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THE FREQUENCY OF CURRENT FLUCTUATIONS IN TWO-VALLEY SEMICONDUCTORS IN AN EXTERNAL ELECTRIC AND STRONG MAGNETIC $(\mu H > c)$ FIELDS

G.M. Mammadova
Institute of Physics,Baku, Azerbaijan Republic
(E_mail: gizbesmamedova@gmail.com)

Abstract
Boltzmann's kinetic equations have not been used to date to study nonequilibrium phenomena in semiconductors, and therefore, to obtain analytical expressions for the oscillation frequency inside the semiconductor and the critical external electric field, it is of theoretical interest. In this theoretical work, the frequency of oscillations occurring inside a two-valley semiconductor of the GaAs type in an external constant electric field and in an external strong magnetic field ($\mu H \gg c$, μ-mobility of charge carriers, H-magnetic field strength, c-speed of light) is calculated. It has been proved that the critical values of the external electric field fully correspond to the values of the electric field, which were obtained by the Gunn experiment. It is proved that unstable waves are excited in GaAs if the crystal dimensions are $L_y > 4L_z$ and $L_x \ll L_y$. Analytical expressions are obtained by theoretical calculation for an external constant magnetic field, when unstable oscillations are excited inside the sample.

Keywords: *oscillations, frequency, distribution function, electric field, magnetic field, current-voltage characteristic, multi-line semiconductors, Boltzmann's kinetic equations.*

Introduction

In theoretical works [1-4], current oscillations in two-valley semiconductors of the GaAs type in an external electric field, and in an external electric and strong magnetic fields are investigated by solving the Boltzmann kinetic equation. In these works, the critical values of the electric and magnetic fields were calculated from the condition

$$\frac{dj}{dE} = \sigma_d = 0 \quad \frac{dj}{dE} = \sigma_d = 0 \qquad (1)$$

(j is the current flux density, E is the electric field, σ_d is the differential conductivity). However, from condition (1) it is impossible to determine the frequency of the current oscillation. Therefore, it is of great interest to determine the current fluctuation in the presence of condition (1). In this theoretical work, we will calculate the frequency of current oscillation and the critical value of the electric and magnetic fields by applying the Boltzmann kinetic equation.

Theory

Typical examples of the dependence of the current density in a spatially uniform system on the field strength under conditions when there is a falling section on the current-voltage characteristic are shown in

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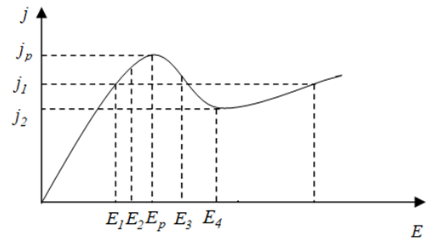

Figure 1. The dependence of the current density on the electric field in two-valley semiconductors of the GaAs type is an N-shaped characteristic.

An essential feature of the characteristic in Figure. 1 is that in a certain range of currents $j_2 < j < j_p$, the field strength is a multivalued function of the current density. In this current range, the system can be in one of three spatially homogeneous states. The Gunn effect is associated with an N-shaped characteristic. With negative differential conductivity, electric charges in the system are distributed unevenly, i.e. spatial regions with different values of charges appear in the system (i.e., electrical domains appear). One of the mechanisms for the appearance of domains is the Ridley-Watkins-Hillsum mechanism [5,6]. In electronic gallium arsenide GaAs, the dispersion law is as follows

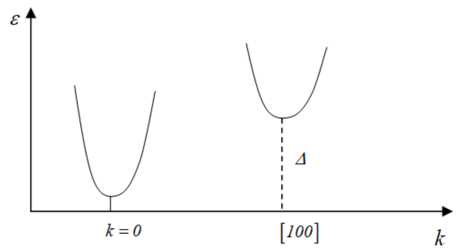

Figure 2. Electron energy versus wave vector in GaAs.

Since the energy distance between the minima is relatively large ($\Delta = 0{,}36 eV, \Delta \gg T_p$, T_p is the lattice temperature) under conditions of thermodynamic equilibrium, the presence of upper valleys (minima) practically does not affect the statistics of electrons.

However, with a sufficiently strong heating of electrons by an electric field, some of them pass into the upper minimum. The effective mass of electrons in the lower valley m_a is much less than the mass of electrons in the upper valley m_b. Therefore, the electron mobilities in the corresponding valleys are related by the relation

$$\mu_b \gg \mu_a \qquad (2)$$

If we designate the concentrations in the valleys $n_a \; and \; n_б$, we can write an expression for the current in the form

$$\vec{j} = en_a\mu_a\vec{E} + en_b\mu_b\vec{E} \qquad (3)$$

$$n = n_a + n_b = const \qquad (4)$$

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(we neglect the diffusion current due to $eEl \gg k_0T$, e is the elementary charge, is the electron mean free path). In works [5-6], without taking into account the intervalley scattering (it is considered small in comparison with the intravalley one), by solving the Boltzmann equation, more specific conditions for the appearance of current oscillations were obtained. In the scientific literature, there are no works devoted to theoretical studies of the Gunn effect taking into account the intervalley scattering based on the solution of the Boltzmann kinetic equation. We will theoretically analyze the influence of a strong magnetic field on the Gunn effect, taking into account the intervalley scattering, and calculate the frequency of the current oscillation under the above conditions by solving the Boltzmann kinetic equation.

Basic Equations Of The Problem

Under the action of external forces, the state of charge carriers is described by the distribution function $f(\vec{k},\vec{r})$, the value that is necessary when considering transport phenomena, $f(\vec{k},\vec{r})$ is the probability that an electron with a wave vector $\vec{k}$ (quasimomentum $\hbar\vec{k}$) is located near the point $\vec{r}$. We consider stationary processes, then $f(\vec{k},\vec{r})$ is clearly independent of time. The distribution function is found from the kinetic Boltzmann equation. It is known that the distribution function changes under the influence of external factors and under the influence of collisions with lattice vibrations (phonons) and crystal defects. In the considered stationary state, the influence of these factors mutually compensate each other.

$$\left(\frac{\partial f}{\partial t}\right)_{external} + \left(\frac{\partial f}{\partial t}\right)_{coll} = 0 \qquad (5)$$

In the presence of external electric and magnetic fields, equation (5) has the form [7]

$$\vec{v}\nabla_{\vec{r}} f + \frac{e}{\hbar}\left\{\vec{E} + \frac{1}{c}[\vec{v}\vec{H}]\right\}\nabla_{\vec{k}} f = \left(\frac{\partial f}{\partial t}\right)_{coll} \qquad (6)$$

Here $\vec{v} = \frac{1}{\hbar}\nabla_k \varepsilon(\vec{k})$ is the electron velocity, $\nabla_{\vec{r}}$ u $\nabla_{\vec{k}}$ is the gradient in the space of coordinates and wave vectors. When solving the problem, we neglect the anisotropy. The fact that no orientation dependence was found in studies of the Gunn effect on GaAs samples speaks in favor of this assumption. We will assume that for the lower valley the intervalley scattering prevails over the intravalley one, and for the upper valley, the intravalley scattering prevails over the intervalley one. Then the Boltzmann equation for the lower and upper valley can be written in the form

$$\left(\frac{\partial f^a}{\partial t}\right)_{internal} + \left(\frac{\partial f^a}{\partial t}\right)_{intervalley} = 0 \quad (7) \quad \left(\frac{\partial f^b}{\partial t}\right)_{internal} + \left(\frac{\partial f^b}{\partial t}\right) = 0 \quad (8)$$

Davydov [8] showed that in a strong electric field the distribution function has the form $f = f_0 + \frac{\vec{p}}{p}\overrightarrow{f_1}$ and from (8)

$$f_0^a = Be^{-\alpha_a(\varepsilon-\Delta)^2} f_1^b = -\frac{em_b l_b}{p}\vec{p}\frac{\partial f_0^b}{\partial p} \qquad l_b = \frac{\pi h^4 \rho u_0^2}{D^2 m_b^2 k_0 T} \qquad \alpha_b = \frac{3D^4 m_b^5 k_0 T}{e^2\pi^2 h^8 \rho^2 u_0^2} \qquad (9)$$

f_0 is the equilibrium distribution function, p is the momentum of charge carriers.

$$f^a = f_0^a + \frac{\vec{p}}{p}\vec{f}_1^a, f^b = f_0^b + \frac{\vec{p}}{p}\vec{f}_1^b \qquad (10)$$

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D is the deformation potential, T is the temperature of the lattice, ρ is the density of the crystal, u_0 is the speed of sound in the crystal. Let's calculate the total current $\vec{j} = \vec{j}_a + \vec{j}_b$. After calculation of the current density j_a and j_b from (16) is get:

$$\vec{j}_a = \frac{e^2 l_a \alpha_a A}{12\pi^2 h^2 m_a^2}\left\{\vec{E}\frac{c^2}{e^2 l_a^2 H^2}\left(\frac{4m_a^2}{\alpha_a}\right)^2 + [\vec{E}\vec{H}]\frac{c\Gamma(7/_4)}{e l_a H^2}\left(\frac{4m_a^2}{\alpha_a}\right)^{7/_4} + \vec{H}(\vec{E}\vec{H})\frac{\Gamma(3/_2)}{H^2}\left(\frac{4m_a^2}{\alpha_a}\right)^{3/_2}\right\} \quad (11)$$

After calculating the total current by the formula

$$j_z' = \frac{8nc^2 m_a^{1/_2}}{3\sqrt{2}\Gamma(3/_2) l_a}\frac{E_z'}{H^2}\cdot\frac{\alpha_a^{-1/_4}}{1+\gamma^{-3/_2} z^{3/_4}\beta}\left\{1 + t\gamma_z^{-2}\beta + \frac{e^2 l_a^2 \alpha_a^{1/_2}}{2c^2 m_a}H^2\Gamma(3/_2)\left[1 + t\gamma^{-1} z^{1/_2}\beta\right]\right\} \quad (12)$$

Here $A = tz^{-1/_2}\gamma^{-1} = \frac{m_b}{m_a}$, $\gamma = \frac{m_a}{m_b}$, $z = \frac{\alpha_a}{\alpha_b}$, $t = \frac{l_b}{l_a}$,

$$\beta = z^{-1}e^{-\alpha_a \Delta^2} e^{-\alpha_a \Delta^2} = e^{-\left(\frac{E_x}{E}\right)^2} = \left(1 - \frac{E_x}{E}\right)^2,\ E_x^2 = \frac{3D^4 m_0 m_a^8 k_0 T}{\pi^2 e^2 h^8 \rho^2 u_0^2} \quad (13)$$

We write (21) in the following form

$$\vec{j} = \sigma\vec{E} + \sigma_1[\vec{E}\vec{h}] + \sigma_2\vec{h}[\vec{E}\vec{h}] \quad (14)$$

$\vec{h}$ is unit vector in the magnetic field. Comparing (14) with (12), one can easily write the expressions $\sigma + \sigma,\ \sigma_1, \sigma_2$. The current density in the presence of electric and magnetic fields has the form

$$\vec{j} = \sigma\vec{E} + \sigma_1[\vec{E}\vec{H}] + \sigma_2\vec{H}[\vec{E}\vec{H}] \quad (15)$$

Let us direct the external electric and magnetic field as follows

$$\vec{E}_0 = \vec{h}E_0\ ,\ \vec{H}_0 = \vec{h}H_0 \quad (16)$$

($\vec{h}$ is the unit vector in z). We find the variable value j_x', j_y', j_z' from (15)

$$j_x' = \sigma\left(1 - \frac{\mu k_z E_0}{\omega}\right)E_x' + \sigma_1\left[\left(1 + \frac{ck_x E_0}{\omega H_0}\right) - \frac{2\sigma_2 ck_z E_0}{\omega H_0}\right]E_y' + \frac{2\sigma_2 ck_y E_0}{\omega H_0}E_z' \quad (17)$$

$$j_y' = -\sigma_1 E_x' + \left(\sigma - \frac{\sigma_1 ck_z E_0}{\omega H_0}\right)E_y' + \sigma_1\left(1 + \frac{ck_y E_0}{\omega H_0}\right)E_z' \quad (18)$$

$$j_z' = (\sigma + \sigma_2)E_z' - \frac{2\sigma_2 ck_y E_0}{\omega H_0}(E_x' + E_y') \quad (19)$$

For magnetic field

$$\left(\frac{H_x}{H_0}\right)^2 = 1,\ \text{т.е.}\ H_x = H_0 = \left[\frac{8c^2 m_a^{1/_2}\alpha_a^{-1/_4}}{3\sqrt{2}\Gamma(3/_2)e\mu l_a}\right]^{1/_2} \quad (20)$$

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Putting the values of $\alpha_a^{-1/4}$ in (37), is obtained

$$H_0 = \left[\frac{8}{3\sqrt{2}\Gamma(3/2)}\right]^{1/2} \cdot \left(\frac{k_0 T}{3m_0 u_0^2}\right)^{1/8} \cdot \left(\frac{c^2 m_a^{1/2}}{\mu}\right)^{1/2} \cdot \left(\frac{1}{el_a}\right)^{1/4} E_0^{1/4} \qquad (21)$$

From (21) is get

$$E_0 = \left(\frac{\mu}{c^2 m_a^{1/2}}\right)^2 el_a \left(\frac{H_0}{\varphi}\right)^4 \qquad \varphi = \left[\frac{8}{3\sqrt{2}\Gamma(3/2)}\right]^{1/2} \cdot \left(\frac{k_0 T}{m_0 u_0^2}\right)^{1/8} \qquad (22)$$

Thus, the value of the electric field is obtained during current fluctuations in the above two-valley semiconductors of the GaAs type. In [8], it was obtained

$$E_0 = E_{кр} = 1500\, V/_{SM} \qquad (23)$$

Supplying (23) to E_0 (22), it is to see that $\mu H_0 \gg c$

For fluctuations

$$\omega_{1,2} = -\frac{ck_z E_0}{2H_0} \pm i\frac{ck_z E_0}{H_0}\left(\frac{L_z}{L_y}\right)^{1/2} \qquad (24)$$

For growing fluctuations

$$\omega = -\frac{ck_z E_0}{2H_0} + i\frac{ck_z E_0}{H_0}\left(\frac{L_z}{L_y}\right)^{1/2} = \omega_0 + i\gamma \qquad (25)$$

From (25) it is seen that in the crystal $L_y > 4L_z$ $(\gamma \ll \omega_0)$. Thus, with the size (L_x-can be any), current oscillations (i.e., instability) are excited under an electric field (22).

Discussion Of The Results

In valley semiconductors of the GaAs type, current oscillations occur under the influence of an external electric and strong ($\mu H_0 \gg c$) magnetic field. The frequency of this oscillation ω_0 (25) is close to the frequency of the Gunn effect, i.e. $\omega_0 \sim 10^7 \div 10^9\ Herz$. This proves that the application of the Boltzmann equation is quite valid, although the Boltzmann equation in strong fields is not always applied. By directing $E_0 = \vec{i}E_0$, $E_0 = \vec{j}E_0$, $H_0 = \vec{i}H_0$, $H_0 = \vec{j}H_0$, one can carry out a theoretical calculation and determine the critical value of the electric field (including the magnetic field) and the frequency of current oscillation.

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