SURFACE PHOTOCONDUCTIVITY IN A MULTIVALLEY SEMICONDUCTOR

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Кўп воҳали яримчексиз яримўтказгичнинг сирт фотоўтказувчанлиги ҳисобланган. Бунда ток ташувчиларнинг сиртдан кўзгули сочилиши эътиборга олинган бўлиб, Больцманнинг кинетик тенгламасига кўра ҳисобланган

***Калит сўзлар**: сирт фотоўтказувчанлиги, кўп воҳали яримўтказгич, сиртда сочилиш, электрон, сирт, Больцманнинг кинетик тенгламаси.*

Рассчитана поверхностная фотопроводимость многодолинного полубесконечного полупроводника. Расчет проведен при зеркальном рассеянии электронов о поверхность в приближении кинетического уравнения Больцмана.

***Ключевые слова**: поверхностная фотопроводимость, многодолинный полупроводник, зеркальное отражение, электрон, поверхность, кинетическое уравнение Больцмана.*

The surface photoconductivity in a semi-infinite multivalley semiconductor has been theoretically researched. The calculation has been carried out by mirror reflection of electrons o'er the surface in the approximation of the Boltzmann kinetic equation.

***Key words:** the surface photoconductivity, multivalley semiconductor, mirror reflection, electron, the surface, the Boltzmann kinetic equation.*

Problems of the surface today are, one of the most interests of physicists. From a purely physical point of view, the study of the surface is fundamentally important. The surface is a two-dimensional system, and not only its structure, but also many of the phenomena look on it quite differently from the volume. In essence, the surface of a solid and its «interior» are two different forms of the same substance. Therefore, surface physics has become a new field of science on the structure of matter in a condensed state.

Below we theoretically research the surface photoconductivity in a semi-infinite multivalley semiconductor. It is calculated by mirror reflection of electrons about the surface in the approximation of the Boltzmann kinetic equation.

For convenience of further calculations, we choose the following geometry of the problem. By directing the x axis in the plane zz' (z' directed along the main axis of the ellipsoidal isoenergetic surface), and the axis y is normal to this plane, we write the energy spectrum in the form $\mathrm{E}=\sum_{\alpha,\beta} A_{\alpha\beta}\, v_\alpha\, v_\beta$ or $\mathrm{E}=\sum_{\alpha,\beta} B_{\alpha\beta}\, p_\alpha\, p_\beta$, where p_i and $v_i = \partial E / p_i$ are the *i*-components of momentum and velocity, respectively.

Now let us discuss about the electron distribution function, with which the photocurrent is determined. Suppose that a light wave with frequency *w* is incident on a semiconductor plate with width $d\ (-d/2 \le z \le +d/2)$ perpendicular to the surface $z=+d/2$, and an electric field with a strength $\vec{\varepsilon} = 2\times \mathrm{Re}\,\vec{\varepsilon}\exp(-i\omega t)$ on the current carriers and a constant external magnetic field with a strength $\vec{H}$, where the z axis is directed along the inner normal to the surface $z=+d/2$, according to which, we assume that the electromagnetic wave propagates.

The nonequilibrium electron distribution function *f* satisfies the kinetic equation

$$\frac{\partial f}{\partial t} + \vec{v}\vec{\nabla}_{\vec{r}} f - e\left(\vec{\varepsilon} + \left(\vec{v}\times\vec{H}\right)\right)\vec{\nabla}_{\vec{p}} f = -\frac{f - f_0}{\tau}, \qquad (1)$$

which is solved in the t-approximation (t is the momentum relaxation time) by the iteration method, where it is impossible to expand $f(\vec{r}, t)$ over the spherical functions by the parameter $l/\left|\vec{\nabla} f / t\right|$, because in the near-surface region *f* varies on the length (or *l/wt)*), where lis the mean free path of an electron, w is the frequency of the exciting light. For this reason we write the collision integral as $-(f - f_0)/\tau$, where f_0 is the equilibrium distribution function of the electrons.

In the following we consider two mechanisms for the scattering of current carriers on a surface: mirror reflection (MR) and diffuse scattering (DS) with which the boundary conditions for the distribution function are determined. We assume that the energy spectrum of the carriers is spherical. Then for MR the tangential components of the momentum are conserved, and the normal component changes sign.

We will also take into account the spatial dependence of the electric field of the light wave, and also take into account that in semiconductors of cubic symmetry $\varepsilon_z = 0$.

To calculate the nonlinear electric field of the electromagnetic wave of photoconductivity ($\chi_{\alpha\beta\delta}$ and $\gamma_{\alpha\beta}$, where $\alpha,\beta,\delta = x,y,z$) a semi-infinite multivalued semiconductor, we will use the energy spectrum $\mathrm{E} = \sum_{\alpha,\beta} B_{\alpha\beta}\, p_\alpha\, p_\beta$ and the calculation method proposed in [2]. Further, we will use that when the mirror is reflected from the boundary of the surface of the semiconductor pate, we have $p_{y_2} = p_{y_1}$, $p_{x_2} = p_{x_1}$. And the interrelation of quantities p_{z_2} and p_{z_1} is determined from the law of conservation of energy, from which we have $p_{z2} + p_{z1} = -\frac{2\overline{D}}{\overline{A}} p_{x1} = \frac{2D}{B} p_{x1}$ or $p_{z2} = -p_{z1} + \frac{2D}{B} p_{x1}$.

If we take into account that $V_y = \frac{\partial E}{\partial p_y} = 2\overline{A}\left(p_x - \frac{D}{B} p_z\right)$. Then

$V_{x1} = 2\overline{B}\left(p_{x1} - \frac{D}{A} p_{z1}\right)$, $V_{x2} = V_{x1} + 2\frac{D}{B} V_{z1}$ or $V_{x2} = V_{x1} + 2\frac{D}{B} V_{z1}$, also $p_{x2} = p_{x1}$,

$p_{z2} = p_{z1} + 2\eta p_{x1}, V_{x2} = V_{x1} + 2\eta V_{z1}, V_{z2} = -V_{z1}$, also $\eta = \frac{D}{B} = \frac{m_{xz}}{m_{xx}}$.

Consequently, on the semiconductor surface for the distribution functions $f_-\left(V_x, V_y, V_z \langle 0\right)$ corresponding to the current carriers coming to the surface and $f_+\left(V_x, V_y, V_z \rangle 0\right)$ corresponding to the current carriers coming from the surface of the sample, we have

$$\begin{aligned} f_-\left(V_x, V_y, V_z; z=0\right) &= f_+\left(V_x + 2\eta V_z, V_y, -V_z; z=0\right), \\ f_+\left(V_x, V_y, V_z; z=0\right) &= f_-\left(V_x + 2\eta V_z, V_y, -V_z; z=0\right). \end{aligned} \tag{2}$$

We will immediately assume that the electromagnetic field is transverse, i.e. $\vec{\varepsilon} = \vec{\varepsilon}(z)$ and the components ε_x, ε_y are nonzero. The solution of the kinetic equation for $f_{11} = f_1(z;t)$ will beas

$$f_1 = f_1(z;t) = f_1(z) \times \exp(i\omega t) \tag{3}$$

Then

$$-i\omega f_1 + V_z \frac{\partial f_1}{\partial z} - e\left(\vec{\varepsilon}\cdot\vec{V}\right)\frac{\partial f_0}{\partial E} = -\frac{f_1}{\tau} \tag{4}$$

Here for the electron $e = |e|$, $\vec{F} = -e\vec{\varepsilon}$.

We seek the solution of the Boltzmann equation in the form

$$f_1(z) = e^{-\frac{\gamma z}{V_z}}\left[C_1 - \frac{e}{V_z}\int_z^\infty e^{-\frac{\gamma z'}{V_z}}\left(\vec{\varepsilon}\cdot\vec{V}\right)\frac{\partial f_0}{\partial E}\,dz'\right] \tag{5}$$

Then

$$f_1(z) = C_1 e^{-\frac{\gamma z}{V_z}} + \frac{e}{\gamma}\left(\vec{\varepsilon}\cdot\vec{V}\right)\frac{\partial f_0}{\partial E} = C_1 e^{-\frac{\gamma z}{V_z}} + \frac{ie}{\omega}\left(1 - \frac{i}{\omega\tau}\right)\left(\vec{\varepsilon}\cdot\vec{V}\right)\frac{\partial f_0}{\partial E} \tag{6}$$

Since $V_z \langle 0$ the distribution function $f_-\left(V_x, V_y, V_z; z\to\infty\right) = 0$, then $C_{1^-} = 0$

$$f_{1^-}(z) = \frac{ie}{\omega}\left(\vec{\varepsilon}\cdot\vec{V}\right)\frac{\partial f_0}{\partial E}\left(1 - \frac{i}{\omega\tau}\right) \Rightarrow \frac{e}{\gamma}\left(\vec{\varepsilon}\cdot\vec{V}\right)\frac{\partial f_0}{\partial E} \tag{7}$$

Then from condition (2) we find that for diffuse scattering (at $z = 0$)

$$f_{1^-} = \frac{ie}{\omega}\left(\vec{\varepsilon}\cdot\vec{V}\right)\frac{\partial f_0}{\partial E}\left(1-\frac{i}{\omega\tau}\right) = \frac{ie}{\omega}\left[\frac{\varepsilon_x b\sin\theta\sin\varphi}{\left(1+\delta\sin(2\varphi)\right)^{1/2}} + \varepsilon_y c\cos\theta\right]\times\frac{\partial f_0}{\partial E}\left(1-\frac{i}{\omega\tau}\right)\sqrt{E} \qquad (8)$$

The same way

$$f_{1^+}(E) = \frac{ie}{\omega}\frac{\partial f_0}{\partial E}\left(1-\frac{i}{\omega\tau}\right)\left[\left(\vec{\varepsilon}\vec{V}\right)\left(1-e^{-\frac{\gamma z}{V_z}}\right)+\frac{2}{3}\frac{\delta}{\left(1-\delta^2\right)^{1/2}}b\varepsilon_x\sqrt{E}e^{-\frac{\gamma z}{V_z}}\right] \qquad (9)$$

The photoconductivity tensor is $\chi_{\alpha\beta\delta}$ determined by solving the Boltzmann kinetic equation [2]. In particular, for a semi-infinite multivalley semiconductor, the solution of the Boltzmann equation in the first in the electric field strength of an electromagnetic wave has the form

$$f_{1+}(z) = \frac{ie}{\omega}\frac{\partial f_0}{\partial E}\left(1-\frac{i}{\omega\tau}\right)\left[\left(2\eta\varepsilon_x V_z\exp(-\gamma z/V_z)+\vec{\varepsilon}\cdot\vec{V}\right)\right] \qquad (10)$$

for mirror reflection,

$$f_{1+}(z) = \frac{ie}{\omega}\frac{\partial f_0}{\partial E}\left(1-\frac{i}{\omega\tau}\right)\times\left[\left(\vec{\varepsilon}\cdot\vec{V}\left(1-\exp(-\gamma z/V_z)\right)\right)+\frac{2}{3}\frac{\delta}{\left(1-\delta^2\right)^{\frac{1}{2}}}\varepsilon_x b\sqrt{E}\exp(-\gamma z/V_z)\right] \qquad (11)$$

for diffuse reflection of electrons about a surface.

The Boltzmann equation for the next iteration of the distribution function can be easily obtained in the form

$$f_{2^+}(0) = f_{2^-}(0) + 8\frac{e^2}{\omega^2}\eta\left\{\varepsilon_x\varepsilon_\alpha^*\left[\begin{array}{l} V_\alpha V_z\left(\dfrac{\partial^2 f_0}{\partial E^2}-\dfrac{\partial f_0}{\partial E}\dfrac{\partial\ln\tau}{\partial\ln E}\right)+ \\ +\eta\left|\varepsilon_x\right|^2 V_z^2\left(\dfrac{\partial^2 f_0}{\partial E^2}-\dfrac{\partial f_0}{\partial E}\dfrac{\partial\ln\tau}{\partial\ln E}\right)\end{array}\right]\right\} \qquad (12)$$

$F_{20}(z) = -e\left(\vec{\varepsilon}_0\vec{\upsilon}\right)\dfrac{\partial f_0}{\partial E} = -e\varepsilon_0\vartheta_z\dfrac{\partial f_0}{\partial E}$ with using of which it is possible to determine the kinetic parameters, in particular the photoconductivity, of the sample, where

$$F_{20}(z) = -e\left(\vec{\varepsilon}_0\vec{\upsilon}\right)\frac{\partial f_0}{\partial E} = -e\varepsilon_0\vartheta_z\frac{\partial f_0}{\partial E}.$$

It is not difficult to see that in order to determine the components of the tensor $\chi_{\alpha\beta\delta}$ and $\gamma_{\alpha\beta}$ for a semi-infinite multivalued semiconductor, we must calculate the following integral

$$\Im = -e\int_0^\infty dz\int d^3V\, f(V)V_\alpha = -eN\frac{\int_0^\infty dz\int d^3V\, f(V)V_\alpha}{\int d^3V\, f_0(V)}$$

or, in the case we are considering,

$$\Im = -eN\frac{\int_{V_z\rangle 0}^{\infty} C_2\tau V_z V_\alpha d^3V}{\int d^3V\, f_0(V)} = -\frac{3}{4\pi}\frac{\left(m_{\text{II}}m_\perp^2\right)^{1/2}}{\left(2E_F\right)^{3/2}}eN\int_{V_z\rangle 0}^{\infty} C_2\tau V_z V_\alpha d^3V.$$

$$\int f_0(V)d^3V = -\frac{3}{4\pi}\frac{\left(2E_F\right)^{3/2}}{\left(m_{II}m_{\perp}^2\right)^{1/2}} = -\frac{8\sqrt{2}}{3}\frac{1}{\left(m_{II}m_{\perp}m_{\perp}\right)^{1/2}}\int\frac{\partial f_0}{\partial E}E^{3/2}dE.$$

Then we have the following relations for the component of the tensor $\chi_{\alpha\beta\delta}$

$$\chi_{\alpha xx} = -\frac{3}{\pi}\frac{\left(m_{II}m_{\perp}^2\right)^{1/2}}{\left(2E_F\right)^{3/2}}e\frac{e^2}{\omega^2}N\eta\frac{1}{2}abc\int\limits_{\cos\varphi\rangle 0}^{\infty}\frac{\sqrt{E}dE}{1+\delta\sin 2\varphi}\sin\theta\,d\theta\,d\varphi\times$$

$$\chi_{\alpha xy} = -\frac{3}{\pi}\frac{\left(m_{II}m_{\perp}^2\right)^{1/2}}{\left(2E_F\right)^{3/2}}e\frac{e^2}{\omega^2}N\eta\frac{1}{2}abc\int\limits_{\cos\varphi\rangle 0}^{\infty}\frac{\sqrt{E}dE}{1+\delta\sin 2\phi}\sin\theta\,d\theta\,d\varphi\times$$

$$\times V_\alpha V_z\tau\left\{\left(\frac{\partial^2 f_0}{\partial E^2}-\frac{\partial f_0}{\partial E}\frac{\partial\ln\tau}{\partial\ln E}\right)V_y V\right\}.$$

We consider it appropriate to cestrict these results, because of the lack of experimental results of the spectral dependences on photoconductivity, wich is quadratic in $\vec{\varepsilon}=\left(\varepsilon_x,\varepsilon_y,\varepsilon_z\right)$ of semi-infinite many-valley semiconductor.

Thus, the theory of the photoconductivity of a multivalley semiconductor due to the scattering of current carriers on the crystal surface and dependent on the degree of polarization of light is developed. It is noted that: a) in the spherical approximation of the energy spectrum, in the sense of mutual compensation of the fluxes of electrons moving to and from the surface, the surfaces themselves are not really distinguished in any way; b) in the case of an ellipsoidal surface, the mutual compensation of the fluxes of electrons moving to and from the surface, both in mirror reflection and in diffuse scattering, depends on the spatial variation of the distribution function and the creation of a normal electric field.

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