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THE PHOTOGALVANIC EFFECT WITHIN SPIN RESONANSE IN QUANTIZING MAGNETIC FIELD

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The paper theoretically investigates the photogalvanic effect in optic transitions between spin subzones of Landau levels within 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.
Keywords: photogalvanic effect, optic transitions, magnetic field, inversion center, polarization, relativistic contributions, Hamiltonian function, resonance.

ФОТОГАЛЬВАНИЧЕСКИЙ ЭФФЕКТ СПИНОВОГО РЕЗОНАНСА В КВАНТОВАННОМ МАГНИТНОМ ПОЛЕ

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В статье исследована теория фотогальванического эффекта в оптических переходах между спинами вокруг уровней Ландау в пределах ультраквантового предела. Рассматривается геометрия, когда поляризация перпендикулярна и электрический ток направлен вдоль магнитного поля. Эффект вызван в соответствии с кубическими членами в гамильтониане, которые существуют из-за отсутствия центра инверсии. Рассмотренное уравнение магнитного поля имеет характер резонанса и имеет два четных и нечетных полевых вклада. Такой характер эффекта связан с резонансом в промежуточном состоянии и использовании вторых амплитуд перехода порядка в релятивистских вкладах в гамильтониане.
Ключевые слова: фотогальванический эффект, оптические переходы, магнитное поле, центр инверсии, поляризация, релятивистские вклады, гамильтониан, резонанс.

ФОТОГАЛЬВАНІЧНИЙ ЕФЕКТ СПІНОВОГО РЕЗОНАНСУ В КВАНТОВАНОМУ МАГНІТНОМУ ПОЛІ

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У статті досліджена теорія фотогальванічного ефекту в оптичних переходах між спінами навколо рівнів Ландау в межах ультраквантової межі. Розглядається геометрія, коли поляризація перпендикулярна та електричний струм спрямований уздовж магнітного поля. Ефект викликаний відповідно до кубічних членів у гамільтоніані, які існують через відсутність центру інверсії. Розглянуте рівняння магнітного поля має характер резонансу та має два парні й непарні польові внески. Такий характер ефекту пов'язаний з резонансом у проміжному стані та використанні других амплітуд переходу порядку в релятивістських внесках у гамільтоніані.
Ключові слова: фотогальванічний ефект, оптичні переходи, магнітне поле, центр інверсії, поляризація, релятивістські внески, гамільтоніан, резонанс.

INTRODUCTION

The paper compares theory with experiment. Since the publication of the work by Rashbaand [1], the phenomenon of combined resonance (light absorption at the expense of the electric component of 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 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 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 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 solving 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 pears shown in Fig. 1 behave almost in the same way as the peak of spin resonance on free carriers does. According to the rules of choice only intracenter transitions between bound states are allowed. Therefore free electrons emerge at the expense of autoionization processes in such transitions.

DISTRIBUTION OF ELECTRIC CURRENT

We will consider an electric current flowing along the direction of a magnetic field H at spreading 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 confirm to the superquantum limit: $\omega_s >> T$; $\omega > E_F$ where $\omega_s = |q|\mu_B H$ – is energy of a spin transition, E_F – is the Fermi level counted from the lower spin subzone, q – q is – factor, μ_B – is Bohr's magneton, $\hbar = 1$. A_0, $A(t) = \mathrm{Re} Ae^{-i\omega t}$ – be vector potentials of a magnetostatic homogeneous field and electromagnetic wave, respectively

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

– is the potential energy of 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 [3 – 4]. 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

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

where

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

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. It is evident that it appears if the probability is calculated in an non-zero order defining the non-center inversion state. We will stem from of the quantum kinetic equation of the form the solution [5]

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

where f – is an addition to the equilibrium distrilention function, I – is an integral of collisions of an electron with impurities, G_α – is the generation probability, $i = (n, p, \sigma)$ – are a set of quantum numbers characteristic of the eigenstates of the Hamiltonian function H_0 in the gage of $A_0 = (0, Hx, 0)$, $p = (p_x, p_y)$ – 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 $n = 0$, in what follows we will omit this index in all the quantities.

The part of the distribution function that is potentially uneven in pulse and that makes an attribute to the current can appear as a result of the unevenness of the function of generalization and scattering probability. 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

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

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

$$\left(F_1\right)_{\beta_i} = \frac{\sqrt{2}eE_0\delta_0}{i\omega a^2}e_B\left(a^2p_z^2 - (1/2)\right)\delta_{pp'}. \qquad (10)$$

Here E_0 – is the field amplitude of an electromagnetic wave, e – is a polarization vector, $a = \sqrt{c\hbar / eH}$ – the function of the direction of a magnetic field with reference to crystallographic axes lie in the coefficients B_{ijk} (Φ – azimuth and Θ – polar angles with the axis (100))

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

ODDNESSES OF SCATTERING PROBABILITY FUNCTION

The paper analyzes the components arising thanks to the oddness of the scattering probability on the basis of impurities in pulse. It was found that in the superquantum limit, unlike the case of the absence of a magnetic field, these components do not result

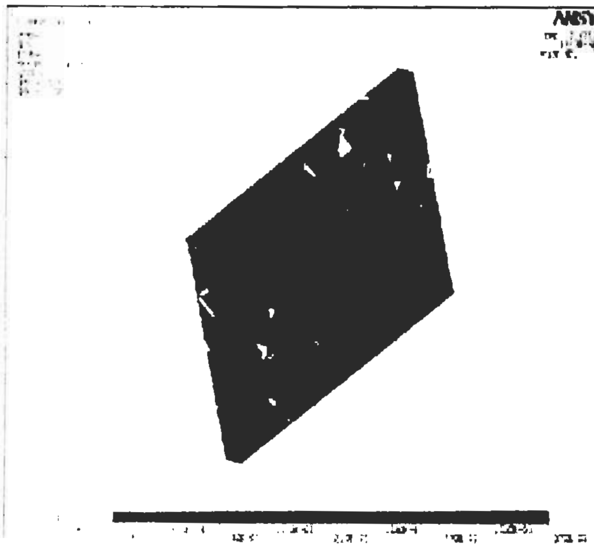

Fig. 1. Calculation of intensity of an electric field.

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 (fig. 2).

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

$$\times p_z(a^2p_z^2 - \tfrac{1}{2})P\delta_\eta(\Delta). \qquad (11)$$

Here $P = \mathrm{Re}(e_- e_+ B_{133})$, $\delta\eta(\Delta) = (\eta/\pi)(\Delta^2 + \eta^2)$ – is the δ-function that is fuzzy in extension $\Delta = \omega - \omega_s$ – resonance component [6].

$$j_z^{(2)} + j_z^{(3)} = -\frac{4\pi\alpha_s e^3 n(\varepsilon)}{\alpha^2\omega^2}E_0^2 \times$$

$$\times\left(\delta_\eta(\Delta) - \frac{\tilde{q}\omega_s}{\alpha_s |q|}\delta'_\eta(\Delta)\right)P'. \qquad (12)$$

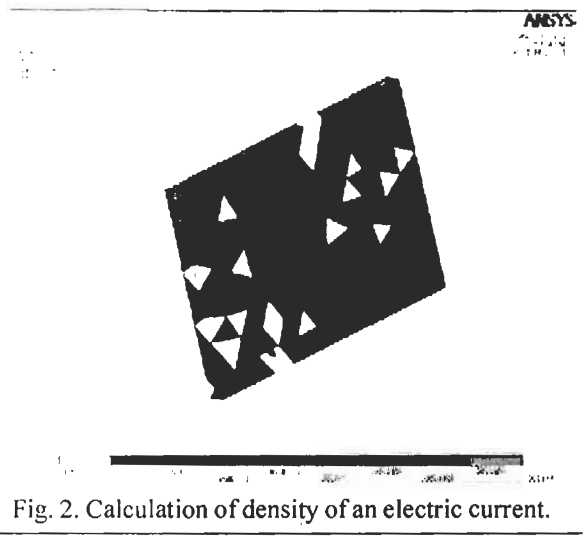

Fig. 2. Calculation of density of an electric current.

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 work consists in the model of photovoltaic and increasing effect showed on spin transitions in GaAs. The analysis of calculations showed that the distribution of electric current density does not depend on the angle between the vector of linear polarization and crystallographic directions. It was made a conclusion, that at the opposite directions of wave vector q light component photovoltaic effect does not depend on the sign of wave vector of the radiation. It was considered a symmetric combination of signals received at the opposite direction of light distribution. The practical significance of work consists in the obtained dependences of parameters of photovoltaic effect from magnetic field of circular polarizations. The change of the sign of the magnetic field does not influence the value of this parameter received from an even contribution to the orientations $H \parallel [001]$. It's possible to get the parameter value of the electromotive force for an odd contribution.

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