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Energy Radiation Theory of Nano-Dimensional Extrinsic Semiconductors Having Electron and Hole Conductivities in an External Electric Field

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Abstract

Energy radiations depending on linearity of intrinsic semiconductors possessing of two types conductivities have been investigated. It is found that in order to start the radiation, the real part of the impedance must be zero. Frequency of the radiation and the relevance electric field strength, have been calculated analytically. It has been proved that in nano-dimension the radiations take place even though at smaller intense of electric fields.

Keywords: nano-dimensional, energy radiation, extrinsic semiconductors, electron and hole conductivities

1. Introduction

The properties of basic semiconductors and their miscellaneous components have been investigated experimentally and theoretically at point of unbalanced states at external electric fields. But in that researches the material investigations were performed in only macroscopic forms (Jameshed, 2007). For example, works of Qann on compound of GaAs, the length of the compound was about 0.1 cm. The main aim of our study is to find radiation conditions in nano dimensions, such as $\ell << 0.1$ cm, for electron and hole conductivity semiconductors in existent of an electric field. In periodical journals the occurring value of electrical radiation is $E \approx 3\times10^3$ V/cm in experimental and theoretical works. Such as electric field value provides the condition of

$$k_B T << e\ell E \tag{1}$$

at the both of liquid nitrogen and room temperatures and this value is known as larger electric value. Where k_B is the Boltzmann constant (1.38×10^{-23} J/K), T is the absolute temperature, e is the charge of electron and ℓ is the length of the semiconductor. At the smaller temperatures ranges, when $\ell \approx 10^{-8}$ cm, conditions of Equation (1) is provided.

2. The Theory of Electical Radiation

Electric current density in electron and hole carriers semiconductors is given in following equation.

$$J_\pm = \sigma_\pm E \pm D_\mp \nabla n_\mp \tag{2}$$

Where $n_\mp$ is the concentration of the hole and electron, $\sigma_\pm = e\mu_\pm n_\pm$ is the conductivity, $\mu_\pm$ is the mobility of hole and electron and $D_\pm$ is the diffusion constant of electrons and holes. From conservation condition of Equation (1)

$$\frac{D_\mp \nabla n_\mp}{\sigma_\pm E} << 1 \tag{3}$$

is obtained. Diffusion current density, $D_\mp \nabla n$, becomes smaller than that of the current, $\sigma_\pm E$, in the intrinsic semiconductors. We will take into consideration Equation (3) in the following theoretical calculations. At larger electric field, the drift velocities of electrons and holes providing (1) condition become $u_\mp = \mu_\mp E$ and are higher than that of temperature emitting velocity [$v_T \approx (k_B T / m_\pm)^{1/2}$]. Where $m_\pm$ is the mass of the hole or the

electron. Founded electric field values from condition of $u_{\pm} \approx v_{T\pm}$ are relating to stronger fields. Assuming that, the external electric field is strong enough to take into consideration.

$$E_o >> \frac{1}{\mu_{\pm}} \left(\frac{k_B T}{m_{\pm}} \right)^{1/2} \tag{4}$$

Note that this result must provide the mentioned condition.

In the intrinsic semiconductors, the larger electric field providing condition of Equation (4) condition ruins the balances of the concentrations of the charge carriers and the semiconductor comes to unbalanced state. The charge carriers, electrons and holes, are detained by doping atoms (recombination) or new carriers occur (generation) (Hasanov, 2009). Process of the recombination and the generation changes inequality the number of free charge carriers and then the system deviates from balance state (Demirel, 2011). Depending on impurity atoms the recombination and the generation gain various characters. Types and charges of impurity atoms can be determined experimentally. By following calculations we will investigate the state of Au doped into Ge semiconductor.

When Au atoms doped into Ge atoms, various states are constructed. These structures can be statement: For neutral Ge, Au takes one positive valence, for one valence negative Ge, Au takes di-valence negative and for Ge di-valence negative, Au takes three-valence negative (Hasanov, 2009, 2011; Demirel, 2011).

For such intrinsic semiconductors, the energy levels are being in various levels in the forbidden zones. In this case these levels are called as deep traps and they can hold electrons and holes (recombination). Keeping of the electron in these levels, decreases the number of electrons in the conduction band so that the conductance of the semiconductor is reduced. Keeping of the holes, decreases the number of them in the valence band. In some experimental conditions the activation of these deep traps can change. For example, when one valence negative and di-valence negative for Ge and Au respectively, Au atoms become more active than that of Ge. These deep traps change the numbers of the electrons and the holes as following. An external electric field E_0 existent, the electrons and the holes gain of $eE_0\ell$ energy. Where ℓ is the mean free path between two collisions, which is in scale of nanometer, and e is the charge of the electron. The electrons having $eE\ell$ energy overcome Coulomb wells surrounding negative one valence doping atoms and then they are seized by these atomic centers. This event is called as the recombination and due to this effect the number of the electrons in the conduction band is diminished. In the other side, the electrons are activated to pass through from deep trap to the conduction band by thermal energy. Thus the recombination decreases the number of the electrons in the conduction bands and on the contrary the generation increases it. With the decreasing of the number of electrons in the valence bands, the number of the holes is increased and the other side the number of holes is decreased in the deep traps. Since the recombination and the generation occurring probabilities are various, then the number of the charge carriers is changed. Let us indicate the number of electrons as n_-, that of the holes as n_+ and that of the deep traps as N_0, which is constant and

$$N_0 = N + N_- . \tag{5}$$

Where N is the one negative valence deep traps number and N_- is the di-valence negative deep traps number.

3. Fundamental Equations System

In mentioned above semiconductor having deep traps, equations characterizing of the movement of the electrons and the holes are basically continuity equations. As mentioned above, the recombination process reduces the number of electrons and the generation process increases it. According to these processes the electrons concentration (n_-) change depending on time can be written as following equation (Hasanov, 2009).

$$\frac{dn_-}{dt} = \left(\frac{dn_-}{dt} \right)_{gen.} - \left(\frac{dn_-}{dt} \right)_{recomb.} \tag{6}$$

$$\left(\frac{dn_-}{dt} \right)_{gen.} = \phi_-(0) n_{1-} N_- \tag{7}$$

Where $\phi_-(0)$ is electron releasing (by thermal activated) coefficient from the deep trap negative di-valence centers we will call it as heat coefficient in absence of the electric field. Concerning of the non degenerated semiconductor, the distribution function of the electrons and holes depending of energy, obeys the Boltzmann distribution as following equation.

$$\left(\frac{dn_-}{dt}\right)_{recomb.} = \phi_-(E)n_-N \tag{8}$$

Where $\phi_-(E)$ and (n_-) are the electron taking coefficients for one negative valence deep trap (N) and for existent of an external electric field respectively. When electric field E = 0, the distribution should be as Equation (9).

$$\phi_-(E) = \phi_-(0)\ ; \quad n_{1-} = \frac{n_1^0 N_0}{N_-^0} \tag{9}$$

If we replace Equations (7) and (8) into Equation (6) we obtain Equation (10).

$$\frac{\partial n_-}{\partial t} + divJ_- = \phi_-(0)n_{1-}N_- - \phi_-(E)n_-N = \left(\frac{\partial n_-}{\partial t}\right)_{recomb.} \tag{10}$$

Where J_- is the electric current density and this density in the absence of the temperature gradient and external magnetic field should be as following.

$$J_- = -n_-\mu_-(E)E - D_-\nabla n_- \tag{11}$$

If Equation (3) is conserved Equation (11) is alternated to Equation (12).

$$J_- = -n_-\mu_-(E)E \tag{12}$$

Similarly Equation (10), the continuity equation for holes becomes as given in Equation (13).

$$\frac{\partial n_+}{\partial t} + divJ_+ = \phi_+(E)n_{1+}N - \phi_+(0)n_+N_- = \left(\frac{\partial n_+}{\partial t}\right)_{recomb.} \tag{13}$$

$$J_+ = n_+\mu_+(E)E\ , \quad n_{1+} = \frac{n_+{}^0 N_-{}^0}{N_0} \tag{14}$$

Where $\phi_+(E)$ is the coefficient of the holes released from the deep traps and $\phi_+(0)$ is the coefficient for holes taken by the negative di-valence deep traps in absence of the external electric field.

$$\phi_+(E) = \phi_+(0)\ , \quad E = 0 \tag{15}$$

In the end of the recombination and generation processes, the number of one valence and di-valence deep traps change (It is clear that the number of deep traps does not change.). Change of the number of the one negative valence deep traps depending on time, changes the number of the negative di-valence deep traps. Thus

$$N_-{}^1 = -N^1 . \tag{16}$$

$N_-{}^1$ and $-N^1$ are the parts of the negative di-valence and the negative one valence centers respectively. It is possible to write the changing of the deep traps as following.

$$\frac{\partial N_-}{\partial t} = \left(\frac{\partial n_+}{\partial t}\right)_{recomb.} - \left(\frac{\partial n_-}{\partial t}\right)_{recomb.} \tag{17}$$

Quasi neutral equations should be added to (10-17) equations systems. In absence of recombination and generation, quasi neutral condition is as $n'_- = n'_+$. In existence of the recombination and the generation, the condition of quasi neutral is that the whole current does not depend on the coordination, but depend on the time. Thus following equation can be written.

$$divJ(t) = e.div(j_+ - j_-) = 0 \tag{18}$$

Occurring of the recombination and the generation in crystal causes taking place of electric field, concentrations and oscillations. These oscillations can spread inside the crystal only, or they can cause to change the current in an outside circuit. When an oscillation takes places in current of outside circuit, the resistance (impedance) of the crystal decreases rapidly. This kind behavior of the crystal is the state of negative resistance. When the crystal in its negative resistance state, energy radiation takes places in its own frequency interval. Such radiation is strongly depends on the dimensions of the crystal. We will prove that as the dimensions of the crystal is lesser to nanometer scale, the frequency of the radiation increases. In other side, as the dimension of the crystal decreases, the need external electric field strength for radiation decreases. That is, nano dimension intrinsic semiconductors can be more useful energy source for the radiation. The radiation of the crystal depends on time of taking and releasing of the free charge carriers. We will concern following characteristics times:

$\frac{1}{\tau_-} = \phi_-(E_0)N_0$: Taking frequency of the free electrons by one negative deep traps

$\frac{1}{\tau_+} = \phi_+(0)N_-^0$: Taking frequency of the holes by two negative deep traps.

$\frac{1}{\tau_e} = \phi_-(E_0)n_-^0 + \phi_-(0)n_{1-}$: Effective frequency for charactering of taking and releasing of the electrons.

$\frac{1}{\tau_p} = \phi_+(E_0)n_{1+} + \phi_+(0)n_+^0$: Effective frequency for charactering of taking and releasing of the holes.

$\frac{1}{\tau_+^E} = \phi_+(E_0)N_0$: Releasing frequency of the holes by one negative deep traps.

$E_-, \tau_+, \tau_e, \tau_p$ and τ_+^E characteristic terms depend on the external electric field and concentrations balance of the electrons and the holes. The radiation of the crystal also depends on these characteristics terms. The radiation of the crystal is a non equal distribution of the external electric field inside the crystal. The electric field E, the whole concentration of the electron n_-, the whole concentration of the holes n_+, one negative traps concentration N and two negative traps concentration N_- can be written for inside crystal as following equation.

$$\left(\vec{E}, n_-, n_+, N, N_-\right) = \left(\vec{E}, n_-, n_+, N, N_-\right)_0 e^{i\left(\vec{k}\vec{r} - \omega t\right)} \tag{19}$$

In Equation (19) to find the value of the amplitude forms fundamental of non linear equations systems. Our aim is to obtain occurred oscillation frequency inside the crystal and changing interval in appropriate external field. Consequently it is possible to write Equation (19) as following form.

$$\begin{aligned} E &= E_0 + E' = E_0 + (E_0')e^{i(kx-\omega t)} \\ n_\pm &= n_\pm^0 + n_\pm' = n_\pm^0 + (n_\pm')_0 e^{i(kx-\omega t)} \\ N &= N_0 + N' = N_0 + (N')_0 e^{i(kx-\omega t)} \\ N_- &= N_1^0 + N_-' = N_1^0 + (N_-')_0 e^{i(kx-\omega t)} \end{aligned} \tag{20}$$

Where k is the wave vector and ω is the oscillation frequency. Since the external electric field is in the direction of J_0, Equation (20) can be written in one dimension. Considering Equation (18) in quasi neutral conditions, Equations (10, 12, 13, 16, 17) can be written as following forms.

$$\begin{aligned} E &= E_0 + E'; E' << E_0 \\ n_\pm &= n_\pm^0 + n_\pm'; n_\pm' << n_\pm^0 \\ N &= N_0 + N'; N' << N_0 \\ N_- &= N_-^0 + N_-'; N_-' << N_-^0 \end{aligned} \tag{21}$$

These conditions are convenient for solutions. With the conditions of Equation (21) it is possible to transform to linear nonlinear Equations (10-17). From Equation (18) we can obtain following equation.

$$E' = \frac{1}{\sigma_d}\left(J' - ev_+n_+' - ev_-n_-'\right) \tag{22}$$

Where σ_d is the conductivity of the crystal and $v_\pm = \mu_\pm(E_0)E_0$ is the drift velocity of the holes and the electrons. The whole conductivity of the crystal is given as the next equation. $\sigma_d = en_+\mu_+\left(1 + \frac{2d\ln\mu_+}{d\ln(E^2)}\right) + en_-\mu_-\left(1 + \frac{2d\ln\mu_-}{d\ln(E^2)}\right)$. Coefficient $\phi_\pm(\vec{E})$ characterizing recombination and releasing of the electrons and the holes, can be written in serial form as this equation $\phi_\pm = \phi_\pm(E_0^2)\left(1 + 2\frac{d\ln\phi_\pm}{d\ln(E^2)}.\frac{\vec{E}'}{\vec{E}_0}\right) = \phi_\pm(E_0^2)\left(1 \pm \beta_\pm^\phi \frac{\vec{E}'}{\vec{E}_0}\right)$. Where $\beta_\pm^\phi$ is a parameter without unit and it depends on taking of the electrons and the holes by the deep traps. Since negative centers attract the holes, as the external

electric field increasing, β_+^ϕ decreases and β_-^ϕ increases, consequently $\beta_+^\phi < 0$, and $\beta_-^\phi > 0$. Radiation frequencies and convenient external electric field values to these frequencies definitely depend on the parameters of $\beta_\pm^\phi$. If we make linear Equation (17) with concerning the conditions of Equations. (21-22), we can obtain following equation.

$$N_-^{'} = \frac{n_-^{'}}{\tau_-\left(\omega_{ep} - i\omega\right)} - \frac{n_+^{'}}{\tau_+\left(\omega_{ep} - i\omega\right)} \tag{23}$$

Where $\omega_{ep} = \frac{1}{\tau_p} - \frac{1}{\tau_e}$ is a characteristic frequency. Replacing (22) and (24) statements into (10-13) we obtain following equation systems to definite $n_\pm^{'}$ values.

$$\begin{aligned}&\left[-i\omega + ikv_+\frac{\sigma_d^-}{\sigma_d} + \frac{1}{\tau_+} - \frac{1}{\tau_p\tau_+\left(\omega_{ep} - i\omega\right)} - \frac{\sigma_{1+}}{\sigma_d}.\frac{1}{\tau_+^E}\beta_+^\varphi\right]n_+^{'}\\&+\left[\frac{1}{\tau_p\tau_-\left(\omega_{ep} - i\omega\right)} - \frac{\mu_-}{\mu_+}\frac{\sigma_+}{\sigma_d}ikv_+^d - \frac{\mu_-}{\mu_+}\frac{\sigma_{1+}}{\sigma_d}.\frac{1}{\tau_+^E}\beta_+^\varphi\right]n_+^{'} = \frac{J^{'}}{\sigma_d E_0}\left(ikv_+^d n_+^0 + \frac{n_{1+}}{\tau_+^E}\beta_+^\varphi\right)\end{aligned} \tag{I}$$

$$\begin{aligned}&\left[\frac{1}{\tau_e\tau_+\left(\omega_{ep} - i\omega\right)} + \frac{\mu_+}{\mu_-}ikv_-^d\frac{\sigma_-^d}{\sigma_d} + \frac{1}{\tau_-}\frac{\mu_+}{\mu_-}\frac{\sigma_-^d}{\sigma_d}\beta_-^\varphi\right]n_+^{'} + \left(-i\omega - ikv_-^d\frac{\sigma_+^d}{\sigma_d} + \frac{1}{\tau_-}\right)n_-^{'}\\&-\left[\frac{1}{\tau_e\tau_-\left(\omega_{ep} - i\omega\right)} + \frac{1}{\tau_-}\frac{\sigma_-^d}{\sigma_d}\beta_1^\varphi\right]n_-^{'} = \frac{J^{'}}{\sigma_d E_0}\left(-ikv_-^d n_-^0 - \frac{n^0}{\tau_-}\beta_-^\varphi\right)\end{aligned} \tag{II}$$

Here $kv_\pm^d = kv_\pm^0\left(1 + \beta_\pm^\mu\right)$; $\beta_\pm^\mu = 2\frac{d\ln\mu_\pm}{d\ln\left(E_0^2\right)}$. Above (I) and (II) equations can be shortened as following form

$$\begin{cases}A_+n_+^{'} + A_-n_-^{'} = A_0J^{'}\\B_+n_+^{'} + B_-n_-^{'} = B_0J^{'}\end{cases} \tag{24}$$

In this equations system current $J^{'}$ is depended only time, but the concentrations $n_\pm$ are depended on time and coordination and them can be written as below.

$$n_\pm^{'} = \Delta n_\pm e^{-i\omega t} + C_\pm e^{i(kx-\omega t)} \tag{25}$$

In Equation (24) equations system, when $J^{'} = 0$, k wave vector is determined, when $k = 0$, $\Delta n_\pm$ coefficients are determined. For calculation of the wave vector k, we will consider characteristic time values $\left(\tau_-, \tau_+, \tau_p, \tau_e, \tau_+^E\right)$ of $\beta_\pm^\phi$ parameter.

$$\tau_- = \tau_+; \frac{\tau_p}{\tau_e} = \left(\frac{\mu_+}{\mu_-}\right)^2; n_-^0\left(1 + \beta_-^\mu\right) = n_+^0\left(1 + \beta_+^\mu\right); \beta_+^\phi = \frac{\sigma_d\tau_+^E}{\sigma_{1+}\tau_+}; \beta_-^\phi = \frac{n_+^0\sigma_d\tau_+^E}{n^0\sigma_{1+}\tau_+} \tag{26}$$

In Equation (26) possibilities for taking of the electrons and the holes are the same, and it is shown that the concentrations $n_\pm^0$ are equal which mean that the semiconductor is approximately intrinsic. Considering Equation (26), the real and imaginer parts of the wave vector given in Equation (24) can be written as below.

$$k = k_0 + ik; k_0 = \frac{\sigma_d}{2\sigma_+^d v_+}\left(\frac{\omega_{ep}}{\tau_+}\right)^{1/2}; k_1 = \frac{\sigma_d}{2\sigma_+^d v_+}\omega_{ep} f(\omega) \tag{27}$$

$$f(\omega) = \left(\frac{\omega^2}{\omega^2 + \omega_{ep}^2} + \omega_{ep}\tau_+ - \frac{1}{\omega_{ep}\tau_+}\right) > 0 \quad ; \quad \omega^2 = \frac{\omega_{ep}}{\tau_+} \tag{27a}$$

Accepting that in Equation (27) $\omega_{ep}\tau_{+} > 1$ and in Equations (26-27) $k = 0$, from Equation (24), $\Delta n_{\pm}$ can be calculated as following statement.

$$\Delta n_{+} = \frac{J'\left(A_{-}B_{0} - B_{-}A_{0}\right)}{A_{+}B_{-} - A_{-}B_{+}}; \quad \Delta n_{-} = \frac{J'\left(A_{+}B_{0} - B_{+}A_{0}\right)}{A_{+}B_{-} - A_{-}B_{+}} \tag{28}$$

Replacing $\left(A_{+}, A_{-}, B_{+}, B_{-}\right)$ coefficients into Equations (I) and (II) we can obtain following equations.

$$\begin{aligned} \Delta n_{+} &= \frac{J'}{ev_{-}}\frac{1}{\omega_{ep}\tau_{+}} + i\frac{J'}{ev_{+}}\left(\frac{1}{\omega_{ep}\tau_{+}}\right)^{3/2} \\ \Delta n_{-} &= -\frac{2\mu_{-}}{\mu_{+}}\frac{J'}{ev_{+}} - i\frac{2\mu_{-}}{\mu_{+}}\frac{J'}{ev_{+}}\left(\omega_{ep}\tau_{+}\right)^{1/2} \end{aligned} \tag{29}$$

By replacing statement of Equation (29) into Equation (25), variables of $n'_{\pm}$ can be determined, but $C_{\pm}$ coefficients can only be solved from limit conditions. To find limit conditions, it must be considered that, the contacts of the applied crystal to the circuit are not whole ohmic. From the contact the charges go into the crystal and vice versa. The same type charge carriers or opposite type of them can across through. The ends of the crystal $x = 0$ and $x = \ell$ play principal roles and for that case we will accept these conditions;

$$n'_{+}(x=0) = \delta_{+}^{0}J'; \quad n'_{-}(x=\ell) = \delta_{-}^{\ell}J' \tag{30}$$

Where δ_{+}^{0} and δ_{-}^{ℓ} are the injection coefficients of the holes and the electrons respectively. If we consider Equation (30) into Equation (25) we can find the coefficients of $C_{\pm}$.

$$C_{+} = \left(\delta_{+}^{0} - \Delta n_{+}\right)J'; \quad C_{-} = \left(\delta_{-}^{\ell} - \Delta n_{-}\right)e^{-ikl} \tag{31}$$

Taking into consideration Equation (30-31) and replacing the electric field of the $n'_{\pm}$ variables into Equation (22), we obtain complex resistance (impedance) of the crystal as following equation.

$$Z = \frac{1}{J'S'}\int_{0}^{\ell} E'(x,t)dt \tag{32}$$

Where S' is the cross section surface of the crystal. If we compute above integral, following statements are obtained.

$$\frac{Z}{Z_{0}} = 1 + ev_{+}(a_{+} + ia'_{+}) + ev_{-}(b_{-} - ib'_{-}) - ev_{+}(\delta_{+}^{0} + a_{0} + ia'_{+})\frac{e^{ikl} - 1}{ik\ell} - ev_{-}(\delta_{-}^{\ell} + b_{-} - ib'_{-})\frac{1 - e^{-ikl}}{ikl} \tag{33}$$

Where

$$Z_{0} = \frac{1}{\sigma_{d}.S}; \quad a_{+} = \frac{2\mu_{-}}{\mu_{+}}.\frac{1}{ev_{+}}; \quad a'_{+} = \frac{2\mu_{-}}{\mu_{+}}.\frac{1}{ev_{+}}\left(\omega_{ep}\tau_{+}\right)^{1/2}; \quad b_{-} = \frac{1}{ev_{-}}.\frac{1}{\omega_{ep}\tau_{+}}; \quad b'_{-} = \frac{1}{ev_{+}}\left(\frac{1}{\omega_{ep}\tau_{+}}\right)^{3/2} \tag{34}$$

If we consider Equation (34) and $k = k_{0} + ik_{1}; e^{ikl} = e^{-ik_{1}\ell}\left(\cos\beta - i\sin\beta\right)$ statements into Equation (33), we obtain real and imaginer parts of the complex crystal impedance as following equations.

$$\begin{aligned} \frac{\operatorname{Re} Z}{Z_{0}} &= 1 + ev_{+}\left(a_{+} + z_{1}a'_{+} + z_{1}\delta_{+}^{0} + z_{1}a_{+}\right) + ev_{-}\left(b_{-} + z_{1}b'_{-} - z_{1}\delta_{-}^{\ell} - z_{1}b_{-}\right) + \cos\beta\left(z_{1}M - zu\right) + \sin\beta\left(z\varphi - z_{1}F\right) \\ \frac{\operatorname{Im} Z}{Z_{0}} &= ev_{+}\left(a'_{+} + za_{+}^{-} + z\delta_{+}^{0} + za_{+}\right) + ev_{-}\left(-b'_{-} + zb'_{-} - z\delta_{-}^{\ell} - zb_{-}\right) + \cos\beta\left(zM - z_{1}u\right) + \sin\beta\left(zF_{-} - z_{1}\varphi\right) \end{aligned} \tag{35}$$

Where

$$\begin{aligned} &M = e^{\alpha}.ev_{-}\left(\delta_{-}^{\ell} + b_{-}\right) - e^{-\alpha}ev_{+}\left(\delta_{+}^{0} + a_{+}\right) \\ &U = e^{\alpha}.ev_{-}b_{-}^{'} + e^{-\alpha}.ev_{+}a_{+} \\ &F = e^{-\alpha}ev_{+}a_{+}^{'} - e^{\alpha}ev_{-}b_{-}^{'} \\ &\varphi = e^{\alpha}ev_{-}\left(\delta_{-}^{\ell} + b_{-}\right) + e^{-\alpha}ev_{+}\left(\delta_{+}^{0} + a_{+}\right) \\ &\alpha = k_1\ell; \beta = k_0\ell; z = \frac{k_0}{\left(k_0^2 + k_1^2\right)\ell}; z_1 = \frac{k_1}{\left(k_0^2 + k_1^2\right)\ell} \end{aligned} \tag{36}$$

The electric field should produce the condition of Equation (1), thus for $\alpha << 1$

$$E_0 >> \frac{\sigma_d.\ell}{2\sigma_{+}^{d}\mu_{+}}\omega_{ep}f(\omega) = E_{ext} \tag{37}$$

Here the function should be $f(\omega) \approx 1$. Equation (37) shows that as the dimension of the crystal getting lesser, E_{ext} decreases and the condition of Equation (37) is well executed. That is radiation condition founded from complex resistance (impedance) prefers lesser values of the E_0 electric field.

Since $\alpha << 1$, if we replace (34-36) statements into Equation (35), we can obtain real part of the impedance as below.

$$\begin{aligned} \frac{\operatorname{Re}Z}{Z_0} = &\left(\frac{2\mu_{-}}{\mu_{+}}\right)^2\left[\left(z_1 + zx^{1/2}\right) + \left(z + z_1x^{1/2}\right)\right] - \frac{2\mu_{-}}{\mu_{+}}\left(z_1 + zx^{1/2}\right)\cos\beta \\ &+ \frac{2\mu_{-}}{\mu_{+}}\sin\beta\left(zx^{1/2} + z_1\right) = d - j\cos\beta + j_1\sin\beta \end{aligned} \tag{38}$$

Here $x = \omega_{ep}\tau$. The sign of Equation (38) is determined by the trigonometric functions $\sin\beta$ and $\cos\beta$. We can rewrite Equation (38) as following form.

$$\frac{\operatorname{Re}Z}{Z_0} = d - \sqrt{j^2 + j_1^2}\cos\left(\beta + Q\right); \quad \cos Q = \frac{j}{\sqrt{j^2 + j_1^2}}; \sin Q = \frac{j_1}{\sqrt{j^2 + j_1^2}} \tag{39}$$

Equality to zero for this equation depends on the values of parameters α, j and j_1 (as $\alpha > 0$, $j > 0$ and $j_1 > 0$).

In the interval of $-1 \le \cos\left(\beta + Q\right) \le 1$ the statement of $\frac{\operatorname{Re}Z}{Z_0}$ becomes positive for $\cos\left(\beta + Q\right) > 0$ and $d > \sqrt{j^2 + j_1^2}$ and becomes negative for $d < \sqrt{j^2 + j_1^2}$. In the other side for $\cos\left(\beta + Q\right) < 0$ this statement becomes greater than zero. Let us investigate the condition of $\frac{\operatorname{Re}Z}{Z_0} = 0$, that is starting of radiation. For the situations of $\cos\left(\beta + Q\right) = \pm 1$ and $\frac{\operatorname{Re}Z}{Z_0} = 0$ parameter of d becomes

$$d = \sqrt{j^2 + j_1^2}\ . \tag{40}$$

Analysis of Equation (40) shows that when $\omega_{ep}\tau = \frac{3}{k_1\ell}$, $\omega^2 = \frac{\omega_{ep}}{\tau_{+}} = \frac{1}{\tau_{+}\tau_{p}}$, $\tau_p = \left(\frac{\sigma_d\ell\tau}{6\sigma_{1+}^{d}v_{+}}\right)^{1/2}$ and $\frac{\operatorname{Re}Z}{Z_0} = 0.$

That is with the frequency of $\omega = \left(\frac{1}{\tau_e\tau_p}\right)^{1/2}$ the radiation starts. From Equation (35), if we write the real part of the impedance as $\frac{\operatorname{Im}Z}{Z_0} = F - F_1\cos(\beta) + F_2\sin\beta$, it is possible to determine easily F, F_1 and F_2 parameters. Thus following equation is obtained.

$$\frac{\operatorname{Im} Z}{Z_0} = F - \sqrt{F_1^2 + F_2^2}\cos(\beta + \varphi_1)\,;\quad \cos\varphi_1 = \frac{F_1}{\sqrt{F_1^2 + F_2^2}}\,;\quad \sin\varphi_1 = \frac{F_2}{\sqrt{F_1^2 + F_2^2}} \tag{41}$$

It is seen from analysis of Equation (41) and Equation (40) (that is $\frac{\operatorname{Re} Z}{Z_0} = 0$), $\frac{\operatorname{Im} Z}{Z_0} > 0$ and when the radiation starts the complex resistance has inductance characteristics.

4. Conclusion

Thus doped semiconductors having electron and hole conductivity, when $E >> E_{ext}$ radiate an energy in a certain frequency. This radiation becomes more effective as the dimension of the semiconductor decreases. As ℓ getting smaller, the radiation takes place in smaller values of the electric field. Related the radiation, the external electric can be written as below.

$$E_0 >> \frac{\sigma_d \ell}{2\sigma_+^d \mu_+}\omega_{ep} f(\omega_{ep}) = E_{ext} = \frac{\sigma_d \ell}{2\sigma_+^d \mu_+ \tau_p} \approx 3\frac{\ell}{\mu_+ \tau_+}$$

Let us in Ge semiconductor the mobility of the holes $\mu \approx 10^4$ cm^2/v.s, the generation time $\tau_p \approx 10^{-9}$ s and the dimension $\ell \approx 100 - 150$ nm, in that conditions obtained external electric field is about 10^4 v/cm. When the dimension of the crystal is in macroscopic scales ($\ell \approx 0.1$ cm) and radiation takes place, the calculated external electric field is about $3 - 4 \times 10^3$ v/cm which is one degree lesser than the above value. It means that when semiconductor dimensions are in nanometer scale, the distribution of the electric field inside the crystal should not be homogenous and at this moment the crystal becomes more effectively radiant.

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