THE CURRENT OSCILLATIONS IN SEMICONDUCTORS IN EXTERNAL ELECTRIC AND MAGNETIC FIELDS.

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The theory of current oscillation in impurity semiconductors in external electric and magnetic fields is given. The strength values of electric and magnetic fields under different experimental conditions, at which instabilities leading to current oscillations in crystal are observed, are obtained. The frequencies of current oscillations are obtained. The theory of oscillation appearance in two-valley semiconductors of GaAs type in strong external electric and magnetic fields is constructed.

INTRODUCTION

The charge carriers: electrons and holes in internal electric field at acceleration by electric field have the additional energy the average value of which in a unit of time on unit of volume is defined as ***jE*** [1], where ***j*** is current density and ***E*** is electric field strength. In stationary state this energy should be equal to energy in average lost in a unit of time by charge carriers at collisions. Let's designate $\dot{\mathcal{E}}$ the energy change in a unit of time of charge carriers because of collisions. It is obvious that $\dot{\mathcal{E}}$ depends on $\mathcal{E}$ energy which the charge carrier has. Averaging it on ε values we obtain $\overline{(\dot{\varepsilon})}_{cm}$. The condition of energy balance of stationary state under consideration will have the following form:

$$\overline{(\vec{j}\vec{E})} = n\overline{(\dot{\varepsilon})}_{cm} \tag{1}$$

where n is concentration of charge carriers. In thermodynamic equilibrium state the charge carriers give energy in a unit of time upon the average to lattice as much as they receive from one, i.e.

$$\overline{(\dot{\varepsilon})}_{cm} = 0 \tag{2}$$

If in the case of external fields the condition (2) is realized then such fields are considered as weak ones. However, the situation essentially changes at presence of external fields at which the energy obtained by charge carriers from the field increases and the value $\overline{(\dot{\varepsilon})}_{cm}$ calculated for states close to thermodynamic equilibrium ones can be less than $\overline{(\vec{j}\vec{E})}$.

Then the average energy of charge carriers begins to increase with respect to its equilibrium value. At small equilibrium disturbance the right part of equation (1) can be expand into series over difference between average energy and its equilibrium value $\frac{3}{2}$kT by the following expression:

$$\overline{(\vec{j}\vec{E})} = \sum \frac{\frac{3}{2}\overline{(\varepsilon)} - kT}{\tau_e} n \tag{3}$$

Here τ_e^{-1} are the expansion coefficients, moreover τ_e is called the average time of energy relaxation, has the time dimension, depends on temperature and scattering mechanism of charge carriers. The average energy of charge carriers in electric field can exceed its thermodynamic equilibrium value because of comparative slowness of energy exchange process between charge carriers and their surroundings in lattice. If only electrons are charge carriers then this effect will lead to the electron gas heating.

For effect description let's introduce the conception of electron temperature T_e which differs from lattice temperature T.

Let's define T_e by the following expression:

$$\overline{(\varepsilon)} = \frac{3}{2} kT_e \tag{4}$$

Note that average energy $\overline{(\varepsilon)}$ should contain the summand connected with kinetic energy of charge carrier system as a whole.

Taking into account the drift of charge carriers the equation (4) is rewritten in the following form:

$$\overline{(\varepsilon)} = \frac{3}{2} kT_e + \mathcal{E}_d \tag{5}$$

Taking into consideration (4) we obtain from (3) the following expression:

$$\overline{(\dot{\varepsilon})} = \frac{k(T_e - T)}{\tau_e} \tag{6}$$

From (6) it follows that "temperature" T_e depends on electric field strength and the scattering mechanism.

The "heating" of charge carriers leads to the series of consequences observed on the experiment being technical interest. Note that Ohm's law is broken under conditions of charge carrier "heating", the mobility and electric conduction depend on field strength, and charge-drift velocity becomes the non-linear function of field strength.

In general, the flow density is the tensor value and depends on external field direction. Therefore it follows that $\vec{j}$ and $\vec{E}$ vectors can be not parallel to each other. The angle between them depends on $\vec{j}$ vector orientation with respect of crystal crystallographic axes. This effect is called Sasaki effect [2].

The presence of external fields leads to the change of conduction charge carrier number and their mobility. The dependence of charge carrier concentration on field strength is connected with specifics of recombination process. Under

the condition of thermodynamic equilibrium the free electron concentration is only defined by position of Fermi level and temperature. The last one is the result of that the probability of charge carrier capture by recombination centers and probability of reversal emission connect with each other by principle of detail equilibrium.

At system deviation from thermodynamic equilibrium the free charge carrier concentration will depend not only on lattice temperature but on relation between probabilities of processes of capture and reversal emission of charge carriers. The electric conduction decrease will connect with change of charge carrier number and mobility.

GUNN EFFECT

For simpleness let's consider the spatially homogeneous crystal [2-8]. In this case the current density is described by the expression:

$$j = \sigma E; \ \sigma = en\mu = \sigma(T_e) \tag{7}$$

and equation $j = j(E)$ defines the volt-ampere characteristic of considered sample the graphic picture of which is usually given in coordinates (j,E). At condition at which Ohm's law is applied, the plot of function $j(E)$ is the direct line passing through origin of coordinates with angular coefficient σ_0 which is equal to conduction value in weak field

As a result of heating of electron gas the volt-ampere characteristic becomes the non-linear one and for its description it is comfortable to introduce the concept of differential conductionσ_d.

When σ is scalar the σ_d value is defined by equation:

$$\sigma_d(E) = \frac{dj}{dE} = \sigma + E\frac{d\sigma}{dE} \tag{8}$$

Using the equilibrium equation:

$$\sigma E^2 = n\frac{T_e - T}{\tau_e} \tag{9}$$

and introducing the variable $R = \left(\frac{T_e - T}{\tau_e}\right)$ we obtain $\sigma E^2 = nR$. The nR value is energy given by current carriers in the lattice in unit of volume. As μ is mobility, n is concentration and τ_e is time depend on temperature T_e then:

$$\sigma_d = \sigma + E\frac{d\sigma}{dT_e}\frac{dT_e}{dE} \tag{10}$$

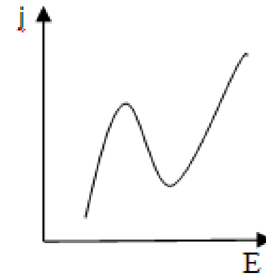
Differentiating over E the expression (9)

$$\frac{dT_e}{dE} = \frac{2\sigma E}{\frac{d(nR)}{dT_e} - E^2\frac{d\sigma}{dT_e}}, \tag{11}$$

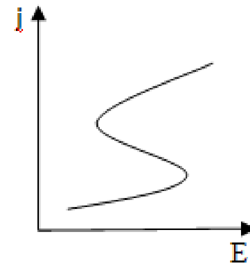
substituting (11) into (10) and changing E^2 on $\frac{nR}{\sigma}$ we obtain:

$$\sigma_d = \sigma\frac{\frac{d(nR)}{dT_e} + \frac{nR}{\sigma}\frac{d\sigma}{dT_e}}{\frac{d(nR)}{dT_e} - \frac{nR}{\sigma}\frac{d\sigma}{dT_e}} \tag{12}$$

In dependence on the fact that the formula (12) increases or decreases on field strength, the plot of volt-ampere characteristic $j(E)$ will be inclined up or down from direct line $j=\sigma_0 E$. The corresponding volt-ampere characteristics of both types have the following form:



N – type characteristics



S – type characteristics

In case of N-type characteristic the differential conduction changes the sign passing zero (the numerator in (12) changes the sign). In case of S-type characteristic the differential conduction changes the sign passing the singular point in which the denominator in (12) takes zero value.

The formation conditions of characteristics of both types are easily found from formula (12):

for N – type characteristics

$$\frac{n^2\mu}{\tau_e} + (T_e - T)\frac{d}{dT_e}\left(\frac{n^2\mu}{\tau_e}\right) = 0 \tag{13}$$

for S – type characteristics

$$1 - \left(\frac{T_e - T}{\tau_e\mu}\right)\frac{d(\tau_e\mu)}{dT_e} = 0 \tag{14}$$

From formula (13) it follows that with increase of electron temperature the product of mobility on concentration of charge carriers should rapidly decrease, moreover T_e should enough exceed the T lattice temperature. In second case (condition (14)), the energy given by electrons in unit of time should rapidly decrease with increase of electron temperature, moreover the overheating $(T_e - T)$ shouldn't be very small one.

One can consider the following facts:

- In homogeneous *n-GaAs* the appearance of N-type characteristic is expected at room temperature. The negative differential conductivity should appear at field strength E≈2300V/cm and disappear at E≈10000V/cm.
- In *n-Ge* doped by aurum or cuprum at lattice temperature 30-35K also should appear the characteristic of N-type.

It is obvious that conception on spatial inhomogeneity in average doesn't exclude the local deviations of physical

values from their average ones. The fluctuations of charge carrier concentrations and electric field strength are caused by random heat motion of charge carriers by other hand and by spontaneous homogeneities in distribution of impurity atoms and other structural defects of crystal lattice. In the case when charge carriers are in the state of thermodynamic balance or close to it the presence of these fluctuations weakly influences on transfer phenomenon. However, the situation can change if charge carriers are strongly "heated". Then at fluctuation of electric field ΔE the fluctuation of charge carrier density should appear and according to Poisson equation it equals to following expression:

$$\Delta\rho = \frac{\varepsilon}{4D} div\ \Delta E \qquad (15)$$

and the current fluctuation has the following form:

$$\Delta j = \sigma_d \Delta E \qquad (16)$$

From this it follows that for $\sigma_d > 0$ and $\sigma_d < 0$ cases the charge inflow into fluctuation region changes and fluctuations can either damp or increase, correspondingly.

Thus, in homogeneous crystal the regions of strong and weak fields can appear, moreover, the distribution of electric fields and charge carriers will be fluctuationally instable, correspondingly. These regions so-called domains can form in any point of homogeneous crystal under influence of heat fluctuations and transfer along crystal until they disappear in one of contact electrodes. The domain path velocity essentially depends on mechanism responsible for their appearance in detail for appearance of negative differential conduction and it is possible the observance of such types of non-linear processes as drift and recombination ones.

Note that multi-valley semiconductors in the mechanism of drift nonlinearity the field dependence of mobility plays the main role. In this case the domain path velocity is drift one of majority carriers in weak field. In the mechanism of recombination nonlinearity the processes of capture and generation of charge carriers play the main role. In the dependence on field strength values the relation of concentrations of free and bound charge carrier changes. The domain movement is caused by redistribution of charge carriers between band and capture levels. This process limits the domain path velocity which as a result can be essentially less than drift one.

So in *n-Ge* doped by aurum the domain path velocity at $T=20K$ varies in interval 10^{-5} - 10^{-2} cm/sec.

During domain movement along technologically homogeneous sample, the current doesn't change. Achieving to electrode the domain destroys that leads to current increase in the electric circuit. The appearance of new domain on another electrode leads to new current decrease in the electric circuit. This cyclic process of origin, motion and destroy of domains leads to periodic current oscillations in electric circuit load. The current oscillation frequency ω is easily evaluated. If v_d is domain path velocity, L is sample length in current direction, then domain time of flight through sample is equal to $t = \frac{L}{v_d}$. From this it follows that

$$\omega = 2\pi \frac{v_d}{L} \qquad (17)$$

In *n-GaAs* the oscillation frequency varies in interval $5 \cdot 10^8 \div 5 \cdot 10^9$ Hz.

The oscillation appearance in *n-GaAs* and in similar materials was firstly observed by Gunn and nowadays is widely used in micro-semiconductor electronics at development of microwave generators.

CURRENT OSCILLATIONS IN IMPURITY SEMICONDUCTORS.

In impurity semiconductors the number of electrons and holes changes because of capture and generation of charge carriers by impurity centers [9-14]. It is possible to experimentally reveal the current oscillations in semiconductors with deep centers (traps) studying the impedance change appearing at introducing of the given semiconductor in electric circuit. Under the given conditions in some frequency region the active resistance introducing by semiconductor into electric circuit and consequently the value of impedance real part can be negative one. The last one means that current oscillations should appear and consequently the instability on impedance can be observed.

There are two types of instabilities. If the oscillations of charge carriers take place only inside the semiconductor, but aren't observed in external electric circuit then such type of instability is called internal instability. If the oscillations of charge carriers are observed in external circuit then such type of instability is called external instability.

In the present paper the external instability has analyzed for semiconductors with certain impurities.

Let's consider the impurity semiconductor with deep negatively charged traps and charge carriers of both signs, i.e. the electrons and holes with n_- and n_+ concentrations. Let's suppose that concentration of deep traps is N_0, N of them is concentration of once negatively charged traps and N_- is concentration of doubly negatively charged traps. Then:

$$N_0 = N + N_-$$

Note that such model is to germanium doped by aurum impurities. The continuity equation for electrons and holes has the following form [15]:

$$\frac{\partial n_-}{\partial t} + div\, j_- = \left(\frac{\partial n_-}{\partial t}\right)_{rec.}$$
$$\frac{\partial n_+}{\partial t} + div\, j_+ = \left(\frac{\partial n_+}{\partial t}\right)_{rec.} \qquad (18)$$

$$\left(\frac{\partial n_-}{\partial t}\right)_{rec.} = \gamma_-(0) n_{1_} N_- - \gamma_-(E) n_- N$$
$$\left(\frac{\partial n_+}{\partial t}\right)_{rec.} == \gamma_+(E) n_{1_+} N_+ - \gamma_+(0) n_+ N \qquad (19)$$

Here $\gamma_-(E)$ and $\gamma_+(E)$ are coefficients of trapping and ejection of electrons by once negatively charged traps at presence of electric field, correspondingly.

At $E=0$; $\gamma_-(E) = \gamma_-(0)$ *u* $\gamma_+(E) = \gamma_+(0)$

$$n_{1-} = \frac{n_-^0 N_0}{N_-^0};\ n_{1+} = \frac{n_+^0 N_-^0}{N_0} \quad (20)$$

The equation describing the concentration variation of charged traps on time in current carrier recombination and generation processes has the form:

$$\frac{\partial N_-}{\partial t} = \left(\frac{\partial n_+}{\partial t}\right)_{rec.} - \left(\frac{\partial n_-}{\partial t}\right)_{rec.} \quad (21)$$

The quasineutrality condition at presence of recombination and generation of charge carriers means that total current doesn't depend on coordinates but depends on time. Thus

$$div\,\mathcal{J} = e\cdot div(j_+ - j_-) = 0;$$

$$j_+ = n_+\mu_+(E)E - D_+\nabla n_+; \quad (22)$$

$$j_- = -n_-\mu_-(E)E - D_-\nabla n_-;$$

It is easily proved that taking into account of dependence of electron and hole mobilities on electric field doesn't lead to essential corrections to mobility values. For example, linearized mobility of electrons and holes will have the form: $\mu_\mp = \mu_\mp^0\left(1 + \frac{d(ln\mu_\mp)}{d(lnE_0^2)}\right)$ и $\frac{d(ln\mu_\mp)}{d(lnE_0^2)} \sim 1$. In the case of dispersion lattice acoustic oscillations have $\mu_\mp \sim E^{-\frac{1}{2}}$ и $\frac{d(ln\mu_\mp)}{d(lnE_0^2)} = -\frac{1}{r}$ and in the case of dispersion on lattice optic oscillations we obtain: $\frac{d(ln\mu_\mp)}{d(lnE_0^2)} = 1$

Let's suppose that concentration of electrons and holes is big enough, so diffusion coefficient satisfy to Einstein relation $D_\pm = \frac{k_0 T}{e}\mu_\pm$. Supposing

$$n_\pm = n_\pm^0 + \Delta n_\pm;\ \ N_- = N_-^0 + \Delta N_-; E = E_0 + \Delta E \quad (23)$$

we linearize the equation (19-22) on small inclinations. The oscillating current $\Delta\mathcal{J}$ is proportional to $\sim e^{-i\omega t}$ and each of rest variables $n_\pm$, N_- и E are the sum of two members the one of which is proportional to $\sim e^{-i\omega t}$, and other one is proportional to $\sim e^{i(kx-\omega t)}$, where *κ* is wave vector, *ω* is oscillation frequency . For example

$$\Delta n_\pm = \Delta n'_\pm e^{-i\omega t} + \Delta n''_\pm e^{i(kx-\omega t)} \quad (24)$$

Let's confine ourselves by the solving plan because of calculation inconvenience. Excluding $\Delta N'_-$, $\Delta N''_-$, $\Delta E'$, $\Delta E''$ we obtain the equation systems for obtaining of $\Delta n'_\pm, \Delta n''_\pm$ and wave vector *κ*:

$$\begin{cases} U_-(k)\Delta n''_- + U_+(k)\Delta n''_+ = 0 \\ C_-(k)\Delta n''_- + C_+(k)\Delta n''_+ = 0 \end{cases}$$

$$\begin{cases} U_-(0)\Delta n''_- + U_+(0)\Delta n''_+ + U\Delta\mathcal{J} = 0 \\ C_-(0)\Delta n''_- + C_+(0)\Delta n''_+ + C\Delta\mathcal{J} = 0 \end{cases} \quad (25)$$

Coefficients $U_\pm(k,0)$ and $C_\pm(k,0)$ depend on character frequency and constant electric field.

To find *κ* wave vector we solve the dispersion equation obtained from determinant of $U_\mp$ and $C_\mp$ coefficients, i.e.

$$U_- C_+ - U_+ C_- = 0 \quad (26)$$

Let's consider solutions of (26) in two limit cases:

1) high-frequency limit: $\omega \gg \nu_\mp,\ \nu_t^E$;
2) low-frequency limit: $\omega \ll \nu_\mp,\ \nu_t^E$

$\nu_- = \gamma_-(E_0)N_0$ is frequency of electron capture by once charged traps;

$\nu_+^E = \gamma_+(E_0)N_0$ is frequency of ejection of holes doubly charged traps;

$\nu_+ = \gamma_+(0)N_-^0$ is frequency of hole capture by doubly charged traps.

To obtain *κ* wave vector values we take into consideration the following condition: $k_0 T \ll lE_0$ at $k_0 T \sim 10^{-14}$ erg, $L \sim 1$ cm, $E_0 \gg 6\cdot 10^{-2}$ V/*cm* (l is sample length).

Neglecting small values we obtain:

$$\Delta n_\pm(x,t) = D_1^\pm e^{ik_1 x} + D_2^\pm e^{ik_2 x} + D^\pm\Delta\mathcal{J} \quad (27)$$

$D_{1,2}^\pm$ contacts are found from boundary conditions. The contacts are always in some degree "straightening" ones. Thus, so-called ohmic contacts present themselves limit cases. One can difference two types of boundary conditions in dependence on filter directions of both contacts:

- the particles of similar signs inject on both contacts

$$\Delta n_+(0) = \delta_+^0\Delta\mathcal{J},\ \Delta n_+(L) = \delta_+^L\Delta\mathcal{J}$$

or

$$\Delta n_-(0) = \delta_-^0\Delta\mathcal{J},\ \Delta n_-(L) = \delta_-^L\Delta\mathcal{J}$$

- the particles of opposite signs inject on both contacts

$$\Delta n_+(0) = \delta_+^0\Delta\mathcal{J},\ \Delta n_-(L) = \delta_-^L\Delta\mathcal{J}$$

or

$$\Delta n_-(0) = \delta_-^0\Delta\mathcal{J},\ \Delta n_+(L) = \delta_+^L\Delta\mathcal{J}$$

Here $\delta_\pm^{0,L}$ are injection rates.

Thus, defining constants $D_{1,2}^\pm$ one can calculate the crystal impedance using the following expression:

$$\Delta E(x,t)=\frac{1}{\sigma}[\Delta\mathcal{J}-ev_-\Delta n_-(x,t)-ev_+\Delta n_+(x,t)+ +\frac{T}{e}\mu_+\nabla n_+(x,t)-\frac{T}{e}\mu_-\nabla n_-(x,t)] \quad (28)$$

$$z=\frac{1}{\Delta\mathcal{J}S}\int_0^L \Delta E(x,t)dx$$

Here L is crystal length, S is crystal cross-sectional area, $v_\pm = \mu_\pm E_0$ are drift velocities of electrons and holes, correspondingly, T is temperature in erg.

The impedance will depend on injection rates $\delta_\pm^{0,L}$ различным образомin dependence on straightening on contacts.

The expression (28) for impedance in general case is very complex and unwieldy. Thus, let's analyze it for following cases:

$$\begin{cases} 1. \ \ n_-^0 \gg n_+^0, \ \ is\ given\ \delta_+^0 \\ 2. \ \ n_-^0 \gg n_+^0, \ \ is\ given\ \delta_-^0 \\ 3 \ \ n_-^0 \ll n_+^0, \ \ is\ given\ \delta_-^L \\ 4. \ \ n_-^0 \ll n_+^0, \ \ is\ given\ \delta_+^L \end{cases} \quad (29)$$

Note that the following equation is taken into consideration before analyzing (28) with help of (29) at linearization of corresponding equation:

$$\beta_\pm^\gamma = \frac{d(\ln(\gamma_\pm(E_0)))}{d(ln(E_0^2))} \gg 1 \quad (30)$$

Taking into consideration (30) and $ev_\pm\delta_\pm^{0,L} \ll 1$, let's write for all cases (29) for real and imaginary impedance parts the following expression:

A. High-frequency limit: $\omega \gg \nu_\mp,\ \nu_t^E$

Case 1: $n_-^0 \gg n_+^0,\ \ is\ given\ \delta_+^0$

$$\begin{cases} \frac{Re(z)}{z_0} = -\frac{v_+}{L\omega}, z_0 = \frac{1}{\sigma_0 S}, \sigma_0 = e(n_-^0\mu_-^0 + n_+^0\mu_+^0) \\ \frac{\mathcal{I}m(z)}{z_0} = 0, ev_+\delta_+^0 = \frac{\mu_+}{2\mu_-} \ll 1, \beta_-^\gamma = \frac{\omega}{2v_-} \gg 1 \\ \beta_1^\gamma = \frac{1}{2}\cdot\frac{n_-^0}{n_+^0}\cdot\frac{v_-}{v_+} \gg 1 \end{cases}$$

The oscillation frequency is found from $\left(-\frac{Re(z)}{z_0} + R\right) = 0$ equation, where R is electrical resistance. From this it follows:

$$\omega = \frac{z_0}{R}\cdot\frac{v_+}{L} \quad (31)$$

Electric field at frequency (31) changes in region

$$v_+ \gg \frac{L\omega}{2} \quad (32)$$

Case 2: $n_-^0 \gg n_+^0,\ \ is\ given\ \delta_-^0$;

$$\omega = 2v_- \cdot \frac{R}{z_0}\cdot\frac{1}{ev_-\delta_-^0}, E \gg \left(\frac{Lv_-R}{z_0\mu_-\mu_+e\delta_-^0}\right)^{1/2}$$

Case 3: $n_-^0 \ll n_+^0,\ \ is\ given\ \delta_-^L$;

In this case the impedance can be negative by only oscillation method.

Case 4: $n_-^0 \ll n_+^0,\ \ is\ given\ \delta_+^L$;

B. Low-frequency limit: $\omega \ll \nu_\mp,\ \nu_+^E$

1 case: $n_-^0 \gg n_+^0,\ \ is\ given\ \delta_+^0$

In this case $\mathcal{I}m(z) > 0$ и $Re(z)$ can be negative as the function of $\sin\alpha$ \ and $\cos\alpha$, $\alpha = \frac{L\omega}{v_\mp}$

2 case: $n_-^0 \gg n_+^0$, задано δ_-^0

The current oscillations can appear in external electric circuit by oscillation form.

3 case: $n_-^0 \ll n_+^0,\ \ is\ given\ \delta_-^L$;
4 case: $n_-^0 \ll n_+^0,\ \ is\ given\ \delta_+^L$

In cases 3 and 4 the oscillations don't appear at all.

The analysis of above mentioned results shows that current oscillations in considered impurity semiconductors mainly take place because of change of electron concentration. The electron capture by impurity centers leads to bigger current oscillation than hole capture. Note that in this process the contacts are inject ones, but not ohmic ones.

For impedance analysis at presence of external magnetic field it is necessary to take into consideration the dependence of current density on magnetic field.

$$\vec{j}_\pm = \pm n_\pm\mu_\pm(E,H)\vec{E} + n_\pm\mu_{1\pm}(E,H)[\vec{E},\vec{h}] \pm \pm n_\pm\mu_{2\pm}(E,H)\vec{h}(\vec{E}\vec{h}) - D_\pm\nabla n_\pm \mp D_{1\pm}[\nabla n_\pm \vec{h}] - -D_{2\pm}(\nabla n_\pm \vec{h}) \quad (33)$$

Here $\vec{h}$ is unit vector on magnetic field; $\mu_\pm(E,H)$, $\mu_{1\pm}(E,H)$, $\mu_{2\pm}(E,H)$ are ohmic, Hall and focusing mobilities of holes and electrons, correspondingly; $D_\pm$, $D_{1\pm}$, $D_{2\pm}$ are ohmic, Hall and focusing coefficients of diffusion charge carriers, correspondingly.

For impedance calculation at the presence of external magnetic field let's consider the case when charge carrier has the effective temperature:

$$D_\pm = \frac{T_{eff.}}{e}\mu_\pm,\ T_{eff.} = \frac{T}{3}\left(\frac{cE_0}{SH}\right)^2 \quad (34)$$

where S is sound speed, c is light speed, T is temperature in erg. Note that the given task is related to three-dimensional ones at the presence of magnetic field and consequently, the

crystal sizes play the essential role. Let's consider the crystal the sizes of which satisfy to following conditions $L_y \ll L_x, L_y \ll L_x$. Let's external electric field is directed along x axis, but magnetic one is directed to Z axis. Let's calculate the impedance for high-frequency $\omega \gg \nu_{\mp},\ \nu_{+}^{E}$ and low-frequency $\omega \ll \nu_{\mp},\ \nu_{+}^{E}$ cases.

The frequency of current oscillations at the presence of magnetic field besides the physical values very strongly depends on injection rates. At small values of magnetic field ($\mu_{\pm}H \ll c$) the variation interval of electric field in which the instabilities on impedance appear, practically doesn't change. Let's consider the classically strong magnetic field ($\mu_{\pm}H \gg c,\ H \gg H_{xar.} = \frac{c}{\mu_{\pm}}$) and after complex algebraic calculations for real and imaginary impedance parts we obtain the following expressions:

1) $\omega \gg \nu_{\mp},\ \nu_{+}^{E}$

$$\frac{Re\, z}{z_0}=\left(\frac{H}{H_{char.}}\right)^2\left(1-\frac{H_1}{H}+\frac{H_2}{H}-\frac{H^2}{H_{char.}H_3}\theta\right);$$

$$\mu_{-}H\theta \ll c$$

$$\frac{Im\, z}{z_0}=\left(\frac{H}{H_4}\right)^4\left(\nu_{+}^{E}H_2'-\nu_{-}H_1'\right)\frac{1}{\omega H};$$

$$\theta=\frac{2L_x\nu_{-}\left(n_{+}\nu_{+}^{E}\beta_{+}^{\gamma}+n_{-}\nu_{-}\beta_{-}^{\gamma}\right)}{n_0 k_y u_0^2} \qquad (35)$$

Here

$$H_1 = aH_{char.}\left(1+\frac{\beta_{+}^{\gamma}}{\beta_{-}^{\gamma}}\cdot\frac{\nu_{+}^{E}}{\nu_{-}}\cdot\frac{n_{+}}{n_{-}}\cdot\frac{\mu_{+}}{\mu_{-}}\right)= = aH_{char.}\left(1+b\frac{\nu_{+}}{\nu_{-}}\right)$$

$$a=\frac{2\nu_{-}n_{-}\beta_{-}^{\gamma}}{n_0\omega\theta};\quad b=\frac{\beta_{+}^{\gamma}}{\beta_{-}^{\gamma}}\cdot\frac{n_{+}}{n_{-}}\cdot\frac{\mu_{+}}{\mu_{-}};$$

$$H_4=\left[\frac{c}{\mu_{-}}\cdot\frac{2Tk_y}{3eE_0}\left(\frac{\nu_{-}}{S}\right)^2\right]^{1/4};$$

$$H_2 = aH_{char.}\left(1+b\frac{\nu_{+}}{\nu_{-}}\right);\ H_1' = H_{char.}a;$$

$$H_2' = H_{char.}a\cdot\frac{n_{+}}{n_{-}}\cdot\frac{\beta_{+}^{\gamma}}{\beta_{-}^{\gamma}};$$

$$H_3 = H_{char.}\cdot\frac{\mu_{-}}{\mu_{+}}\cdot\frac{\theta}{eu_{-}\delta};\ \delta=\delta_{-}^{0}+\delta_{+}^{0}+\delta_{-}^{L}+\delta_{+}^{L}$$

At *Re z* current oscillations passing through zero becomes negative value and moreover, *Im z* can take any sign. From (35) it follows that there are different variation intervals of magnetic field in which *Re z* and *Im z* can change the signs. For simpleness we confine ourselves by following case:

Re z=0 и *Im z=0* .

From (35) one can easily find that at $\frac{\beta_{+}^{\gamma}}{\beta_{-}^{\gamma}}=\frac{\nu_{-}}{\nu_{+}}\cdot\frac{n_{-}}{n_{+}}$ $Im\, z = 0$ and at $H_1=H_2$, i.e. when hole radiation frequency ν_{+}^{E} will be equal to hole capture frequency $\nu_{+}^{E}=\nu_{+}$, at following values of external magnetic field,

$$H = H_{char.}\left(\frac{1}{e\nu_{-}\delta}\right)^{1/2} \qquad (36)$$

the impedance real part *Re z=0*, the current oscillations appear and take place.

2) $\omega \ll \nu_{\mp},\ \nu_{+}^{E}$

$$\frac{Re\, z}{z_0}=\left(\frac{H}{H_x}\right)^2\left[1-\left(\frac{\nu_{+}^{E}H_2'}{\nu_{+}H}+\frac{H}{H_3}\right)\frac{\mu_{-}H\theta}{c}\right];$$

$$Im\, z = 0;\ \frac{\beta_{+}^{\gamma}}{\beta_{-}^{\gamma}}=\frac{\nu_{-}}{\nu_{+}^{E}}\cdot\frac{n_{-}}{n_{+}}$$

Re z = 0 at $H=(H_{char.}H_3)^{1/2}$ when the condition is carried out:

$$\frac{\nu_{+}^{E}}{\nu_{+}}<\frac{1}{2}\frac{n_0}{n_{+}}\cdot\frac{1}{\beta_{+}^{\gamma}}$$

Thus at the presence of external magnetic field the capture and radiation of holes play the essential role.

CURRENT OSCILLATIONS IN TWO-VALLEY SEMICONDUCTORS.

The current oscillations in external magnetic field in two-valley semiconductors of GaAs type had been firstly studied by Gunn. Beginning from given value of electric field, the current oscillations with microwave frequency $\omega\sim 10^9\div 10^{11}Hz$ appear. This effect is studied in many theoretical works only near threshold, i.e. when differential conductivity $\sigma_d=\frac{dj}{dE}=0$ (N-type characteristics).

When conductivity becomes negative one, i.e. $\sigma_d<0$ the distribution of electric field *E* in crystal becomes inhomogeneous one, the strongly expressed electric field regions, i.e. domains form. Moreover, the amplitude of current oscillations from some moment begins to depend on time, the task becomes nonlinear one and its theoretical solving becomes the complex one. In this part the some results of theoretical investigations of nonlinear Gunn effect in region $\sigma_d<0$ at presence of constant electric field will be discussed [16-18].

Let's total concentration of charge carriers is as follows *N*= *n* + *n* , the mobilities of charge carriers *μ* and *μ'*, diffusion coefficients *D* and *D'* satisfy the following conditions:

$$D \gg D';\ \mu \gg \mu';\ n \gg n';n=fN=f(E)N(E)$$

$$f(E)=(m-1)\left[m-1+\left(\frac{E}{E_a}\right)^m\right]^{-1} \qquad (37)$$

Parameter *m* is calculated from experimental data as the relation of ohmic current to actual one in point $E_0=E_a$ ($\sigma_d \neq 0$).

The rate of σ dynamic conductivity to conductivity in weak field σ_0 has the form:

$$S_0 = \frac{\sigma}{\sigma_0} = \frac{1}{\sigma_0 E_a}\frac{df_0}{dx_a} = \left(f_0 + x_0\frac{df_0}{dx_a}\right) \quad (38)$$

Since $x_0 = \frac{E_0}{E_a}$ then in the point of zero inclination we have $x_0 = 1$; $f_0 = -\frac{df_0}{dx_a}$ and static current in it is as follows:

$$\mathcal{J}_p = \frac{m-1}{m}\sigma_0 E_a; \quad m = \frac{1}{1-\frac{\mathcal{J}_p}{\sigma_0 E_a}} \quad (39)$$

The dynamics of current passage through sample is described by following equations:

$$\mathcal{J}=efN\mu E+De\frac{\partial(fN)}{\partial x};\frac{\partial\mathcal{J}}{\partial x}=e\frac{\partial N}{\partial t}$$

$$\mathcal{J}_1+\mathcal{E}\frac{\partial E_1}{\partial t}=0;\ u_0=-\mu E_0 \quad (40)$$

Supposing $\mathcal{J} = \mathcal{J}_0 + \mathcal{J}_1;\ E = E_0 + E_1;\ N = N_0 + N_1$ and all inclinations from equilibrium values have the following form: $(E_1, \mathcal{J}_1, N_1) \sim e^{i\omega t}$. From equation (40) for all values $(E_1, \mathcal{J}_1, N_1) \lesseqgtr (E_0, \mathcal{J}_{10}, N_{10})$ and $y = \frac{N_1}{N_0}$ we obtain:

$$\frac{\partial^2 y}{\partial t^2} + \omega_0^2 y = \frac{\sigma_0 f_0}{\mathcal{E}\omega_0}\Phi\left(y, \frac{dy}{dt}, \frac{d^2y}{dt^2}\right) \quad (41)$$

Here $\omega_0^2 = \frac{\sigma_0 f_0}{\mathcal{E}}(ku_0 + Dk^2)$. Let's introduce the designations: $r = \frac{\sigma_0 f_0}{\mathcal{E}\omega_0}$ and $\tau = \omega_0 t$. From this it follows that equation (41) is to equations of Van-der-Pole type

$$\frac{\partial^2 y}{\partial t^2} + \omega_0^2 y = rF\left(y, \frac{dy}{dr}, \frac{d^2y}{dr^2}\right) \quad (42)$$

For crystal GaAs *r* is small parameter (*r<<1*), $D = 130\frac{sm^2}{s}$, $u_0 \approx 10^7\frac{sm}{s}$, $\omega_c = \frac{\sigma_0}{\mathcal{E}} \approx 10^{12}s^{-1}$.

The solution (42) at *r=0* has the form $y = a(0)cos(\tau + \theta) = a\cos\psi$. To solve the differential equation (42) at value *r≠0* let's use Bogolubov-Mitropolsky's method:

$$\frac{da}{d\tau} = rA_1(a) + r^2A_2(a)_+;$$

$$\frac{d\psi}{dt} = \omega_0 + rB_1(a) + r^2B_2(a) + \cdots;$$

$$A_1(a) = -\frac{\omega_0}{2\pi}\int_0^{2\pi} F\left(y, \frac{dy}{d\tau}, \frac{d^2y}{d\tau^2}\right)\sin\psi d\psi; \quad (43)$$

$$B_1(a) = -\frac{\omega_0}{2\pi a}\int_0^{2\pi} F\left(y, \frac{dy}{d\tau}, \frac{d^2y}{d\tau^2}\right)\cos\psi d\psi$$

Let's confine ourselves by second approximation and after easy calculations we obtain:

$$a_1 = a_0 exp\left(\frac{r}{2}\left[\frac{m(1-f_0)Dk\mathcal{E}}{u_0}\right]\omega t\right) \quad (44)$$

$$a_2 = \frac{a_0}{\left[exp\left(-\frac{mDk\sigma_0 f_0}{2u_0}t\right) + \frac{m\omega_0\ Dk\mathcal{E}}{48ku_0\ u_0}a_0^2\right]} \quad (45)$$

From (44) it follows that when external field satisfies to condition $E_0 > E_a\left(\frac{2u_0}{3Dk\mathcal{E}}\right)^{1/2}$ then the amplitude increases in first approximation and in second approximation $a_2 \to \left(\frac{48ku_0}{m\omega_0}\cdot\frac{u_0}{Dk\mathcal{E}}\right)^{1/2}$ tends to constant (limiting) value.

For current density propagating in crystal in external electric $\overrightarrow{E_0}$ and magnetic $\overrightarrow{H_0}$ fields let's write the following equation:

$$\vec{J} = en\mu\vec{E} + en\mu'\left[\vec{E}\vec{H}\right] + eD\nabla\vec{n} + eD'\left[\nabla\vec{n}\vec{H}\right] \quad (46)$$

One can chose the following geometry for electric and magnetic fields: $\overrightarrow{H_0} = H_{0z}\vec{h}$, $\overrightarrow{E_0} = E_{0x}\vec{\imath}$ where $\vec{h}$ and $\vec{\imath}$ are unit vectors along z and x axes. Van-der-Pole equation at presence of magnetic field has the following form:

$$\frac{\partial^2 R}{\partial t^2} + \omega_0^2 R = r\Phi\left(R, \frac{\partial R}{\partial t}\right); R = \frac{n'}{n_0}$$

$$r = \frac{\omega_0}{k_x u_0} \ll 1;\ \omega_0 = \left[\frac{\sigma_0 f_0(ku_0 + k_x^2 D^+)}{\mathcal{E}}\right]^{1/2}; \quad (47)$$

$$\Phi = \omega\frac{\partial R}{\partial t}\left[\frac{f_0 m(1-f_0)\sigma_0 D' k_x(1+R)}{u_0\omega_0} + mR(f_0 - 1) - m - 1\right]$$

$$+\left(\frac{\partial R}{\partial t}\right)^2\frac{m(1-f_0)+R+2}{ku_0\omega_0}$$

From (47) we find the amplitude:

$$A = A_0 e^{-\frac{r\omega_0\gamma t}{2}}$$

$$\gamma = 2r + \frac{\sqrt{2}}{f_0^2}\cdot\frac{H_0}{H_{char.}} + \frac{k_x D}{f_0 u_0} + \frac{\sqrt{2k_x D'}}{f_0^2 u_0}\left(\frac{L_x}{L_y} - 1\right) \quad (48)$$

The crystal is in instable state at appearance of current oscillations and at definite magnetic field strength $\overrightarrow{H_0}$ the wave the frequency of which can be defined in nonlinear approximation from the solution of following equation

$$\frac{\partial^2 R}{\partial t^2} + \omega_1\frac{\partial R}{\partial t} + \omega_2^2 R = 0 \quad (49)$$

where ω_1 and ω_2 are character frequencies

From equation solution it follows that the external magnetic field strength varies in interval

$$H_1 < H_0 < H_2$$

where

$$H_1 = \frac{\sqrt{2m}}{m-1}H_{char.};$$

$$H_2 = H_{char.}\cdot\frac{u_0 L_x}{D}\left[\frac{mu_0}{2\pi L_x\sigma_0(m-1)}\right]^{1/2}$$

The wave frequencies

$$\omega_0 = \frac{H_{char.}}{H_0}\left[\frac{\sigma_0 k_x u_0(m-1)}{m}\right]^{1/2}$$

decrease with magnetic field increase.

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