantity of dissipated energy, the vibrations will be damped.

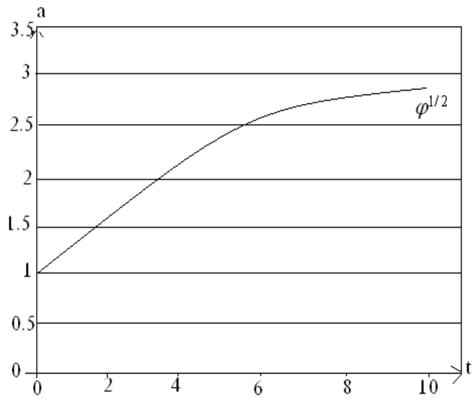

Figure 1. Dependence of the amplitude oscillation $a(t)$ from time

The graph $a(t)$ clearly shows that at $t\to\infty$, $a(t)\to\varphi^{1/2}$. Fluctuations in the first approximation can be calculated from the Equation (9).

$$\omega=\frac{d\varphi}{dt}=$$
$$=\omega_0-\frac{\varepsilon}{2\pi\omega_0 a}\times\int_0^{2\pi}f\left(y,\frac{dy}{dt},\frac{dy}{dx}\right)\cos\psi d\psi=$$
$$=\omega_0+\frac{3\nu_1\nu_+}{4\omega_0}\beta_-^\gamma a^2+\frac{5k\upsilon_-\beta_-^\gamma a}{4}+$$
$$+\frac{k\upsilon_-\beta_-^\gamma 7a^4}{4\varepsilon}+\frac{5\upsilon_-k\beta_-^\gamma a^6}{64}-\frac{3\omega a^2}{8} \quad (31)$$

From (31) at $\beta_-^\gamma=\frac{\omega_0^2}{2\nu_1\nu_+}$ we obtain the following:

$$\omega=\omega_0\left(1+\frac{5\omega_0\varepsilon a}{8\nu_1}+\frac{21\omega_0 a^4}{8\nu_1}+\frac{15\varepsilon\omega_0 a^6}{128\nu_1}\right) \quad (32)$$

The expression (32) indicate that the frequency of oscillation in the above semiconductor in the first approximation is greater than in zero approximation.

Substituting the value of β_-^γ in (25) we obtain the value of the constant β_+^γ

$$\beta_+^\gamma=\frac{1}{14}\left(\frac{\omega_0\nu_-}{\nu_1\nu_+}\right)^2-\frac{1}{21} \quad (33)$$

β_-^γ and β_+^γ positive constants and, therefore, from (33)

$$\omega_0>\frac{\nu_1\nu_+}{\nu_-}\left(\frac{2}{3}\right)^{1/2} \quad (34)$$

V. CONCLUSIONS

Oscillation of electric field occurs in the above impurity semiconductors, concentration of charge carriers, and finally, the current density in the dynamic mode. The frequency of these oscillations in the first approximation is more than the initial oscillation frequency, and the amplitude increasing over time in dynamic mode, tends to a stable value.

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BIOGRAPHIES

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