INSTABILITY IN SEMICONDUCTORS WITH DEEP TRAPS

[1] E.R.HASANOV, [2] RASOUL NEZHAD HOSSEIN
[1] Baku State University,
AZ-1148, Z.Xalilova, 23
[2] Institute of Physics of the Azerbaijan National Academy of Sciences
named by academician G.M. Abdullayev
H. Cavid pr., 33, Baku, Az 1143

Nəzəri olaraq göstərilmişdir ki, dərin tələli yarımkeçiricilərdə, xarici elektrik sahəsində dayanıqsız dalğa yayılır. Elektronların tutulma tezliyi, deşiklərin tutulma tezliyindən iki dəfə böyük olur.

Теоретически показано, что во внешнем электрическом поле E_0 в полупроводниках с глубокими ловушками распространяется неустойчивая волна. Частота захвата электронов в два раза превышает частоту захвата дырок.

It is theoretically proved, that at certain value of external electric field E_0 in concrete intrinsic semiconductor there is unstable recombination wave. Frequencies and increments this wave are defined. It is established, that the unstable wave arises, when frequency of capture of electrons by the intrinsic centers twice exceeds frequencies of capture of holes.

Some impurity in the semiconductor create the centers which are capable to be in the several charged conditions (unitary, twice, etc. positively or negatively charged). So, for example, [1,2] atoms of gold in germanium can except a neutral condition, to be positively charged and unitary, twice and triple negatively charged centers, atoms of copper, except a neutral condition can be unitary, twice and triple negatively charged centers, etc. To the intrinsic centers there correspond in the forbidden zone some energetic levels. Such energetic levels are located on different distances from a conductivity zone (or from an upper edge of valence zone) in the forbidden zone of the semiconductor. Depending on energetic distance of these levels from a valence zone (or conductivity zones) them name deep. These deep levels (the intrinsic centers) are capable to grasp electrons or holes depending on their charging conditions. As a result of such capture concentration of electrons in a conductivity zone, concentration of holes in a valence zone, and therefore, conduction the semiconductor changes. Presence of such deep traps in the semiconductor leads to change of concentration of the electrons and holes.

In the presence of electric field, electrons (and also holes) receive from electric field energy of an order $eE_0 l$, (e is the positive elementary charge, E_0 is the value of electric field, l is the free run length of electrons). Therefore, in the presence of electric field, electrons can overcome Coulomb barrier of unitary charged centre and to be grasped (i.e. recombined with this centre). Besides, owing to thermal transfer of electrons can be generated from traps in conductivity zones. Capture process reduces, and process of transition increases the number of electrons in a conductivity zone. As to holes their number increases owing to capture of electrons deep traps from a valence zone and decreases owing to capture of electrons from deep traps holes. Different probabilities of generation and recombination lead to change of concentration of carriers in a crystal. We will theoretically investigate recombination waves in concrete semiconductors with deep traps and two types of current carriers with concentration of electrons n_-, holes n_+. Besides, in the semiconductor there are negatively charged deep traps of N_0. From them a part of N is the concentration of the unitary negatively charged traps, N_- is the concentration of the twice negatively charged traps.

$$N_0 = N + N_- \tag{1}$$

The equation of indissolubility for electrons in the semiconductor with the above-stated types of traps will look like: [3].

$$\frac{\partial n_-}{\partial t} + div\vec{j}_- = \gamma_-(0) n_{1\_} N_- - \gamma_-(E) n_- N = \left(\frac{\partial n_-}{\partial t}\right)_{rec.} \tag{2}$$

Here $\vec{j}_-$ is the stream density of electrons, n_- is the concentration of electrons, $\gamma_-(0)$ is the emission factor of electrons by the twice negatively charged traps in absence of electric field. $\gamma_-(E)$ is the capture factor of electrons by the unitary negatively charged traps in the presence of electric field. At $E = 0$, $\gamma_-(E) = \gamma_-(0)$. In the equation of (2) the unknown constant of $n_{1\_}$ is the dimensional concentration is defined in equilibrium [3] conditions from $\left(\frac{\partial n_-}{\partial t}\right)_{rec.} = 0$

$$n_{1\_} = \frac{n_-^0 N_0}{N_-^0}, \quad \gamma_-(E) = \gamma_-(0) \tag{3}$$

The density of current stream in the absence of magnetic field and temperature gradient is defined by expression [4]

$$\vec{j}_- = -n_- \mu_-(E)\vec{E} - D\vec{\nabla} n_- \tag{4}$$

Where $\mu_-(E)$ is the mobility of electrons, D_- is the diffusion factor of electrons.

The equation of indissolubility for holes will look like [3]:

$$\frac{\partial n_+}{\partial t} + div\vec{j}_+ = \gamma_+(E)n_{1+}N - \gamma_+(0)n_+N_- = \left(\frac{\partial n_+}{\partial t}\right)_{rec.} \quad (5)$$

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

Here $\mu_+(E)$ is the mobility of holes, D_+ is the factor of diffusion of holes, $\gamma_+(E)$ is the factor of emission of holes by the unitary negatively charged traps in the presence of electric field, $\gamma_+(0)$ is the factor of capture of holes by the twice negatively charged traps in absence of electric field. The constant n_{1+} is defined from $\left(\frac{\partial n_+}{\partial t}\right)_{rec} = 0$ [3], at $\gamma_+(0) = \gamma_+(E)\,;n_{1+} = \frac{n_+^0 N_-^0}{N_0}$. Change the twice negatively charged traps by time define the change of unitary negatively charged traps. Therefore the equation defining changes of traps by time looks like [3] as:

$$\frac{\partial N_-}{\partial t} = \left(\frac{\partial n_+}{\partial t}\right)_{rec.} - \left(\frac{\partial n_-}{\partial t}\right)_{rec.} \quad (6)$$

To the equations of (1-6) it is necessary to add a condition of neutrality, i.e. the full current does not depend on coordinates, but depends on time

$$div\vec{J} = ediv(\vec{j}_+ - \vec{j}_-) = 0 \quad (7)$$

Presence of recombination and generation of electrons and holes in the semiconductor leads to occurrence of accruing fluctuation of the concentration of carriers and electric field in a crystal. These fluctuations can accrue in a crystal, or to leave in an external chain (i.e. in an external chain there are current fluctuations). We will consider increase of a wave in a crystal and consequently frequency of fluctuation is complex size and the wave vector in material size and is defined from a condition of standing waves in a crystal. i.e.

$$\omega = \omega_0 + i\gamma\,;\; k = \frac{2\pi}{L}m\,,\; m = 0, \pm1, \pm2\pm... \quad (8)$$

(L is the size of a crystal, m is the quantum number).

For the finding of dispersive equation (i.e. dependence of frequency of wave $\omega(k)$ on wave vector of $\vec{k}$) it is necessary to solve system of the equations (1-7). Flat $n_\pm(\vec{r}_1 t) = n_\pm^0 + n_\pm^{'}(x_1 t)$; $N_-(\vec{r}_1 t) = N_-^0 + N_-^{'}(\vec{r}_1 t)$, $E(\vec{r}_1 t) = E_0 + E^{'}(\vec{r}_1 t)$ and, entering instead of factors recombination frequencies of capture and emission by the equilibrium centers

$$\nu_- = N_0\gamma_-(E_0),$$
$$\nu_+ = \gamma_+(0)N_-^0, \quad (9)$$
$$\nu_+^E = \gamma_+(E_0)N_0$$

and also "combinative " frequencies of capture and emission by the non-equilibrium centers

$$\nu_-^{'} = \gamma_-(E_0)n_-^0 + \gamma_-(0)n_{1-}$$
$$\nu_+^{'} = \gamma_+(0)n_+^0 + \gamma_+(E_0)n_{1+} \quad (10)$$

and, at last, having designated the numerical multipliers defined by dependences of sizes $\gamma_\pm(E)$, $\mu_\pm(E)$ from electric field

$$\beta_\pm^\gamma = 2\frac{d\ln\gamma_\pm(E)}{d\ln(E_0^2)},$$
$$\beta_\pm^\mu = 1 + 2\frac{d\ln\mu_\pm(E)}{d\ln E_0^2} \quad (11)$$

Linearity of (1-7) on small deviations of corresponding sizes, we will receive

$$\frac{\partial n_-^{'}}{\partial t} + \frac{\partial}{\partial\vec{r}}j_-^{'}(\vec{r},t) = -\nu_- n_-^{'}(\vec{r},t) - \nu_- n_-^0\beta^\gamma\frac{E^{'}(\vec{r},t)}{E_0} + \nu_-^{'}N_-^{'}(\vec{r},t)$$

$$\frac{\partial n_+^{'}}{\partial t} + \frac{\partial}{\partial\vec{r}}j_+^{'}(\vec{r},t) = -\nu_+ n_+^{'}(\vec{r},t) + \nu_+^E n_{1-}\beta_+^\gamma\frac{E^{'}(\vec{r},t)}{E_0} - \nu_+^{'}N_-^{'}(\vec{r},t)$$

$$\frac{\partial N_-^1(\vec{r},t)}{\partial t} = \left[\frac{\partial n_+^{'}(\vec{r},t)}{\partial t}\right]_{rec.} - \left[\frac{\partial n_-^{'}(\vec{r},t)}{\partial t}\right]_{rec.}$$

$$\frac{\partial}{\partial\vec{r}}\left[j_+^{'}(\vec{r},t) - j_-^{'}(\vec{r},t)\right] = 0 \quad (12)$$

$$j_\pm^{'} = \pm\vartheta_\pm^0 n_\pm^{'}(\vec{r},t) \pm n_\pm^0\mu_\pm^0\beta_\pm^\mu E^{'}(\vec{r},t) - D_\pm\frac{\partial}{\partial\vec{r}}n_\pm^{'}(\vec{r},t)$$

Here $\vartheta_{\pm}^{0} = \mu_{\pm}^{0} E_0$ is the drift speeds of holes and electrons. Including fluctuations $n_{\pm}^{'}(\vec{r}_1 t)$, $N^{'}(\vec{r}_1 t)$, $N_{-}^{'}(\vec{r}_1 t)$ in a crystal proportional $\sim ei(\vec{k}\vec{r} - \omega t)$ we will receive representing waves from (7) following values for components of variable electric field in a crystal

$$E_x^{'} = -\frac{e}{\sigma^{\mu}}\left[(\vartheta_{+} - iD_{+}k_k)n_{+}^{'} + (\vartheta_{-} + iD_{-}k_x)n_{-}^{'}\right]$$

$$E_y^{'} = -i\frac{ek_y}{\sigma^{\mu}}\left(D_{+}n_{+}^{'} + D_{-}n_{-}^{'}\right), \qquad (13)$$

$$E_z^{'} = \frac{ie}{\sigma^{\mu}}\left(D_{+}k_z n_{+}^{'} - D_{-}k_z n_{-}^{'}\right);$$

$$\sigma^{\mu} = \sigma_{-}^{\mu} + \sigma_{+}^{\mu};\ \sigma_{\pm} = en_{\pm}\mu_{+}^{0}\beta_{\pm}^{\mu}.$$

Considering, as $n_{\pm}^{0} << N_{-}^{0}, N^{0}$ and $\frac{\nu_{\pm}^{'} N_{-}^{'}}{\nu_{\pm} n_{\pm}^{0}} << 1$, substituting of (3) in (2-5) we will receive following two equations for $n_{\pm}^{'}$:

$$\begin{cases} A_{-}n_{-}^{'} + A_{+}n_{+}^{'} = 0 \\ B_{-}n_{-}^{'} + B_{+}n_{+}^{'} = 0 \end{cases} \qquad (14)$$

Substituting values of $A_{\pm}$ and $B_{\pm}$ from (14) we will receive the dispersive equation $A_{-}B_{+} - A_{+}B_{-} = 0$ i.e.

$$\left[-i\omega - ik\vartheta_{-} + D_{-}k^2 + \nu_{-} - \nu_{-}\beta_{-}^{\gamma}\frac{\sigma_{-}}{\sigma^{\mu}}\left(1 + i\frac{D_{-}k^2}{k\vartheta_{-}}\right)\right]\cdot\left[-i\omega + i\vec{k}\vec{\vartheta}_{+} + D_{+}k^2 + \nu_{+} + \frac{\sigma_{+}}{\sigma^{\mu}}\frac{n_{1+}}{n_{+}}\beta_{+}^{\gamma}\nu_{+}^{E}\left(1 - i\frac{D_{+}k^2}{\vec{k}\vec{\vartheta}_{+}}\right)\right] -$$

$$-\left[\beta_{-}^{\mu}\frac{\sigma_{-}}{\sigma^{\mu}}\left(D_{+}k^2 + i\vec{k}\vec{\vartheta}_{+}\right) - \nu_{-}\beta_{-}^{\gamma}\frac{\mu_{+}}{\mu_{-}}\frac{\sigma_{-}}{\sigma^{\mu}}\left(1 - i\frac{D_{+}k^2}{\vec{k}\vec{\vartheta}_{+}}\right)\right]\cdot\left[\beta_{+}^{\mu}\frac{\sigma_{+}}{\sigma^{\mu}}\left(D_{-}k^2 - i\vec{k}\vec{\vartheta}\right) + \beta_{+}^{\gamma}\nu_{+}^{E}\frac{n_{1+}}{n_{+}}\frac{\sigma_{-}}{\sigma^{\mu}}\left(1 + i\frac{D_{-}k^2}{\vec{k}\vec{\vartheta}}\right)\right] = 0 \qquad (15)$$

Having designated $\frac{\sigma_{+}}{\sigma^{\mu}}\frac{n_{1+}}{n+}\beta_{+}^{\gamma}\nu_{+}^{E} = \tilde{\nu}_{+}^{E}$; $\nu_{-}\beta_{-}^{\gamma}\frac{\sigma_{-}}{\sigma^{\mu}} = \tilde{\nu}_{-}$, and considering, that mobility of electrons more than mobility of holes, i.e. $\mu_{-} >> \mu_{+}$ we will receive from (15) equation for definition of frequency ω of fluctuation in a crystal

$$\omega^2 + \left[\vec{k}\vec{\vartheta}_{-} + a\vec{\nu}_{-} + b\tilde{\nu}_{+}^{E} + i\left(\nu_{-} + \nu_{+} + a\vec{k}\vec{\vartheta}_{-} + \tilde{\nu}_{+}^{E} - \tilde{\nu}_{-}\right)\right]\omega - k^2\vartheta_{-}\vartheta_{+} - \vec{k}\vec{\vartheta}_{-}\nu_{+}a -$$
$$-\nu_{-}k\vartheta_{+}a - \nu_{-}\tilde{\nu}_{+}^{E} + \nu_{+}\tilde{\nu}_{-} + \nu_{-}\nu_{+} + i\left(\vec{k}\vec{\vartheta}_{-}\nu_{+} + \vec{k}\vec{\vartheta}_{-}\tilde{\nu}_{+}^{E} - \nu_{-}\vec{k}\vec{\vartheta}_{+} + b\nu_{-}\tilde{\nu}_{+}^{E} + \vec{k}\vec{\vartheta}_{+}\tilde{\nu}_{-} +\right.$$
$$\left. + a\nu_{+}\tilde{\nu}_{-} + \beta_{-}^{\mu}\frac{\sigma_{-}}{\sigma^{\mu}}\vec{k}\vec{\vartheta}_{+}\tilde{\nu}_{+}^{E} + \beta_{+}^{\mu}\frac{\sigma_{+}}{\sigma^{\mu}}\tilde{\nu}_{-}\vec{k}\vec{\vartheta}_{-}\right) = 0 \qquad (16)$$

Here $a = \frac{D_{-}k^2}{\vec{k}\vec{\vartheta}_{-}}$; $b = \frac{D_{+}k^2}{\vec{k}\vec{\vartheta}_{+}}$.

The equation (16) we will write in a following kind

$$\omega^2 + (\alpha + i\beta)\omega + \Omega^2 + i\theta^2 = 0 \qquad (17)$$

The decision (17) looks like:

$$\omega_{1,2} = -\frac{\alpha + i\beta}{2} \pm \sqrt{\frac{\alpha^2 - \beta^2}{4} - \Omega^2 + i\left(\frac{\alpha\beta}{2} - \theta^2\right)}$$

For allocation of material and imaginary part $\omega_{1,2}$ we will designate $\frac{\alpha^2 - \beta^2}{4} - \Omega^2 = \Omega_1^2$; $\frac{\alpha\beta}{2} - \theta^2 = \Omega_2^2$ then $\sqrt{\Omega_1^2 + i\Omega_2^2} = x + iy$ and $\Omega_1^2 + i\Omega_2^2 = x^2 - y^2 + i2xy$

$$x = \frac{1}{\sqrt{2}}\cdot\left[\sqrt{\Omega_1^4 + \Omega_2^4} + \Omega_1^2\right]^{1/2};\ y = \frac{1}{\sqrt{2}}\cdot\left[\sqrt{\Omega_1^4 + \Omega_2^4} - \Omega_1^2\right]^{1/2} \qquad (18)$$

$$\omega_1 = x - \frac{\alpha}{2} + i(y - \beta/2);\quad \omega_2 = -(x + \alpha/2) - i(y + \beta/2)$$

From (18) it is visible, that at $\beta > 0$ a root ω_2 corresponds to fading wave in a crystal $\left(n'_{\pm}, E'\right) \sim e^{-i\omega t} \sim e^{-i\left(\omega_2^0 + i\gamma\right)t} \sim e^{\gamma t}\cos\left(\omega_2^0 t + \psi\right)$ because $\omega_2 = \omega_2^0 + i\gamma;\ \gamma < 0$. From expression β it is easily visible, as $\beta < 0$ and $\beta/2 > y$ it is impossible. The wave ω_1 with frequency of $\omega_1^0 = x - \alpha/2$ and with increment of $\gamma = y - \beta/2$ at $y > \beta/2$ is accruing.

Substituting values of y and $\beta/2$ it is easy to check up a condition $y > \beta/2$. i.e.

$$\theta^4 + \beta^2\Omega^2 > \alpha\beta\theta^2. \qquad (19)$$

From obvious expressions of $\alpha, \beta, \Omega, \theta$ it is visible, that check the condition (19) is too bulky, and consequently we will consider following experimentally carried out cases

$$\nu_{\pm} > D_{\pm}k^2;\quad \vartheta_-\vartheta_+ > \left(\nu_+ D_+, \nu_- D_-\right);\quad D_- >> D_+$$

$$\beta_-^{\gamma} = \frac{\sigma^{\mu}}{\sigma_-} >> 1,\quad \beta_+^{\gamma} = \frac{n_+}{n_{1+}} \cdot \frac{\sigma^{\mu}}{\sigma_+} >> 1. \qquad (20)$$

At performance of a condition (20) we will receive

$$\Omega^2 = \nu_-\nu_+,\quad \theta^4 = \left(2\vec{k}\vec{\vartheta}_-\nu_+\right)^2\left(1 + \frac{a+b}{2}\cdot\frac{\nu_-}{k\vartheta_-}\right)^2 \qquad (21)$$

$$\alpha = k\vartheta_-\left(1 + \frac{b\nu_+}{k\vartheta_-} + \frac{a\nu_-}{k\vartheta_-}\right);$$

$$\beta^2 = \left(2\nu_+\right)^2\left(1 + \frac{D_- k^2}{2\nu_+}\right)^2$$

Substituting of (21) in (19) with the account of (20) we will receive a condition occurrence of accruing waves (i.e. instability of a wave)

$$\nu_- > 2\nu_+ \qquad (22)$$

When frequency of capture of electrons to become twice more than frequency of capture of holes in a crystal extends an unstable wave with frequency of $\omega_0 = x - \dfrac{\alpha}{2}$ and with increment of $\gamma = y - \beta/2$. Frequency ω_0 and increment waves corresponds to certain value of external electric field

$$E_0^2 >> \frac{\nu_- D_-}{\mu_-\mu_+}; \qquad (23)$$

Substituting values of y and β in ω_0 also γ we will easily receive

$$\omega_0 = \left(k\vartheta_-\nu_+\right)^{1/2};\quad \gamma = \nu_+\left(\frac{4}{\sqrt{2}} - 1\right) \qquad (24)$$

From (24) it is visible, as $\dfrac{\gamma}{\omega_0} \approx 2\left(\dfrac{\nu_+}{k\vartheta_-}\right)^{1/2}$ in force of (23) $\gamma << \omega_0$.

Thus, when external electric field reaches to value (23) in specified intrinsic semiconductor because of capture of electrons and holes by the intrinsic centers arises the recombination wave with certain frequency. Increment it is much less than this wave, than frequency of a wave. Thus frequency of capture of electrons twice more than frequency of capture of holes.

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