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INTERNAL AND EXTERNAL CURRENT OSCILLATIONS IN TWO VALLEY SEMICONDUCTORS OF TYPE GaAs

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Abstract- A theory is constructed in two-valley semiconductors of the GaAs type for internal and external instabilities. An analytical expression is found for the frequency and for the electric field in the case of internal and external instability. When calculating the impedance, ohmic boundary conditions for an alternating electric field were used. In the theoretical calculation, it was taken into account that the transition time from valley a to valley b is much less than the transition time from *b* to *a*, i.e., $\tau_{ab} << \tau_{ba}$. The sample under study is homogeneous and of the electronic type of charge carriers. Therefore, the electron concentration $n=n_a+n_b$=const. It is taken into account that the current density along the coordinate axes has the form: $j'_x \neq 0$, $j'_y = 0$, $j'_z = 0$. When internal instability appears, analytical expressions are obtained for the oscillation frequency of charge $\omega_0 = -\dfrac{4E_0 ck}{H_0}$, carriers and the growth increment $\omega_1 = \dfrac{3}{2}\dfrac{E_0 ck}{H_0}\dfrac{\vartheta_2}{kD_2}$. With external instability, the oscillation frequency is a matter variable, and the wave vector is a complex quantity. With the appearance of external instability, analytical expressions for the electric field (33) and the frequency of current oscillations are obtained.

Keywords: Current Oscillations, Growth Rate, Oscillation Frequencies, Sample Impedance, Boundary Conditions, Radiation.

1. INTRODUCTION

The development of semiconductor electronics has created completely new methods for modern technology. First, the low-frequency region was developed. Already in the 50s of the last centuries, new methods were rapidly developing in the field of microwave current oscillations based on semiconductors in multi-valley energy levels. The use of semiconductor devices in microwave technology has led to a significant increase in reliability and a very noticeable reduction in the dimensions of the devices used. Currently, there are several types of semiconductor microwave devices, tunnel diodes, microwave transistors, avalanche diodes, Gunn diodes. Gunn diodes can operate at frequencies of several tens of gigahertz. Gunn diodes use phenomena in the volume of a homogeneous semiconductor, and this is the advantage of Gunn diodes. In the operation of Gunn diodes, mainly with an increase in the electric field strength, a decrease in the conductivity of the semiconductor occurs, i.e., the current-voltage characteristic has a section of negative differential conductivity and the state of the semiconductor is unstable.

In Gunn diodes, the current-voltage characteristic is N-shaped, i.e., one current value corresponds to several voltage values. In this case, domains appear inside the sample. In Gunn's experiment, the GaAs semiconductor was included ohmic in the circuit. In theoretical works, it was proved that current oscillations in GaAs occur due to the transition of charge carriers under the action of an external electric field from a valley with a lower energy value to a valley with a higher energy value. In this case, the mobility of the current carriers sharply decreases and, in this case, the current decreases. The domains propagate at a speed of 10^7 cm/sec, and the domain transit time is t~10^{-10} sec and generated frequency is ω~10^{10} Hz [1, 2].

Theoretical studies of the Gunn effect without the influence of an external magnetic field *H* were performed in several works. The influence of an external magnetic field on the Gunn effect was first performed by us. In this theoretical work, we will theoretically investigate the influence of an external magnetic field ($\mu H >> c$) on the Gunn effect. When an oscillation occurs inside the sample (but without oscillation in the circuit), the excited waves can grow (instability) or decay. When growing waves appear inside the sample, the oscillation frequency is a complex quantity, the wave vector is a real quantity. When a current oscillation appears in the circuit, the oscillation frequency is a real value, and the wave vector is a complex value [2-7].

In this theoretical work, we will investigate the internal and external instability in two-valley semiconductors of the GaAs type. Let us calculate the real and imaginary parts of the frequency inside the sample and the critical electric field when oscillations appear inside the sample and when the current oscillates in the external circuit. Let us show that the direction of the external magnetic role plays a significant role for the appearance of oscillations inside the sample and for the appearance of current oscillations in the circuit.

2. BASIC EQUATIONS OF THE PROBLEM

The energy spectrum of charge carriers in GaAs has two minima along the crystal axes [100]. The energy gap between the minima is significant $\Delta\varepsilon = 0.36\ \text{eV}$. If we designate these valleys as *a* and *b*, then the time of transition is τ_{ab} from valley *a* to valley *b* and the time of transition is τ_{ba} from valley *b* to valley *a* differ, i.e.

$$\tau_{ab} << \tau_{ba} \tag{1}$$

The total concentration n in both valleys is constant due to ohmic contact and due to the absence of recombination and generation processes

$$n = n_a + n_b = \text{const},\ n'_a = -n'_b \tag{2}$$

The continuity equations in the valleys have the form:

$$\begin{aligned} &\frac{\partial n'_a}{\partial t} + \text{div} j_a = \frac{n'_a}{\tau_{ab}} \\ &\frac{\partial n'_b}{\partial t} + \text{div} j_b = \frac{n'_b}{\tau_{ba}} \end{aligned} \tag{3}$$

The j_a and j_b are current flux density in valleys *a* and *b*.

$$\begin{aligned} \vec{j}_a &= n_a\mu_a\vec{E} + n_a\mu_{1a}\left[\vec{E}\vec{H}\right] + n_a\mu_{2a}\vec{H}\left(\vec{E}\vec{H}\right) - \\ &-D_a\nabla n_a - D_{1a}\left[\vec{\nabla} n_a\vec{H}\right] - D_{2a}\vec{H}\left[\vec{\nabla} n_a\vec{H}\right] \end{aligned} \tag{4}$$

$$\begin{aligned} \vec{j}_b &= n_b\mu_b\vec{E} + n_b\mu_{1b}\left[\vec{E}\vec{H}\right] + n_b\mu_{2b}\vec{H}\left(\vec{E}\vec{H}\right) - \\ &-D_b\nabla n_b - D_{1b}\left[\vec{\nabla} n_b\vec{H}\right] - D_{2b}\vec{H}\left[\vec{\nabla} n_b\vec{H}\right] \end{aligned} \tag{5}$$

$$\frac{\partial\vec{H}}{\partial t} = -\text{crot}\vec{E} \tag{6}$$

Choosing the next coordinate system

$$\vec{H}_0 = \vec{i}H_0,\ \vec{E}_0 = \vec{i}E_0 \tag{7}$$

3. THEORY

3.1. Internal Instability

Representing all variable physical quantities in the form of monochromatic waves, i.e.

$$\vec{E} = \vec{E}_0 + \vec{E}',\ n_a = n_{a0} + n'_a,\ \vec{H} = \vec{H}_0 + \vec{H}'$$

$$\vec{E}' << \vec{E}_0,\ n'_a << n_{a0},\ \vec{H}' << \vec{H}_0$$

From (4), (5), (6)

$$\begin{aligned} j'_{ax} &= \left(\vartheta_{a0} + \vartheta^0_{2a}\right)n'_a - ik\left(D_a + D_{2a}\right)n'_a + \\ &+\left(n_{a0}\mu_{a0}\gamma_a + n_{a0}\mu_{a0} + n_{a0}\mu^0_{2a}\gamma_{2a}\right)E'_x + \\ &+3n_{a0}\mu^0_{2a}\frac{E_0}{H_0}\frac{ck}{\omega}\left(E'_z - E'_y\right) \end{aligned}$$

$$j'_{ay} = n_{a0}\mu_{a0}E'_y + n_{a0}\mu^0_{2a}\frac{E_0}{H_0}\frac{ck}{\omega}\left(E'_x - E'_z\right) - D_a ikn'_a$$

$$\begin{aligned} j'_{az} &= n_{a0}\mu_{a0}E'_z + n_{a0}\mu^0_{1a}\frac{E_0}{H_0}\frac{ck}{\omega}\left(E'_x - E'_z\right) - \\ &-n_{a0}\mu^0_{1a}E'_y + n_{a0}\mu^0_{2a}\frac{E_0}{H_0}\frac{ck}{\omega}\left(E'_y - E'_x\right) - \\ &-ik\left(D_a - D_{1a}\right)n'_a \end{aligned}$$

$\gamma_{1a} = 2\dfrac{d\ln\mu_{1a}}{d\ln E_0^2}$, $\gamma_{2a} = 2\dfrac{d\ln\mu_{2a}}{d\ln E_0^2}$, are obtained.

Considering that $D_{1a} >> D_a$, $\mu_{2a} >> \mu_{a1}$ from

$$j'_{ay} = j'_{az} = 0 \tag{8}$$

is obtained

$$E'_y = AE'_x,\ E'_z = BE'_x \tag{9}$$

Substituting (9) to j'_{ax} the following dispersion equations are obtained

$$\begin{aligned} &\left(\vartheta_2 - ikD_2\right)\phi_1^2 + \mu E_{char}\phi_1^2\left(ik\vartheta_2\tau + k^2D_2\tau\right) + \\ &+3\mu E_{char}\frac{\Omega}{\omega}\left(\frac{\mu H}{c}\right)^2\left(1 - \frac{\Omega}{\omega}\right)\phi_1 - 3\left(\frac{\mu H}{c}\right)^2\frac{\Omega}{\omega}\mu_{1a}E_{char}\phi \\ &\left[\phi_1\left(ik\vartheta_2\tau + k^2D_2\tau\right) - 3\frac{\Omega}{\omega}\left(\frac{\mu H}{c}\right)^2\left(1 - \frac{\Omega}{\omega}\right)\right] + \\ &+3\frac{\Omega}{\omega}ikD_a\left(1 - \frac{\Omega}{\omega}\right)\left(\frac{\mu H}{c}\right)^2\phi\phi_1 = 0 \end{aligned}$$

where,

$$\phi = 2\left(\frac{\Omega}{\omega}\right)^2 + \frac{\Omega}{\omega}\ \phi_1 = 1 + \left(\frac{\mu H}{c}\right)^2\left(\frac{\Omega}{\omega}\right)^2 - \left(\frac{\mu H}{c}\right)^3\frac{\Omega}{\omega}$$

$\Omega = ck\dfrac{E_0}{H_0}$, where, k is wave vector.

$$E_{char} = \frac{i}{k\mu_2\tau}\cdot\frac{1}{\dfrac{3\mu_2}{\mu}\dfrac{\Omega}{\omega}\left(\dfrac{\mu H}{c}\right)^3\dfrac{\phi}{\phi_1} - 1} \tag{10}$$

At $\phi_1 = \alpha\dfrac{\Omega}{\omega}\dfrac{\mu H}{c}\phi$, here $\alpha = 3\left(\dfrac{\mu H}{c}\right)^2$. From (10) relatively ω the dispersion Equation (11) is obtained.

$$\omega^2 + \Omega\left(-1 + \phi\right)\omega + 2\phi\Omega^2 = 0 \tag{11}$$

From solution (11)

$$\omega_1 = \frac{E_0 ck}{H_0}\left(-4 - i\frac{\vartheta_2}{kD_2}\right) + \frac{5}{2}i\frac{E_0}{H_0}ck\frac{\vartheta_2}{kD_2} \tag{12}$$

$$\omega_2 = \frac{E_0 ck}{H_0}\left(-4 - i\frac{\vartheta_2}{kD_2}\right) - \frac{5}{2}i\frac{E_0}{H_0}ck\frac{\vartheta_2}{kD_2} \tag{13}$$

are obtained.

It can be seen from (12) and (13) that a wave with a frequency is incremental.

$$\omega = -\frac{4E_0 ck}{H_0} + \frac{3}{2}\frac{iE_0 ck}{H_0}\frac{\vartheta_2}{kD_2} \tag{14}$$

and increment is $\omega_1 = \dfrac{3}{2}\dfrac{E_0 ck}{H_0}\dfrac{\vartheta_2}{kD_2}$.

Thus, for internal instability (i.e., $\omega = \omega_0 + i\omega_1$), the value of the radiation frequency $\omega_0 = -\frac{4E_0 ck}{H_0}$ is the rise impedance ω_1. These values (ω_0 and ω_1) are obtained if the external electric field

$$E_0 >> \frac{1}{5}\frac{2\pi T}{eL} \tag{15}$$

where, L is the size of the sample, e is the elementary charge, T is the temperature in ergs.

Estimation (15) shows that under experimental conditions $E_0 >> 100$ V/cm this value corresponds to the experiment in GaAs where it was obtained for

$$E_0 \sim 2\times 10^3 \text{ V/cm} \tag{16}$$

3.2. External Instability (Impedance Instability)

When the current density j'_{ax} appears in the external circuit (i.e., current fluctuations) the impedance of the sample (GaAs) becomes a complex quantity. This occurs at the complex value of the wave vector (k) and at the real value of the current oscillation frequency (ω_0). For sample impedance calculation, the boundaries (i.e., $l = 0$ and $l = l_x$) are the main factor, i.e., boundaries can be ohmic and injecting. In the Gunn experiment, the GaAs boundaries were ohmic;

$$\begin{aligned} &E'_x(0) = 0 \quad \text{at} \quad l = 0 \\ &E'_x(l) = 0 \quad \text{at} \quad x = l \end{aligned} \tag{17}$$

An alternating electric field will be sought in the following form;

$$E'_x(x) = c_1 e^{ik_1 x} + c_2 e^{ik_2 x} + \frac{j'_x}{\sigma} \tag{18}$$

where, $\sigma = en\mu$.

The complex wave vectors k_1 and k_2 are calculated from the dispersion equation respect to k from (11), i.e.

$$\begin{aligned} &k^4 + \left(\frac{H_0}{E_0}\frac{\omega}{2c} + i\frac{\vartheta_2}{D_2}\right)k^3 + \frac{iH_0}{E_0}\frac{\omega\vartheta_2}{cD_2}k^2 - \\ &-\frac{H_0}{E_0}\frac{\omega}{cD_2\tau_1}k + \frac{\omega^2}{2c^2 D_2\tau_1}\left(\frac{H_0}{E_0}\right)^2 = 0 \end{aligned} \tag{19}$$

$$k_{char}^4 = \left(\frac{H_0}{E_0}\right)^2 \frac{\omega^2}{2c^2 D_2 \tau_1}$$

$$\frac{1}{\tau_1} = \frac{1}{\tau_{ab}} - \frac{1}{\tau_{ba}}$$

We introduce $\frac{k}{k_{char}} = y$ from (19) at $y = y_0 + iy_1$, $y_1 << y_0$, for determining y_0 and y_1 the Equations (20) and (21);

$$y_0^4 + \alpha_0 y_0^3 - 3\alpha_1 y_0^2 y_1 - 2\beta y_0 y_1 - \gamma y_0 + 1 = 0 \tag{20}$$

$$4y_0^3 y_1 + 3\alpha_0 y_0^2 y_1 + \alpha_1 y_0^3 + \beta y_0^2 - \gamma y_1 = 0 \tag{21}$$

are obtained.

Analysis of (20), (21) shows that;

$$y_0^{(1,2)} = -\frac{\alpha, u}{2} \pm \left(1 - \frac{2\beta}{\alpha_1^2 u}\right)$$

$$\beta = \frac{4}{5}\alpha_0\alpha_1, \ \alpha_0 = \frac{H_0\omega}{2cE_0 k_{char}}, \ \alpha_1 = \frac{\vartheta_2}{D_2 k_{char}} \tag{22}$$

$$y_1 = \frac{y_0^3 + \alpha_0 y_0^2 - \gamma}{3\alpha_1 + 2\beta}$$

From Equations (20)-(21)

$$\begin{aligned} &y_0^{(1)} = -\alpha_0 \\ &y_0^{(2)} = -\frac{3}{2}\alpha_0 \end{aligned} \tag{23}$$

are found.

Substituting (23) to (22)

$$y_1 = -\frac{2\beta}{\alpha_1 u} + i\frac{4\alpha_0^4\beta^2}{3\alpha_1^9} = y_{10} + iy'_1$$

$$y_2 = -\alpha_1 u - \frac{1}{3}\alpha_1^2 u^3 = -y_{20} + iy'_2$$

$$u = \frac{\vartheta_2}{k_{xar} D_2}\left(\frac{2k_{xar}E_0 c}{H_0\omega}\right)^2 = \left(\frac{E_0}{E_1}\right)^3$$

$$\alpha_0 = \frac{H_0\omega}{k_{xar}E_0 2c} = \frac{E_2}{E_0}$$

$$\alpha_1 = \frac{\vartheta_2}{k_{xar}D_2} = \frac{E_0}{E_3}$$

are found.

Substituting the boundary conditions for the electric field (17) into (18), the constants c_1 and c_2

$$c_1 = -\frac{J'}{\sigma}\cdot\frac{e^{iy_2} - 1}{e^{iy_2} - e^{iy_1}}$$

$$c_1 = -\frac{J'}{\sigma}\cdot\frac{e^{iy_2} - 1}{e^{iy_2} - e^{iy_1}}$$

are found.

Pattern’s impedance

$$\begin{aligned} &Z = \frac{1}{\sigma J'}\int_0^l E'(x)dx \\ &J' = j'_{ax} S \end{aligned} \tag{24}$$

Substituting $E'(x)$ constants c_1 and c_2 to Equation (24) after integrated:

$$Z = \frac{l}{\sigma S}\left[-\frac{\left(e^{iy_1} - 1\right)\left(e^{iy_2} - 1\right)}{e^{iy_2} - e^{iy_1}}\cdot\frac{i\left(y_2 - y_1\right)}{y_1 y_2}\right] \tag{25}$$

are obtained.

Substituting y_1 and y_2, to (25) for the impedance the following complex values.

$$Z = \frac{l}{\sigma S}\left\{1 - \left[1 + A\cdot\left(\cos\phi'_2 + i\sin\phi'_2\right)\right]\times\frac{a + ib}{a_1 + ib_1}\right\} \tag{26}$$

$$A=\frac{1}{\phi_3 E_0^{9/2}},\ a=\left(\frac{\vartheta_2}{D_2 k_{char}}\right)^3\left(\frac{2cE_0 k_{char}}{H_0\omega}\right)^2,$$

$$b=\left(\frac{\vartheta_2}{D_2 k_{char}}\right)^8\left(\frac{2cE_0 k_{char}}{H_0\omega}\right)^3,\ a_1=\left(\frac{E_0}{E_1'}\right)^4,$$

$$b_1=\frac{8}{3}\left(\frac{E_0}{E_2}\right)^{9/2}$$

are obtained.

Separating the imaginary and real parts of the impedance from (26) we obtain;

$$\operatorname{Re} Z=-Z_0 A\frac{aa_1+bb_1}{a_1^2+b_1^2}\cos y_2'+Z_0 A\frac{ba_1-ab_1}{a_1^2+b_1^2}\sin y_2' \quad (27)$$

$$\operatorname{Im} Z=-Z_0 A\frac{ba_1-ab_1}{a_1^2+b_1^2}\cos y_2'-Z_0 A\frac{aa_1+bb_1}{a_1^2+b_1^2}\sin y_2' \quad (28)$$

From (27)-(28) shows that at

$$y_2'=\frac{1}{3}\alpha_1^2 u^3=\pi \quad (29)$$

$$\operatorname{Re} Z=-Z_0 A\frac{aa_1+bb_1}{a_1^2+b_1^2} \quad (30)$$

$$\operatorname{Im} Z=-Z_0 A\frac{ba_1-ab_1}{a_1^2+b_1^2} \quad (31)$$

are obtained. Denoting

$$\psi=Z_0 A\frac{aa_1+bb_1}{a_1^2+b_1^2},\ \psi_1=Z_0 A\frac{ba_1-ab_1}{a_1^2+b_1^2}$$

From Equations (30)-(31)

$$\frac{ba_1-ab_1}{aa_1+bb_1}=\frac{R_1}{R} \quad (32)$$

is obtained.

From Equation (29)

$$E_0=H_0\left(\frac{2}{27}\frac{eH_0}{k_{xar}T}\right)^{1/2}\left(\frac{\omega}{k_{xar}c}\right)^{3/2} \quad (33)$$

the value of the electric field is obtained.

In deriving (33), the inequality $R_1>\sqrt{3}R$ is used, where, R is ohmic resistance, R_1 is capacitive or inductive resistance. In deriving the electric field (33), the inequality

$$E_0>\left(\frac{9}{2}\right)^{1/5}\frac{E_3^{9/5}E_1^{1/5}}{E_2} \quad (34)$$

is used.

Substituting (34) to (33)

$$\omega>k_{char}c\frac{k_{char}T}{eH},\quad k_{char}c=\omega_{char},\quad \omega>\omega_{char}\frac{k_{char}T}{eH}$$

interval change in frequency of current oscillation is obtained.

4. CONCLUSION

Thus, we have constructed a theory of internal and external instability when the external magnetic field is directed along the external electric field. The magnetic field is strong, i.e., $\mu H>c$. With internal instability, an analytical formula for the oscillation frequency and the electric field at which internal unstable waves are excited are obtained, and the growth rate of the oscillation inside the crystal is found. When the current begins to oscillate in the external circuit, the sample (i.e., GaAs) emits energy at a certain frequency. The limit of change in the frequency of current oscillations in the external circuit, as well as the value of the electric field at the beginning of radiation, are calculated.

From $\frac{\omega_0^{external}}{\omega_0^{internal}}$

$$\frac{\omega_0^{external}}{\omega_0^{internal}}\sim\frac{1}{2}\cdot 10^{-4}<<1$$

is found. Thus, the frequency and electric field are decreased.

From the relation $\frac{E_0^{internal}}{E_0^{external}}$ electric field is

$$\frac{E_0^{internal}}{E_0^{external}}=\frac{5\times 10^{-12}\times 10^{-11}}{\pi\times 10^{-14}}\sim 10^{-7}$$

As the electric field decreasing, in external current circuit the oscillation frequency of current increases.

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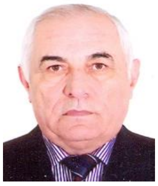
BIOGRAPHIES



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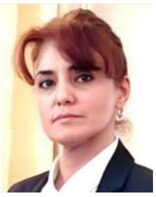

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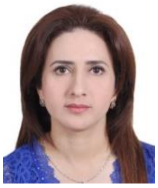

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