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RADIATION OF ENERGY OF SEMICONDUCTORS WITH DEEP TRAPS

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Abstract- The theory of current oscillation in semiconductors with deep traps in an electric field is constructed in this paper. It is proved that the ratio of the equilibrium values of electrons and holes is the main parameter for the appearance of a current oscillation in the circuit. The oscillation frequency varies as a function of injection at the contacts. It is proved that there are four possible cases for the appearance of a current oscillation in the external circuit. Analytical formulas are found for the frequency, electric field, and for capacitive or inductive resistance in the circuit. It is obtained that when the frequency of the current oscillation is greater than all characteristic frequencies in the theory, only one wave is excited inside the semiconductor. It is proved that in the frequency region less than all the characteristic frequencies in the theory, several waves are excited inside the semiconductor.

Keywords: Impedance, Instability, Current Oscillations, Frequency, Electric Field.

I. INTRODUCTION

A lot of work has been devoted to the experimental and theoretical investigation of current instability in impurity semiconductors and to the arising vibrational phenomena. The appearance of such a number of works is connected with the possibility of practical use of the phenomenon of current instability in semiconductors for the creation of high-frequency generators, amplifiers, and also the desire to develop theoretical models for explaining the various causes of the appearance of instabilities in semiconductors. The Gunn effect [1, 2] due to the special structure of the conduction band of some semiconductors became very widely known.

In [3-5], current oscillations in semiconductors with deep impurity levels are investigated. The rate of capture of charge carriers by an impurity center in a semiconductor, in general, depends on the energy of the charge carriers. The presence of an electric field can increase the energy of the charge carriers should depend on the electric field. Thus, the stationary concentration of charge carriers can change with increasing electric field.

The rate of capture of charge carriers *c* in electric fields increases when impurity centers (i.e. traps) represent a repulsive Coulomb center for electrons.

It will be possible to experimentally detect current oscillations in semiconductors with deep traps by investigating the impedance introduced into the circuit by a semiconductor. Under certain conditions of wave growth, the active resistance introduced into the circuit by a semiconductor is negative in some frequency region. Some impurities in the semiconductor create centers that are capable of being in several charged states (once, doubly, triply, positively or negatively charged).

Gold atoms in germanium can, apart from the neutral state, can be once positively charged and single, doubly and triply negatively charged centers. Such impurity centers correspond to several energy levels in the forbidden band. These levels are able to capture electrons or holes depending on their charge states. As a result of the capture and emission of charge carriers by such deep traps, current oscillations in the semiconductor occur. (i.e. impedance imbalance).

In [5-7], a linear and nonlinear theory of current oscillations in semiconductors with deep traps was constructed. In these theoretical works, the values of the electric field and the frequency of the current oscillation are found for an unstable state of the semiconductor. In this theoretical work, we will investigate the current oscillations with a certain frequency in a semiconductor in the presence of concrete deep traps in an external constant electric field [8, 9].

II. EXPERIMENTAL PART AND DISCUSSIONS

In the future we shall have a semiconductor with carriers of both signs, i.e. electrons and holes with concentrations of n_- and n_+, respectively. In addition, there are negatively charged deep traps with a concentration of N_0 in the semiconductor. The part-concentration of singly charged traps α, N_- is the concentration of negatively charged traps

$$N_0=N_+N_- \, , \, (n_-^0,n_+^0)<<(N_0,N^0,N_-^0) \quad (1)$$

The continuity equation for electrons in a semiconductor with the above trap types will have the form: The continuity equation for electrons in a semiconductor with the above trap types will have the form of:

$$\frac{\partial n}{\partial t}+di\vartheta \vec{j}_{-}=\alpha_{-}(0)n_{1-}N_{-}-\alpha_{-}(E_0)n_{-}N=\left(\frac{\partial n_{-}}{\partial t}\right) \quad (2)$$

where, j_{-} is the electron flux density, $\alpha_{-}(E)$ is the electron capture coefficient of singly negatively charged traps in the presence of an electric field.

$$E=0,\ \alpha_{-}(0)=\alpha_{-}(E) \quad (3)$$

In Equation (2), n_{1-} is determined for stationary and equilibrium conditions

$$\frac{\partial n_{-}}{\partial t}=0, \quad \alpha_0=\alpha_{-}(E), \quad n_{1-}=\left(\frac{N_{-}^{0}N_0}{N_{-}^{0}}\right) \quad (4)$$

The flux density j_{-} in the absence of a magnetic field and the temperature gradient is given by

$$\vec{j}_{-}=-n_{-}\mu_{-}(E)\vec{E}-D_{-}\vec{\Delta}n_{-} \quad (5)$$

where, μ_{-} is the electron mobility and D_{-} is the electron diffusion coefficient.

The equation of continuity for holes will have the form

$$\frac{\partial n_{+}}{\partial t}+\text{div}j_{+}=\alpha_{+}(E)n_{1+}N-\alpha_{+}(0)n_{+}N_{-}=\left(\frac{\partial n_{+}}{\partial t}\right)_{rek} \quad (6)$$

$$\vec{j}_{+}=n_{+}\mu_{+}(E)\vec{E}-D_{+}\vec{\nabla}n_{+} \quad (7)$$

where, $\alpha_{+}(E)$ is the coefficient of e mission of holes once by negatively charged traps in the presence of an electric field. The $\alpha_{+}(E)$ is the hole capture coefficient of doubly negatively charged traps without an electric field.

$$\left(\frac{\partial n_{+}}{\partial t}\right)_{rek}=0, \quad \alpha_{+}(E)=\alpha_{-}(0), \quad n_{1+}=\left(\frac{n_{+}N_{-}^{0}}{N_0}\right) \quad (8)$$

In non-stationary conditions, the number of doubly and once negatively charged traps changes and determines the change in the once negatively charged traps. Therefore, the equation defining the change in the traps with time has the form:

$$\frac{\partial N_{-}}{\partial t}=\left(\frac{\partial n_{+}}{\partial t}\right)_{rek}-\left(\frac{\partial n_{-}}{\partial t}\right)_{rek} \quad (9)$$

In the presence of recombination and generation of charge carriers, the quasineutrality condition means that the total current is independent of the coordinates, but depends on the time

$$\text{div}\vec{J}=e.\text{div}(\vec{j}_{+}-\vec{j}_{-})=0 \quad (10)$$

When there is a fluctuation in the current in the external circuit, the current-voltage characteristic of the semiconductor has a falling section and the real part of the impedance is negative. Therefore, you need to calculate the impedance of the semiconductor. In the presence of a vibration in the outer chain, the wave vector of the oscillation is complex, and the frequency is a real quantity.

We represent the quantities $n_{\pm}$, N, N_{-} E as follows

$$n_{+}=n_{+}^{0}+\Delta n_{+}, \quad n=n_{-}^{0}+\Delta n, \quad N=N^{0}+\Delta N$$

$$N=N^{0}+\Delta N,\ E=E_0+\Delta E \quad (11)$$

$$(\Delta n_{+},\ \Delta n_{-}, \Delta N, \Delta E)\sim e^{i(\vec{k}\vec{r}-\omega t)}$$

where, $\Omega=\alpha_{-}(E_0)N_0$ is frequency of electron capture by singly charged traps, $\Omega_{+}=\alpha_{-}(E_0)N_0$ is frequency of emission of holes by singly charged traps, $\Omega_{+}=\alpha_{+}(0)N_{-}^{0}$ is frequency of trapping holes by doubly charged traps, $\Omega'_{+}=\alpha_{+}(0)n_{+}^{0}+\alpha_{+}(E_0)n_{1+}$ is combined frequency of capture and emission of holes by nonequilibrium traps and $\Omega'=\alpha_{-}(0)n_{1-}^{0}+\alpha_{-}(E_0)n^{0}$ is combined frequency of capture and emission of electrons by nonequilibrium traps as well as the coefficients.

$$\beta_{\pm}^{\gamma}=2\left(\frac{\text{din}\alpha_{\pm}E_0}{\text{din}(E_0^2)}\right)^{n}$$

From Equations (2), (6) and (9) it can be easily obtained that

$$1.\ (\Omega_{-})\Delta n''_{-}+\left(\frac{n''_{-}\Omega_{-}\beta\gamma_{-}}{E_0}-ik\mu_{-}n_{-}^{0}\right)\Delta E''-\Omega'''_{-}\Delta N''_{-}=0$$

$$(\Omega_{+})\Delta n''_{+}+\left(ik\mu_{+}n_{+}-\frac{n''_{1+}\gamma_{+}\beta_{+}^{\gamma}}{E_0}\right)\Delta E''-\Omega''_{+}\Delta N''_{-}=0$$

$$\Delta N''_{-}=\frac{1}{\Omega_{-}'+\Omega'_{-}-i\omega}\left[\Omega_{-}n''_{-}-\Omega_{+}\Delta n''_{+}+(n_{1+}\gamma_{+}\beta_{+}^{\gamma}n_{-}\Omega_{-}\beta_{-}^{\gamma})\frac{\Delta E''}{E_0}\right]$$

$$\Delta E''=\frac{1}{\sigma}(-\vartheta_{-}\Delta n''-\vartheta_{+}\Delta n''_{+}+ik\frac{T}{e}\mu_{+}\Delta n''_{+}-ik\frac{T}{e}\mu_{-}\Delta n''_{-}$$

$$2.\ (\Omega_{-}-i\omega)\Delta n'_{-}+n^{0}\Omega_{-}^{\gamma}\beta_{-}^{\gamma}\frac{\Delta E'}{E_0}-\Omega'_{-}\Delta N'_{-}=0$$

$$(\gamma_{-}-i\omega)\Delta n'_{+}-n_{1+}\gamma_{+}\beta_{+}^{\gamma}\frac{\Delta E'}{E_0}-\Omega'_{+}\Delta N'_{-}=0$$

$$\Delta N''_{-}=\frac{1}{\Omega_{-}'+\Omega'_{-}-i\omega}\left[\Omega_{-}n''_{-}-\alpha_{+}\Delta n'_{+}+(n_{1+}\gamma_{+}\beta_{+}^{\gamma}n_{-}\beta_{-}^{\gamma})\frac{\Delta E'}{E_0}\right]$$

$$\Delta E''=\frac{1}{\sigma}(\Delta J-e\vartheta_{-}\Delta n'_{-}-e\vartheta_{+}\Delta n'_{+}$$

$$\vartheta_{+}=\mu+E_0,\ \Delta n_{+}=\Delta n'_{+}+n''_{+} \quad (12)$$

$$\Delta n_{+}=\Delta N'_{-}+N''_{-},\ \sigma=\sigma_{-}+\sigma_{+}$$

Eliminating $\Delta N'_{-}$, $\Delta N''_{-}$, $\Delta E'$, $\Delta E''$ from (11) and (12), we obtain the following system of equations for determining $\Delta n_{\pm}$, $\Delta n_{\pm}$ and the wave vector

$$\begin{aligned}&\varphi_{-}(k)\Delta n''_{-}+\varphi_{+}(k)\Delta n''_{+}=0\\&F_{-}(k)\Delta n''_{-}+F_{+}(k)\Delta n''_{+}=0\end{aligned} \quad (13)$$

$$\begin{aligned}&\varphi_{-}(0)\Delta n'_{-}+\varphi_{+}(0)\Delta n'_{+}+\varphi\Delta J=0\\&F_{-}(0)\Delta n'_{-}+F_{+}(0)n'_{+}F\Delta J=0\end{aligned} \quad (14)$$

The coefficients $\varphi_{\pm}$, $F_{\pm}$ and φ, F are easily obtained when passing from (11)-(12) to (13)-(14)

To obtain the value of the wave vector k, we solve the dispersion equation obtained from

$$\varphi_-(k)\ \ F_+(k)=\varphi_+(k)\ \ F_-(k) \qquad (15)$$

However, the expressions for determining the wave vector from (15) are too cumbersome, and therefore we obtain from (15) the expressions for the wave vector in the two limiting cases.

1. High-frequency case $\omega >> \Omega_\pm,\ \gamma_+,\ \Omega'_\pm$

$$k_1=\frac{\sigma\left[\omega(n_-^0-n_+^0)+i(n_-^0\Omega_\pm-n_+\Omega_-+n_{1+}\gamma_+\beta_+^\gamma+n_-^0\Omega_-\beta_-^\gamma)\right]}{e\mu\mu_+E_0\left[(n_+^2-n_-^2)+\dfrac{(\beta_-^\gamma n_-^0\Omega_++\beta_+^\gamma n_{1+}\gamma_+n_{1+}+n_-^0\Omega_-\beta_-^\gamma)^2}{\omega^2}\right]}$$

$$k_2=\frac{eE_0}{T}\frac{[\sigma n_-^0n_+^0(\Omega_--\Omega_+)-(\beta_-^\gamma n_-^0\Omega_++\beta_+^\gamma n_{1+}\gamma_+).}{\sigma\omega(n_-^0-n_+^0)^2} \qquad (16)$$

$$\underline{.(n_+^0\sigma_-+n_+^0\sigma_+)]-i\omega\sigma(n_-^2-n_+^2)}$$

When solving the dispersion Equation (15) or using small parameters

$$\frac{\Omega'_\pm}{\Omega_+}<<1\ ,\ \frac{T\Omega_+}{eE_0\vartheta_\pm}<<1\ ,\ \frac{T}{eE_0L}<<1\ ,\ D_\pm=\frac{T}{e}\mu_\pm$$

are length semiconductors and T is temperature and ergs.

2. Low-frequency case $\omega << \Omega_\pm,\ \ \Omega'_\pm\ ,\ \gamma_+$

$$k_1=\frac{f_1}{f_2}=\frac{\omega\sigma[n_-^0\Omega_-^2-n_+^0\Omega_+^2-(\Omega_-+\Omega_+)(n_-\Omega_-\beta_-^\gamma+n_{1+}\gamma_+\beta_+^\gamma)]}{e\mu\mu_+E_0(n_+^0\Omega_+-n_-\Omega_-+n_-^0\Omega_-\beta_-^\gamma+n_{1+}\gamma_+\beta_+^\gamma)^2}$$

$$k_2=\frac{f_3-if_4}{f_5}$$

$$f_3=\sigma^2\omega[2n_-n_+(\Omega_-+\Omega_+)-(n_-\Omega_-\beta_-^\gamma+n_{1+}\gamma_+\beta_+^\gamma)(n_-+n_+)]$$

$$+\sigma\omega(n_-\beta_-^\gamma\Omega_-+n_{1+}\gamma_+\beta_+^\gamma)(n_-+n_+)(\sigma_-+\sigma_+) \qquad (17)$$

$$f_4=i\sigma(n_+\Omega_+-n_-\Omega_-\beta_-^\gamma+n_{1+}\gamma_+\beta_+^\gamma)[(n_-\beta_-^\gamma\nu_-+n_{1+}\gamma_+\beta_+^\gamma)\cdot$$

$$(\sigma_-+\sigma_+)-\sigma(n_-\Omega_-+n_+\Omega_+)]$$

$$f_5=[(\sigma_-+\sigma_+)(n_-\nu_-\beta_-^\gamma+n_{1+}\gamma_+\beta_+^\gamma)-\sigma(n_-\Omega_-+n_+\Omega_+)]^{-2}$$

The deviation from the equilibrium values $\Delta n_\pm$ is representable $\Delta n_+(x_1t)=u_1^+e^{ik_1x}+u_2^+e^{ik_2x}+U^+\Delta I$ in the following from

$$\Delta n_+(x_1t)=\theta_1^+e^{ik_1x}+\theta_2^+e^{ik_2x}+\theta^-\Delta I \qquad (18)$$

The constants u and θ are determined from the boundary conditions. To formulate the boundary conditions, we take into account that the contacts are always rectifying to some extent, so the so-called ohmic contacts represent not more than a limiting case. And depending on the transmission directions of both contacts, two types of boundary conditions can be distinguished.

On both contacts, particles of the same sign are injected

$$\Delta n_+(0)=\delta_+^0\Delta I,\ \ \Delta n_+(L)=\delta_+^L\Delta I$$
$$\Delta n_-(0)=\delta_-^L\Delta I,\ \ \Delta n_-(L)=\delta_+^L\Delta I \qquad (19)$$

On both contacts, particles of opposite signs are injected

$$\Delta n_+(0)=\delta_+^0\Delta I,\ \ \Delta n_-(L)=\delta_-^L\Delta I$$
$$\Delta n_-(0)=\delta_-^0\Delta I,\ \ \Delta n_+(L)=\delta_+^L\Delta I \qquad (20)$$

Using the boundary conditions (19)-(20), we determine the constants u and θ and after that, we can calculate the impedance of the crystal as follows

$$Z=\frac{1}{\Delta IS'}\int_0^L\Delta E(x,t)dx \qquad (21)$$

$$\Delta E(x,t)=\frac{1}{\sigma}[\Delta I-e\vartheta_-\Delta n(x,t)-e\vartheta_+\Delta n_+(x,t)+$$

$$+\frac{T\mu_+}{e}\nabla n_+(x,t)-\frac{T\mu_+}{e}\nabla n_+(x,t)] \qquad (22)$$

$$D_\pm=\frac{T}{e}\mu_\pm$$

After algebraic calculations from (21) we obtain expressions for the impedance of the following for

$$Z=Z_0[1-(e^{ik_1L}-1)\mu_1+(e^{ik_2L}-1)\mu_2+\mu_0 \qquad (23)$$

The values μ,μ_1,μ_2,μ_0 are cumbersome, we do not write them out.

$$Z=\frac{1}{\sigma S'}\ ,\ \ \sigma=e(n_-^0\mu_-^0+n_+^0\mu_+^0)$$

where, S' is cross section of the crystal. Substituting the values of k_1 and k_2 in the high-frequency and low-frequency cases, we determine the real (ReZ) and imaginary (ImZ) part of the impedance. Analysis of the Equation (23) shows that, depending on the ratios of the concentrations of the charge carriers $(T.e.\frac{n_-^0}{n_+^0}>>1$ or $\frac{n_-^0}{n_+^0}<<1)$ injections on contacts. And in the general case there are four variants in which ReZ and ImZ have a definite sign.

The $(n_-^0>>n_+^0)$ is given by δ_+^0, $2)(n_-^0>>n_+^0)$ is given by δ_-^0, $3)(n_-^0<<n_+^0)$, we have δ_+^0, $4)(n_-^0<<n_+^0)$ is given δ_+^L. In these cases, in the high-frequency and low-frequency limits, have a definite sign. When a particular frequency. Current fluctuations $\omega=2\nu_-$

$$\frac{\text{Re}\,Z}{Z_0}=\frac{E_0}{E_1}+\left(\frac{E_0}{E_2}\right)^2\left(\frac{3}{2}\sin\alpha+\cos\alpha\right) \qquad (24)$$

$$\frac{\text{Im}\,Z}{Z_0}=1-\frac{3E_0}{E_1}+\left(\frac{E_0}{E_2}\right)^2\left(\sin\alpha+\frac{3}{2\beta_-^\gamma}\cos\alpha\right) \qquad (25)$$

where,

$$E_1=\frac{L\Omega_+^2\beta_-^\gamma n}{2\gamma_+\mu_+\beta_+^\gamma n}\ ;\ E_2=\left(\frac{L\Omega\nu\beta_-^\gamma}{\mu_-\mu_+e\delta_+^0}\right)^{1/2}$$

If there is a fluctuation of the current in the external circuit ReZ<0, a ImZ can have any sign. To find the electric field from (25) at frequency (24), we must solve the system

$$\begin{cases}\dfrac{\text{Re}\,Z}{Z_0}+\dfrac{R}{Z_0}=0\\[2ex]\dfrac{\text{Im}\,Z}{Z_0}+\dfrac{R_1}{Z_0}=0\end{cases} \qquad (26)$$

where, R is the positive ohmic resistance in the circuit for reversing the resistance in the circuit and R_1 is resistance capacitive or inductive nature. From the solution of (26) we easily obtain:

$$E_0 = E_1\left(\frac{3}{7} + \frac{R_1 - R}{Z_0}\right) \quad (27)$$

If $R_1 > 0$ and $R_1 = 2Z_0$, $E_0 = \frac{10}{7}E_1$ with the boundary condition (25) from the solution (26) we obtain:

1) $R = \frac{8\beta^\gamma}{3}Z_0$; $R_1 = 1 + \frac{4\beta^\gamma}{3}$; $E_0 = 2E_1\left(\frac{\beta^\gamma}{3}\right)^{1/2}$

2) $R = Z_0$; $\beta^\gamma = \frac{\mu_+}{\mu_-}\frac{E_1}{E_2}\left(\frac{n_+}{n_-}\right)^{1/2}$; $E_0 = \frac{E_2^2}{E_1}$

3) $E_1 = \frac{4L\Omega - \beta^\gamma n_+\mu_+}{n\mu^2}$; $E_2 = \frac{2}{\beta^\gamma}\left(\frac{L}{\mu}\right)$

4) $R = R_1 = Z_0$; $R_1 > 0$; $E_0 = E_1$; $\beta^\gamma = \frac{n_+^0}{n_-^0}$

$$E_1 = \left(\frac{2L\Omega_-}{e\sigma_+^2\mu\mu_+}\right)^{1/2}$$

Thus, in all four cases, the values of the electric field, ohmic resistance, inductive or capacitive nature were found. In the low-frequency case, substituting the values of the wave vectors (17) into (23) after algebraic calculations, we obtain:

1) $R = Z_0$, $R_1 = 3Z_0$, $\omega = -\frac{1}{7}\Omega_+$, $E_0 = \frac{E_2^2}{E_1}$

$$E_1 = \frac{L\Omega_+^2\mu_- n_-}{n_+\gamma_+\mu_+^2\beta_+^\gamma}; \quad E_2 = \left(\frac{L\Omega_+\mu}{\mu\mu_+ e\sigma_+^0\beta_+^\gamma}\right)^{1/2}$$

2) $\omega = \frac{\Omega_+}{6}\frac{E_1}{E_2}$; $R_1 > 0$; $|R_1| = R = Z_0$, $E_0 = \frac{E_2^2}{E_1}$

$$E_1 = \frac{L\Omega_+}{\mu_+\beta_+^\gamma}; \quad E_2 = \left(\frac{L\Omega_+}{\mu_+\mu_- e\sigma_-^0\beta_-^\gamma}\right)^{1/2}$$

3) $E_0 = E_1 \quad \beta_-^\gamma\alpha_1^{1/2}$; $\omega = \Omega_+(\alpha + \alpha_1^{1/2}\beta_-^\gamma)\frac{Z_0}{R_1}$

$$\alpha = \frac{\gamma_+\beta_+^\gamma}{\Omega_+} + \frac{\mu_- n_-\beta_-^\gamma}{\mu_+ n_+}; \quad \alpha_1 = \frac{\mu_- n_-\Omega_-}{\mu_+ n_+\Omega_+}$$

4) $E_0 = \frac{E_2^2}{E_1}$; $\omega = \dfrac{\Omega + \left(\frac{E_1^2}{E_2^2} - \frac{R_1}{Z_0}\right)}{1 - \alpha + \frac{R}{Z_0} - \frac{E_1^2}{E_2^2} + \alpha_1(\beta_-^\gamma)^2}$

$$E_1 = \left(\frac{L\Omega_+ n_+}{\mu_+\mu_- e\sigma_-^L\beta_-^\gamma}\right)^{1/2}; \quad E_2 = \frac{L\Omega_+ n_+}{\mu_+ n_-\beta_-^\gamma\beta_-^\gamma}$$

III. CONCLUSIONS

In semiconductors with the above-mentioned deep traps, in a constant external electric field, unstable waves with different frequencies are excited. These waves are excited in different values of the external electric field. Semiconductor contacts are injecting. The injection at the contacts varies very much depending on the equilibrium ratios of carrier concentrations $n_- / n_+ = \delta$. The values of parameter δ determine the frequencies and the electric field at which indicated semiconductor is in an unstable state.

In all cases, an inductive or capacitive resistance appears in the circuit. In the high-frequency case (i.e., when the oscillation frequency of the current is more than all the recombination and generation frequencies are typical), one wave with a certain frequency is excited in this semiconductor. In the low-frequency case, several waves are excited depending on the contact directions of the crystal contacts. The obtained values of the electric field and the oscillation frequency are quite achievable experimentally.

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