Studying Physical Processes in Crystals without Inversion Centre

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Abstract - **The paper theoretically investigates the photogalvanic effect in optic transitions between spin subzones of Landau levels within an ultraquantum limit. A geometry is considered when polarization is perpendicular and the electric current is directed along the magnetic field. The effect is caused by cubic terms in the Hamiltonian function, which exist due to the absence of an inversion center. The considered magnetic field relation is of resonance character, the said relation having both odd and even field contributions. Such an effect character is related to the resonance in the intermediate state and interference of second order transition amplitudes in relativistic contributions in the Hamiltonian function.**

Key words: **photogalvanic effect, optic transitions, magnetic field, inversion center, polarization, relativistic contributions, Hamiltonian function, resonance.**

INTRODUCTION

The paper compares theory with experiment. Since the publication of the work by Blokh M.D. and Magarill L.I. [1], the phenomenon of combined resonance (light absorption at the expense of the electric component of an electromagnetic wave that is conditioned by electronic transitions with a spin flip) has remained in the sphere of solid-state physics interests. Thus, the phenomenon of interference of magnetic dipole and electric dipole resonances in the Vogt configuration in crystals without an inversion center has been found and studied. The research of the photo-galvanic effect (PGVE) has been of particular interest in this case as both light absorption and PGVE are defined by the non-center inversion state of a medium. The dependence on light polarization and crystal orientation helps to single it out among other photoelectric effects. The PGVE in a magnetic field was studied in a number of works [2-4], but the case of quantizing a field has not been considered prior to our paper. The aim of the paper is to investigate the PGVE within spin resonance as well as construction of mathematical model for calculating zone parameters, as the same components in the Hamiltonian can result both electric dipole transitions and PGVE current. The problems which are solved in the paper describe observed polarization relations in the considered magnetic field orientations related to crystallographic directions. The comparison of theoretical and experimental values of signals for an even resonance contribution to the PGVE allows to determine the parameters. The values of these parameters are in good agreement with their values calculated in Kane's model. The theoretical value of the contribution that is odd in Δ is almost by three orders of magnitude greater than the experimentally observed one. Partially it may be due to the fact that the nonuniformity of the magnetic field in the volume, occupied by a sample leads to the suppression of alternating signal and has a slight effect on the value of constant sign contribution. Other contributions are possible which are not taken into account by theory and which describe a peak, even in Δ. The impurity pairs shown in Fig. 1 behave almost in the same way as the peak of spin resonance on free carriers does. Therefore free electrons emerge at the expense of auto ionization processes in such transitions.

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I. DISTRIBUTION OF ELECTRIC CURRENT

We will consider an electric current flowing along the direction of a magnetic field H at propagation of light along the same direction (Faraday geometry). Light polarization and orientation H with respect to crystallographic axes are considered random. Assume that the conditions are fulfilled which conform to the superquantum limit: $\omega_s >> T$; $\omega > E_F$ where $\omega_s = |q|\mu_B H$ is the energy of a spin transition, E_F is the Fermi level calculated from the lower spin subzone, μ_B is Bohr's magneton, $\hbar = 1$. $A_0, A(t) = \operatorname{Re} Ae^{-i\omega t}$ are the vector potentials of a magnetostatic homogeneous field and electromagnetic wave, respectively [4].

$$U(r) = \sum_i u(r - r_i) \qquad (1)$$

is the potential energy of an interaction of electrons with chaotically distributed impurities (r_i is a coordinate of r-th impurity center).

The Hamiltonian function of the considered system has the form

$$H = H_0 + H_1 + H_2 + H_U + U + F, \qquad (2)$$

where H_0 is the Hamiltonian of a free electron in a parabolic approximation

$$\begin{cases} H_0 = \dfrac{k^2}{2m} + \dfrac{1}{2} q \mu_B H_i \sigma_i; \\ k = p + \dfrac{e}{c} A_0. \end{cases} \qquad (3)$$

The components H_1, H_2, H_U correspond to three possible mechanisms with a spin flip [5]. The component $H_1 = \delta_0 \sigma \Phi \Omega$ is related with the absence of the center of inversion in the main axes of the crystal

$$\begin{cases} \Omega_1 = k_2 k_1 k_2 - k_3 k_1 k_3; \\ \Omega_2 = k_3 k_2 k_3 - k_1 k_2 k_1; \\ \Omega_3 = k_1 k_3 k_1 - k_2 k_3 k_2. \end{cases}$$

$$H_2 = \bar{q} \mu_B \{(Hk)(\sigma k) + (\sigma k)(Hk)\}, \qquad (4)$$

with the function of *q*-factor of a pulse,
and the component

$$H_U = \alpha_s ([\nabla U, k]\sigma) \qquad (5)$$

is a spin-orbital interaction of an electron with impurities. The terms in the Hamiltonian denoted by the letter *F* define the interaction of electrons with an electromagnetic wave, at that

$$F = F_0 + F_1 + F_2 + F_3 + F_U, \qquad (6)$$

where
$$\begin{cases} F_0 = \dfrac{e}{mc}(kA); \\ F_1 = i\dfrac{e\delta_0}{c}(\sigma\Omega) rA; \\ F_2 = 2q\dfrac{e}{c}\mu_B (\sigma A) Hk; \\ F_U = \alpha_s \dfrac{e}{c}(\sigma[\nabla U A]). \end{cases} \qquad (7)$$

II. Function of a longitudinal pulse

The existence of a current along the field *H* direction requires the probability imparity of a transition as the function of a longitudinal pulse p_z. We will stem from the solution of the quantum kinetic equation of the form [6]

$$If_i + G_a = 0, \qquad (8)$$

where *f* is an addition to the equilibrium distribution function, I is an integral of collisions of an electron with impurities, G_a is the generation probability, *i* is a set of quantum numbers characteristic of the eigenstates of the Hamiltonian function H_0 in the range of A_0, *p* is an electron pulse, *n* is the level number, $\sigma = \pm 1$ (we will use the signs + and – to denote a projected spin). As we are interested in electron transitions within the Landau level *n*=0, we will omit this index in all the quantities. The part of the distribution function that is potentially odd in pulse and that makes an attribute to the current can appear as a result of the oddness of the function of generalization and scattering probability (Figure). When neglecting the interaction with impurities in perturbation theory the asymmetric part of a transition probability can occur due to the interference of contributions F_1 and F_2

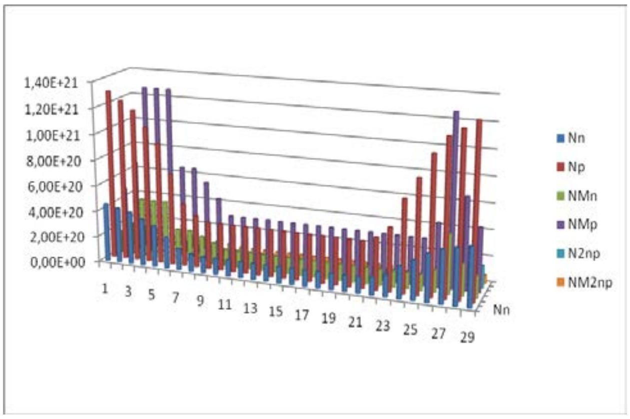
$$\omega^{(1)}_{i\beta} = \frac{\pi}{2} \mathrm{Re}\left[(F_1)_{\beta i} (F_2)_{\beta i}\right], \qquad (9)$$

where $i = p,+, \beta = p',-$,

$$(F_1)_{\beta i} = \frac{\sqrt{2} e E_0 \delta_0}{i\omega a^2} e_B (a^2 p_z^2 - 1/2)\delta_{pp'}. \qquad (10)$$

Here E_o is the field amplitude of an electromagnetic wave, *e* is a polarization vector, $a = \sqrt{c\hbar / eH}$ is the function of the direction of a magnetic field with reference to crystallographic axes located in the coefficients B_{ijk} (Φ is an azimuth, Θ is polar angles).

$$\begin{cases} B_{133} = \cos 2\Phi \cos 2\Theta - i/2 \sin 2\Phi \cos\Theta (3\cos^2\Theta - 1); \\ B_{233} = -3i/2 \sin 2\Phi \sin\Theta \sin 2\Theta; \\ e_B = e_- B_{133} + e_+ B_{233}. \end{cases}$$



Calculation of distribution of concentration of carriers of charge n and p type on X coordinate in *GaAs* at flowing a current 0,1 A and action of a 1 T magnetic field

III. Oddnesses of scattering probability function

The paper analyzes the components arising thanks to the oddness of the scattering probability in pulse at the availability of impurities. It was found that in the superquantum limit, unlike the case of the absence of a magnetic field, these components do not result in a photovoltaic effect. Besides, there is no oddness of generation function in the parabolic approximation for the spectrum of electrons. Taking into account the nonparabolic spectrum character we have calculated the space distribution of the current density [7].

$$j_z^{(1)} = -\frac{e^3\delta_0\tilde{q}\,\omega_B^2 E_0^2 m}{\pi a^4 |q| \varepsilon_q \omega^2}\int dp_z f_{pz}^{(0)} + \frac{\partial}{\partial m}(\tau_{p_z}, +\upsilon_{pz}^z)\times$$
$$\times\, p_z(a^2 p_z^2 - 1/2)\,P\delta_\eta(\Delta). \qquad (11)$$

Here $P = \mathrm{Re}(e_- e_+ B_{133})$, $\delta_\eta(\Delta) = \eta/\pi(\Delta^2 + \eta^2)$ is the delta - function that is fuzzy in the extension $\Delta = \omega - \omega_s$ of resonance components.

$$j_z^{(2)} + j_z^{(3)} = -\frac{4\pi\alpha_s e^3 n(\varepsilon)}{\alpha^2\omega^2}E_0^2\left(\delta_\eta(\Delta) - \frac{\tilde{q}\,\omega_s}{\alpha_s|q|}\delta'_\eta(\Delta)\right)P'. \qquad (12)$$

Besides the considered contribution to the current there may be components depending on the interaction of electrons and impurities, the spin of electrons changing.

Conclusion

The scientific novelty of the paper consists in modelling of PGVE shown on spin transitions in *GaAs*. The analysis of calculations has shown that the distribution of electric current density does not depend on the angle between the vector of linear polarization and crystallographic directions. A conclusion has been made in the paper that at the opposite directions of the light wave vector PGVE does not depend on the sign of the radiation wave vector. A symmetric combination of signals at the opposite light distribution is considered. The practical significance of the work lies in the obtained parameters that are dependent on a circular polarization magnetic field. The change of the sign of the magnetic field does not influence the value of the parameters.

References

[1] Blokh M.D., Magarill L.I. "Theory of photogalvanic effect on free carriers" // PTG, vol. 22, №8, 1980, pp. 2279-2284. (in Russian)

[2] Chernyshov N.N. "Theory of transfer phenomena in an electric field for crystals without an inversion centre"// Physical surface engineering, vol. 10, №1, NPTC, Kharkov, 2012, pp. 96-101. (in Russian)

[3] Chernyshov N.N. "Photogalvanic effect in crystals without a centre of inversion in view of electron-hole interaction"/All- Ukrainian collected volume // Radiotechnika, № 177, KhNURE, 2014, pp. 94-97. (in Russian)

[4] Dember H., "Über einer photoelectromotorische kraft in Kupferoxydul – kristallen" // Phys. Zeit, vol.32, № 14, 1931, pp.554 - 556.

[5] Dresselhaus G. "Spin-Orbit Coupling Effects in Zinc Blende Structures" // Phys. Rev., vol. 100, 1955, pp.580-586.

[6] Chernyshov N.N., Slipchenko N.I., Tsymbal A.M., Umyarov K.T, Lukianenko V.L. "The photogalvanic effect within spin resonance in quantizing magnetic field" // Physical surface engineering, vol. 11, №4, NPTC, Kharkov, 2013, pp. 427-430.

[7] Y.F. Chern, M. Dobrovolska, et al. "Interference of electric-dipole and magnetic-dipole interactions in conduction-electron-spin resonance in InSb" // Phys. Rev. B., vol. 32, 1985, pp. 890-902.

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