Quantum-interference resonant photocurrent in transitions between free-electron states

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The observation of a quantum-interference resonant photocurrent, a new phenomenon, was reported previously [A. P. Dmitriev *et al.*, JETP Lett. **49**, 584 (1989)]. In the present letter it is shown that this effect occurs not only during transitions between bound states of an electron but also during transitions of free electrons. This result is evidence that this phenomenon is of a fundamental nature. A quantitative theory is derived, and the results are compared with experiment.

The experiments were carried out in the region of spin-flip optical transitions in n-InSb. The experiments were carried out in the Faraday geometry on samples with a comparatively high electron density ($n_0 = 5.5\times10^{14}$ cm^{-3}). The light source was an optically pumped pulsed laser.[2] The wavelength was 90.6 μm, the pulse length 40 ns, and the intensity $I\sim 30$ W/cm^2. The light was circularly polarized. The fast component ($\sim$40-ns) of the longitudinal photocurrent, with respect to the light, was measured. The experimental geometry is shown in the inset in Fig. 1.

Figure 1 shows the photocurrent **j** as a function of the magnitude of the magnetic field **H** for the active and inactive polarizations of the light. In the inactive polarization (curve a), two resonances are seen in the photocurrent. Their positions along the magnetic field scale indicate that resonance A corresponds to $000^+ \to 000^-$ impurity spin transitions, while resonance B corresponds to $0^+ \to 0^-$ band-band spin transitions.[1,3] Each resonance has the following characteristic features. 1. The depth of the modulation of the background by the resonant signal can exceed 100%, although the corresponding transitions are nearly forbidden. 2. The wings of the resonance curves have a relatively gentle slope ($\sim 1/\delta H$, where $\delta H = H - H_{\rm res}$ is the deviation from resonance in terms of the magnetic field), while the absorption lineshape is Lorentzian.[3] 3. The effect is of odd parity in the photon wave vector $\vec{\kappa}$, it is even parity in **H**, and it does not occur in the active polarization of the light (curve b).

We had observed resonance A in Ref. 1., where it was shown that this feature stems from a quantum interference of optical transitions of an electron from an impurity into the band. In the present study we examined free-electron resonance B. At first glance, it might appear that this resonance is due to $0^+ \to 0^-$ direct interband transitions. This is not the case, however. In n-InSb, such transitions may be electric dipole transitions (as a result of the k^3 terms in the Hamiltonian) or magnetic dipole transitions. The first of these possibilities is ruled out, since the light was propagating along a principal axis of the crystal in our experiments.[4,5] The probability of a magnetic dipole transition, on the other hand, is very low, and estimates show that this transition could not by itself cause a significant component of the photocurrent.

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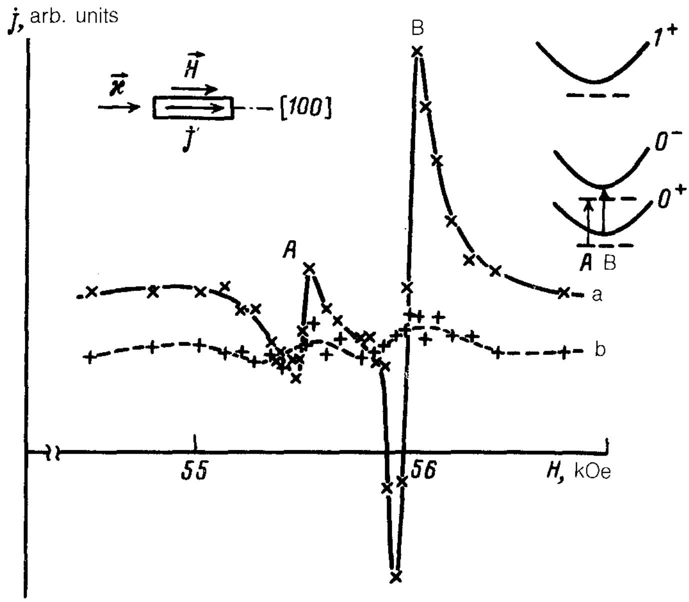

FIG. 1. The photocurrent as a function of the magnetic field. *a*—Inactive polarization of light; *b*—active polarization.

We believe that the band-band resonance, like the impurity resonance, is a consequence of a quantum interference of two optical transitions, one of which contains an intermediate resonance state. However, while the role of this state is played by the 000^- discrete level in the case of the impurity resonance, in the case of the band-band resonance it is played by a free-electron state in the 0^- band. Furthermore, the corresponding optical transitions are indirect, and they are accompanied by a simultaneous scattering of an electron by charged impurities.

One of these transitions is shown in Fig. 2(a). A Coulomb interaction with an impurity causes an electron to be scattered from the initial state 1 into the 0^+ band, into an intermediate state 4 in the 1^+ band, and then (through the absorption of a photon) into final state 3. The amplitude for such a transition, P, is equal to the product of the matrix element of the impurity potential, V_{41}, and the matrix element for the $4\rightarrow3$ optical transition, divided by the difference between the energies of the final and intermediate states:

$$P = -\frac{eE\hbar}{m^*\omega a_H}\,\frac{V_{41}}{\epsilon_{k'} - \epsilon_{k'-\kappa} - \hbar\omega_c - \hbar\omega}\,. \qquad (1)$$

Here E is the electric field of the wave in the crystal, m^* is the effective mass, ω is the light frequency, ω_c is the cyclotron frequency, a_H is the magnetic length, V_{41} is the impurity-potential matrix element between states 1 and 4, $\epsilon_{k'-\kappa}$ and $\epsilon_{k'}$ are the energies of the electron in the states 4 and 3, reckoned from the bottom of the 1^+ and 0^+

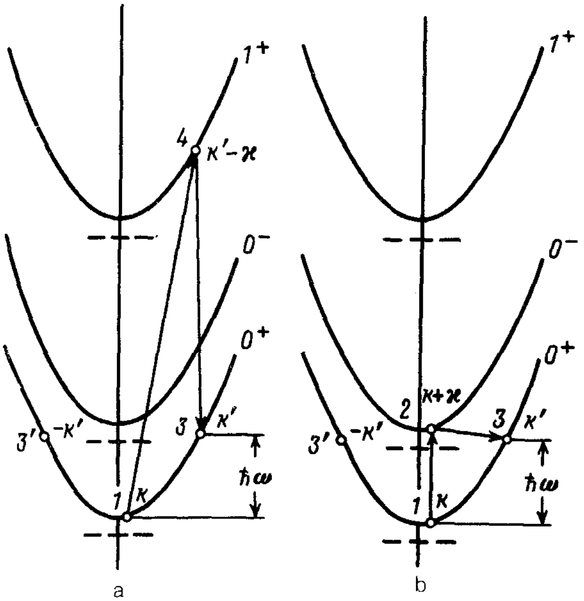

FIG. 2. Scheme of (a) electric dipole transitions and (b) magnetic dipole transitions from state 1 to state 3 induced by light of inactive polarization.

bands, respectively [the indices specify the longitudinal (with respect to **H**) momenta of the electron in states 4 and 3]. The denominator of this expression is obviously not resonant, since we have $\epsilon_{k'-\kappa} + \hbar\omega_c + \hbar\omega - \epsilon_{k'} \approx \hbar\omega_c + \hbar\omega$.

The second transition is shown in Fig. 2(b). This is a $1 \to 2$ magnetic-dipole transition, followed by a $2 \to 3$ transition due to spin-orbit scattering by an impurity. Its amplitude can be written

$$R = -\kappa \frac{\alpha k\,|g|\,\mu_B cE}{\omega \hbar^2 a_H} \frac{V_{23}}{\epsilon_{k'} - \epsilon_{k+\kappa} - \epsilon_S}; \qquad \alpha = \frac{\hbar^2 \Delta(2\epsilon_g + \Delta)p^2}{3m_0^2 \epsilon_g^2(\epsilon_g + \Delta)^2}, \qquad (2)$$

where $g \approx -50$ is the g-factor of an electron in InSb, μ_B is the Bohr magneton, ϵ_S is the Zeeman splitting of the zeroth Landau level, Δ is the spin-orbit splitting of the valence band, p is the interband matrix element of the momentum, and m_0 is the mass of a free electron. The denominator of this expression *is* resonant, since we have $\epsilon_{k'} - \epsilon_{k+k} - \epsilon_S \approx \hbar\omega - \epsilon_S$. Only those transitions which are caused by the interaction of an electron with the same impurity interfere, of course.[1)]

The total probability (W) for a transition from 1 to 3 is proportional to the square of the total transition amplitude $M = P + R$: $W \sim |P|^2 + |R|^2 + P^*R + PR^*$. Only the W component which is linear in κ is important in a calculation of the photocurrent. There is such a component in, first, $|P|^2$; it causes a background photocurrent. Second, the vector $\vec{\kappa}$ is proportional to the interference term (since $R \sim \kappa$) which corresponds to the resonant part of the photocurrent.

The expression for the probability for a transition of an electron from 1 to the point 3′, which is symmetric with respect to 3, is calculated in a corresponding way (Fig. 2).

The photocurrent j is proportional to the difference between W and W'. The interference terms $PR^* + P^*R$ and $P'R'^* + P'^*R$ are summed, since the amplitude R' differs from R in sign (because the spin-orbit operator is of odd parity in the electron momentum). Under the assumption that the momentum relaxation is a consequence of a scattering by impurities, we find the expression

$$j = en\frac{\kappa}{m}\frac{I}{I^*}(1 + \frac{H^*}{\delta H}) \qquad (3)$$

for the photocurrent, where n is the electron density in the 0^+ band, and I^* and H^* are quantities which depend on $\hbar\omega$, H_{res}, the temperature, and the band parameters of the crystal. Under the experimental conditions, these quantities have the values 6.2×10^5 W/cm^2 and 20 Oe, respectively. This expression gives a good description of the behavior outlined earlier. It is interesting to note that the photocurrent is independent of the impurity concentration N. The reason for this result is that the transition probability satisfies $W\sim N$, while the momentum relaxation time satisfies $\tau_p \sim N^{-1}$.

We note in conclusion that we have carried out a quantitative comparison of theory and experiment. It turns out that agreement can be reached by assuming that the number of electrons in the band is about 10% of the total density of electrons. This conclusion seems quite reasonable since the photoionization of the impurity is carried out by fairly intense light ($I\approx 30$ W/cm^2).

[1)] In our first study,[1] it was asserted on the basis of some estimates that a $000^+ \to 0^+$ transition, with a simultaneous resonant scattering by the 000^- level, was one of the interfering transitions in the case of the impurity resonance. An exact calculation has shown, however, that again in this case the dominant transition is the $000^+ \to 000^-$ magnetic-dipole transition, followed by a decay of the 000^- state into the 0^+ band.

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[4]É. I. Rashba and V. I. Sheka, Fiz. Tverd. Tela (Leningrad) **3**, 1735 (1961) [Sov. Phys. Solid State **3**, 1257 (1961)].
[5]G. F. Chen *et al.*, Phys. Rev. B **32**, 890 (1985).

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