# OSCILLATIONS OF CURRENT IN TWO-VALLEY SEMICONDUCTORS IN A STRONG ELECTRIC FIELD

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For the first time, the Boltzmann kinetic equation was used to study current oscillations in two-valley semiconductors of the GaAs type. Taking into account the intravalley and intervalley scattering of charge carriers into the Boltzmann equation does not complicate the solution of this equation. The obtained values of the critical field at which instability begins are in agreement with Gunn's experiment.

**Keywords**: Boltzmann equation, nonequilibrium process, valleys, energy spectrum, energy gap, mean free path, instability.
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## INTRODUCTION

Current fluctuations (instability) in semiconductors are of interest from several points of view. First, it provides an easy way to convert electromagnetic energy using semiconductors. From the point of view of radio engineering, a sample in which there are resting or moving valleys is a system with a substantially nonlinear current-voltage characteristic (CVC). Generation and amplification of electromagnetic oscillations are possible here, depending on the experimental conditions. Second, the mechanisms responsible for the onset of instability reflect one or another specific feature of a solid. Finally, thirdly, we have here a case when physics came face to face with the properties of an essentially nonequilibrium macroscopic system.

In theoretical works [1-4], current oscillations in two-valley and impurity semiconductors are investigated. Typical examples of the dependence of the current density in a spatially homogeneous system on the field strength under conditions when there is a falling section on the volt-ampere characteristics are shown in fig. 1.

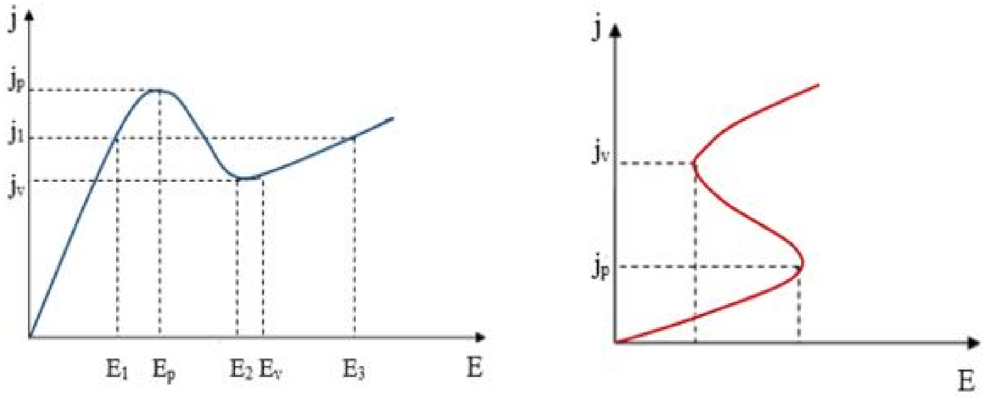


*Fig*.1. a) N-shaped current-voltage characteristic, b) N-shaped current-voltage characteristic.

An essential feature of the characteristic in fig. 1.a. consists in the fact that in a certain range of currents, the field strength is a multivalued function of the current density. When $E = E_1$ and $E = E_3$ the differential conductivity is positive, when $E = E_2$ it is negative. In fig. 1.b. the current density is an inhomogeneous function $E$ , at $E = E_p$ and $E = E_\upsilon$ the differential conductivity becomes infinite.

We will theoretically investigate the instability in semiconductors with a characteristic in fig. 1.a. In these semiconductors, under the influence of external factors (electric field, magnetic field), valleys appear in which the charge densities differ. A typical example of these semiconductors is GaAs. In a GaAs compound in 1964, the English scientist Gunn first observed current fluctuations (i.e., instability). The physical mechanism of the Gunn effect was explained in [5-6]. This mechanism leads to the appearance of a falling section on the volt-ampere characteristics due to the peculiarities of the energy spectrum of charge carriers. The idea is to use an electric field to heat the carriers in a subband with high mobility, as a result of which they, having acquired a sufficiently high energy, will pass into a subband with high energy and low mobility. In GaAs, the carrier dispersion law is as follows.



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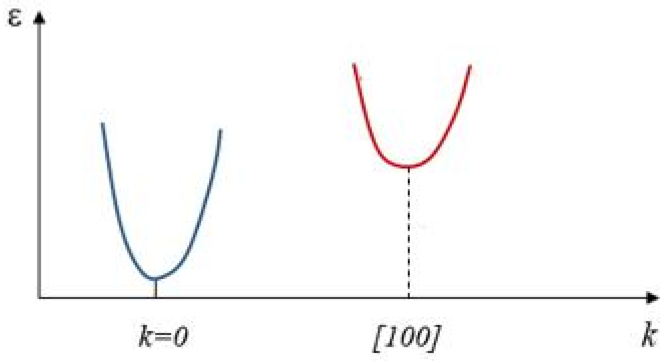


*Fig. 2.* Energy dependence on the wave vector in GaAs.

The dispersion law near the main minimum is isotropic. The effective masses are as follows $m_a = 0{,}72m_0$, $m_б = 1{,}2m$. Energy distance between $\Delta = 0{,}36eV >> k_0T$ is minimum. With a sufficiently strong heating of the electrons, some of them pass into the upper minimum. The mobility of carriers in valleys is very different and $\mu_a >> \mu_б$.

The current density with neglect of the diffusion current has the form

$$j = (en_a\mu_a + en_б\mu_б)E = en\mu(E)E\,,$$

$$\mu(E) = \frac{n_a(E)\mu_a(E) + n_б(E)\mu_б(E)}{n}\,,$$

$$n = n_a + n_б = const\,.$$

On the basis of the Gunn effect, generators are prepared that operate the entire volume of the sample. In all theoretical works in the literature on the Gunn effect, it is assumed that intervalley scattering is small compared to intra-valley scattering. In this theoretical work, on the basis of solving the Boltzmann kinetic equation, taking into account intervalley scattering under the influence of an external electric field, we calculate the total current in two-valley (GaAs) semiconductors and determine the critical electric field at which the current oscillates.

## BASIC EQUATIONS OF THE PROBLEM

The study of current carriers in a nonequilibrium state, when they move in a crystal, under the influence of applied external fields, electric, magnetic and thermal, is of great theoretical and practical interest. Such processes are associated with the movement of charge carriers, i.e., kinetic effects require mathematical analysis. For the analysis of kinetic effects, the basic equation is the Boltzmann kinetic equations. However, the application of this equation to nonequilibrium processes is not always justified. This issue was studied in [7-8] and came to the conclusion that for a simple structure and weak interaction only with acoustic phonons, the equation of motion of the density matrix is reduced to the kinetic Boltzmann equation. Generally speaking, there is no reason why the Boltzmann equation would be less suitable for strong fields than for weak ones, which is usually considered. We will study the current instability in semiconductors with a band structure in Fig. 1. applies the kinetic equations of Boltzmann. It is assumed that scattering occurs by acoustic phonons. The fact that the study of the Gunn effect on GaAs samples did not reveal any orientation dependence suggests that there is no anisotropy. We assume that for valleys "a" intervalley scattering prevails in comparison with intravalley scattering, and for valleys "b" we will assume that intravalley scattering prevails over intervalley scattering.

Then the Boltzmann equation for valley "a" can be written in the form

$$\left(\frac{\partial f^a}{\partial t}\right)_{external} + \left(\frac{\partial f^a}{\partial t}\right)_{interdomain} = 0 \qquad (1)$$

and for valley “b” it will be written as

$$\left(\frac{\partial f^b}{\partial t}\right)_{external} + \left(\frac{\partial f^b}{\partial t}\right)_{intradomain} = 0 \qquad (2)$$

In [9], it was proved that in a strong electric field the distribution function can be represented in the form

$$f = f_0 + \frac{\vec{P}}{p}\vec{f}_1 \qquad (3)$$

On this basis, we represent the functions are distributed $f^a$ and $f^b$ in the form

$$f^a = f_0^a + \frac{\vec{P}}{p}\vec{f}_1^a\,, \quad f^b = f_0^b + \frac{\vec{P}}{p}\vec{f}_1^b \qquad (4)$$

The distribution function $f^b$ was found from equation (2) in [10]

$$f_0^b = Be^{-\alpha_b(\varepsilon-\Delta)^2} \qquad (5)$$

$$\vec{f}_0^b = -\frac{em_b l_b}{p}\vec{E}\frac{\partial f_0^b}{\partial p} \qquad (6)$$

$$l_b = \frac{\pi\hbar^4\rho u_0^2}{D^2 m_b^2 k_0 T} \qquad (7)$$

$$\alpha_b = \frac{3D^4 m_b^5 k_0 T}{e^2 \pi^2 \hbar^8 \rho^2 u_0^2} \cdot \frac{1}{E^2} \qquad (8)$$

$l_b$ – free path in valley “b”
$D$ – deformation potential
$T$ – grate temperature
$k_0$ – Boltzmann constant
$u_0$ – sound speed
$\rho$ – crystal density

In the presence of external electric and magnetic fields, equation (1) has the form

$$\vec{V}\nabla_r f + \frac{e}{\hbar}\left\{\vec{E} + \frac{1}{c}\left[\vec{V}H\right]\nabla_k f\right\} = \left(\frac{\partial f}{\partial t}\right)_{interdomain} \qquad (9)$$

Here $\vec{V} = \frac{1}{\hbar}\nabla_k \varepsilon$ is the speed of the electron, $e$ is its charge, $\nabla_{\vec{r}}$ and $\nabla_{\vec{k}}$ gradients in the space of coordinates and wave vector $\vec{k}$.

**THEORY**

The stationary solution of equation (9) has the form

$$\left(\frac{\partial f^a}{\partial t}\right)_{external} = \frac{e}{\hbar}\vec{E}\nabla_p f^a, \ \left(\frac{\partial f^a}{\partial t}\right)_{interdomain} = \frac{f_1^a}{\tau}, \ \tau = \frac{l_a m_a}{P}, \ e\vec{E}\frac{\partial f^a}{\partial P} + \frac{P f_1^a}{l_a m_a} = 0, \ f_1^a = -\frac{e m_a l_a}{P}\vec{E}\frac{\partial f_0^a}{\partial P} \qquad (10)$$

In (10), at $\hbar u_0 q << kT$ for $f_0^a$ was obtained the following equation

$$(\varepsilon + S k_0 T) f_0^{a''} + \left(\frac{\varepsilon}{k_0 T} + 2 + \frac{S k_0 T}{\varepsilon}\right) f_0^{a'} + \frac{\varepsilon}{k_0 T} f_0^a = 0 \qquad (11)$$

$$S = \frac{E^2}{E_0^2}, \ E_0 = \frac{\left(6 m_0 u_0^2 k_0 T\right)^{1/2}}{e l_a}, \ l_a = \frac{\pi \hbar^4 \rho u_0^2}{D^2 m_a^{3/2} m_b^{1/2} k_0 T}$$

Representing $f_0^a = A e^{-\alpha_a \varepsilon^2}$ from (11) we find:

$$\alpha_a = \frac{3D^4 m_0 m_a^3 m_b k_0 T}{\pi^2 e^2 \hbar^8 \rho^2 u_0^2 E^2} \qquad (12)$$

To find the constants A and B, we use the balance equations for the concentration of charge carriers

$$n_a + n_b = n \quad (13) \qquad \frac{dn}{dt} = 0 \qquad (14)$$

$n_a$ and $n_b$ concentration of carriers in valleys “a” and “b”. Equation (13) has the form

$$A\int_0^\infty e^{-\alpha_a \varepsilon^2} \frac{dP_x dP_y dP_z}{(2\pi\hbar)^3} + B\int_0^\infty e^{-\alpha_b(\varepsilon - \Delta)^2} \frac{dP_x dP_y dP_z}{(2\pi\hbar)^3} = n \qquad (15)$$

In the first integral $\varepsilon = \frac{P^2}{2m_a}$, and in the second integral $\varepsilon - \Delta = \frac{P^2}{2m_b}$, finding and supplying in (15) $P$ and $dP$ we get:

$$A\frac{(2m_a)^{3/2}}{2\pi^2\hbar^3}\int_0^\infty \varepsilon^{1/2} e^{-\alpha_a \varepsilon^2} d\varepsilon + B\frac{(2m_b)^{3/2}}{2\pi^2\hbar^3}\int_0^\infty (\varepsilon - \Delta)^{1/2} e^{-\alpha_b(\varepsilon-\Delta)^2} d(\varepsilon - \Delta) = n \qquad (16)$$

Introducing the notation $\beta = \dfrac{\int_1^\infty \left[x(x-1)\right]^{1/2} e^{-\alpha_a \Delta^2 x^2} dx}{\int_0^\infty \left[x(x+1)\right]^{1/2} e^{-\alpha_b \Delta^2 x^2} dx} \triangleright$

From (14) and (16) we get:

$$A=\frac{(2\pi)^2\hbar^3\alpha_a^{3/4}n}{(2m_a)^{3/2}\Gamma^{3/4}\left[1+\gamma^{-3/2}Z^{3/2}\beta\right]};\ \ B=\frac{(2\pi)^2\hbar^3\alpha_a^{3/4}n\beta}{(2m_a)^{3/2}\Gamma^{3/4}\left[1+\gamma^{-3/2}Z^{3/2}\beta\right]}$$

$$\gamma=\frac{m_a}{m_b};\ \ Z=\frac{\alpha_a}{\alpha_b}$$

Also

$$\frac{n_a}{n}=\frac{1}{1+\gamma^{-3/2}Z^{3/4}\beta};\ \ \frac{n_b}{n}=\frac{\gamma^{-3/2}Z^{3/4}\beta}{1+\gamma^{-3/2}Z^{3/4}\beta}$$

To study the current fluctuations, we calculate the total current

$$j=j_a+j_b \tag{17}$$

$$\vec{j}_a=\int_0^\infty e\vec{V}\frac{\vec{P}}{p}f_1^a d\vec{k}=\frac{e}{4\pi^2\hbar^3 m_a}\int_0^\infty f_1^a p^3dp=\frac{2e^2nl_a\alpha_a^{1/4}\vec{E}}{3(2m_a)^{1/2}\left[1+\gamma^{-3/2}Z^{3/4}\beta\right]}\frac{\Gamma^{3/2}}{\Gamma^{3/4}}$$

$$\vec{j}_b=\frac{2e^2nl_b\alpha_b^{1/4}}{3\gamma^{3/2}(2m_b)^{1/2}}\cdot\frac{\Gamma^{3/2}}{\Gamma^{3/4}}\cdot\vec{E}\cdot\frac{\vec{Z}^{3/4}\beta}{1+\gamma^{-3/2}Z^{3/4}\beta}$$

The total current $j$ will be

$$j=\Phi\alpha_a^{1/4}E\frac{1+t\beta\gamma^{-1}Z^{1/2}}{1+\gamma^{-3/2}Z^{3/4}\beta},\ \ t=\frac{l_b}{l_a}$$

$$\Phi=\frac{2e^2nl_a}{3(2m_a)^{1/2}}\cdot\frac{\Gamma^{3/2}}{\Gamma^{3/4}}$$

You can find the mobility of carriers in valleys “a” and “b”

$$j_a=en_a\mu_aE,\ \ \mu_a=\frac{2el_a\alpha_a^{1/4}}{3(2m_a)^{1/2}}\cdot\frac{\Gamma^{3/2}}{\Gamma^{3/4}}$$

$$j_b=en_b\mu_bE,\ \ \mu_b=\frac{2el_b\alpha_b^{1/4}}{3(2m_b)^{1/2}}\cdot\frac{\Gamma^{3/2}}{\Gamma^{3/4}}$$

$$\left(\frac{\mu_a}{\mu_b}\right)=\left(\frac{m_a}{m_b}\right)^{1/2}\left(\frac{\alpha_a}{\alpha_b}\right)^{1/4}=\left(\frac{m_a}{m_b}\right)^{5/4}$$

To study current fluctuations (i.e., instability), we represent $\beta$ in the following form

$$\beta=\frac{\int_1^\infty\left[x(x-1)\right]^{1/2}e^{-\alpha_a\Delta^2x^2}dx}{\int_0^\infty\left[x(x+1)\right]^{1/2}e^{-\alpha_b\Delta^2x^2}dx}\approx\frac{\int_1^\infty xe^{-\alpha_a\Delta^2x^2}dx}{\int_0^\infty xe^{-\alpha_b\Delta^2x^2}dx}\approx Z^{-1}e^{-\alpha_a\Delta^2}$$

Then the total current has the form

$$j=RE^{1/2}\frac{1+Ae^{-\alpha_a\Delta^2}}{1+Be^{-\alpha_a\Delta^2}} \tag{18}$$

$$R=\Phi\left(\frac{3D^4m_0m_a^3m_bk_0T}{e^2\pi^2\hbar^8\rho^2u_0^2}\right)^{1/4}$$

$$A = t \cdot Z^{-1/2} \gamma^{-1} = \frac{m_б}{m_a};$$

$$B = \gamma^{-3/2} Z^{-1/4} = \left(\frac{m_b}{m_a}\right)^{9/4}$$

We introduce the characteristic field $E_{char}$

$$E_{char}^2 = \frac{3D^4 m_0 m_a^3 m_b k_0 T}{e^2 \pi^2 \hbar^8 \rho^2 u_0^2}$$

then

$$\alpha_a \Delta^2 = \frac{E_{char}^2}{E^2}$$

At $E >> E_{char}$ $e^{-\frac{E_{char}^2}{E^2}} = 1 - \frac{E_{char}^2}{E^2}$

Let us calculate by formula (18) $\frac{dj}{dE} = 0$, then we obtain the following formulas for the critical value of the electric field, at which the current oscillations begin, i.e., instability.

$$E_{critical}^2 = 2E_{char}^2 \cdot \frac{A + 2,5}{A + 1} \tag{19}$$

If we estimate $E_{critical}$ by formula (19), we easily obtain $E_{critical} \approx 2800 V/sm$.

Note that if we take in the final formulas $m_a = m_b$ and $A = B = 1$

Then the instability is removed. This means that there is no transition of charge carriers from valley "a" to valley "b".

Then $j \sim E^{\frac{1}{2}}$ the instability is removed. This means that there is no transition of charge carriers from valley "a" to valley "b".

## 1. DISCUSSION OF THE RESULTS

Thus, instability manifests itself for fields of the order $\sim 2800 \frac{V}{sm}$. In Gunn's experiment, oscillations were observed at values of the electric field $2 \cdot 10^3 \div 4 \cdot 10^3 V/sm$. This proves that the study of current oscillations using the Boltzmann kinetic equation is quite valid.

We in works [1-4] theoretically conducted research of current fluctuations in two-valley semiconductors by applying the continuity equation and Poisson's equation. In this case, the excited vibrations inside the sample were analyzed by solving the obtained dispersion equations. The use of the kinetic equation for nonequilibrium processes in strong electric fields is quite justified. Of course, the Boltzmann equation can also be used for other scattering of charge carriers. For this, it is necessary to find criteria for the applicability of the Boltzmann kinetic equation.

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