Interference resonant photocurrent in semiconductors

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An interference resonant photocurrent has been observed in a semiconductor for the first time. The effect was observed in *n*-InSb in the region of an extrinsic spin resonance in a quantizing magnetic field. The direction of the current depends on the direction in which the frequency of the light deviates from the resonant frequency and also on the light propagation direction. A theory is proposed for the effect.

The experiments were carried out in the Faraday geometry on samples of pure *n*-InSb [$n = 6\times10^{13}$ cm, $\mu = 7\times10^5$ cm^2/(V·s)] at $T = 2$ K. An optically pumped pulsed NH$_3$ laser was used. The output wavelength was $\lambda = 90.55$ μm, and the pulse length was $\tau_p = 40$ ns. The intensity of the unpolarized light incident on the sample was 100 W/cm^2. A photocurrent was observed to arise in the longitudinal direction with respect to the magnetic field. The magnitude of this current was measured as a function of the strength of the magnetic field H in the region of spin-flip optical transitions.

The results are shown by curve a in Fig. 1. Note the two clearly defined resonances (A and B). The same resonances were observed in the photoconductivity. To identify these resonances, we measured the photoconductivity of the sample with various voltages across it (curves b and c in Fig. 1). We see that at voltages above the impurity breakdown threshold the second resonance increases sharply, while the first decreases. It can be concluded from this behavior that resonance A corresponds to transitions from an impurity level, while resonance B corresponds to transitions of free electrons. This conclusion is supported by the data of Refs. 1 and 2, in which the same resonances ($000^+ \to 000^-$ and $0^+ \to 0^-$) were observed in the absorption and photoconductivity. A result which is surprising from our point of view is the existence of a resonant photocurrent associated with transitions between impurity levels. We will restrict the discussion in the present letter to this resonance.

It can be seen from curve a in Fig. 1 that this is a bipolar resonance with a modulation depth comparable to the background signal. The distance between the current minimum and the current maximum along the H scale is extremely small in comparison with the width of the wings. On the other hand, the resonant curves of the photoconductivity (curves b and c in Fig. 1) and in the absorption[1] have a Lorentzian shape. To determine the nature of the effect, it is important to note two experimental facts. First, the kinetics of the photocurrent reproduces that of the laser pulse ($\tau_p = 40$ ns), while the duration of the photoconductivity signal, which is determined by the energy relaxation time, is greater than 100 ns. These results mean that the current observed here could not have been a consequence of various photogradient

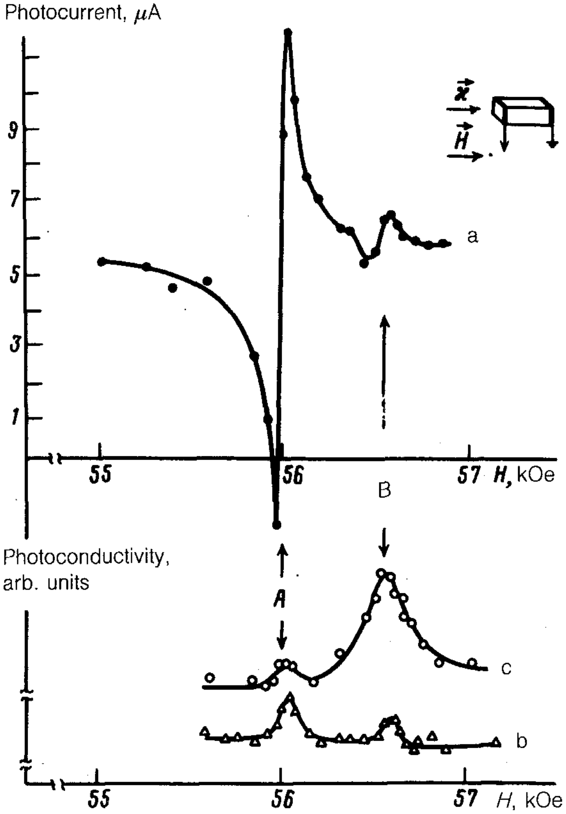

FIG. 1. a—Photocurrent versus the magnetic field H; b,c—photoconductivity versus H at voltages of 0.1 and 4 V/cm, respectively, across the sample.

effects (Ref. 3, for example). Second, the photocurrent is of odd parity in the wave vector of the light and of even parity in **H**. It thus could not be a consequence of a photovoltaic effect.[4]

We would like to suggest a mechanism for the occurrence of this photocurrent. Under the experimental conditions, most of the electrons are in a bound state in the 000^+ level. The light sends some of them into a free state. The photocurrent arises because of a difference between the total amplitudes for transitions from bound state 1 to continuum states 3 and 3′ (Fig. 2). Away from the resonance, we have the ordinary drag effect during the photoionization of the impurity.[5] The difference between the amplitudes (P and P') for transitions to states 3 and 3′ (Fig. 2a) stems from the photon momentum $\vec{k}$.

At the resonance, however, where the energy of the final state of the electron approaches that of the 000^- impurity level, the situation is qualitatively different. In addition to the transition from state 1 to state 3 (or 3′) described above, there are two more transitions: 1) an electric dipole transition 1→2, which is a consequence of k^3 terms in the Hamiltonian,[6,7] followed by a transition to state 3 (or 3′) as a result of the spin-orbit coupling V^{SO} in the Coulomb field of the impurity (Fig. 2b); 2) a transition

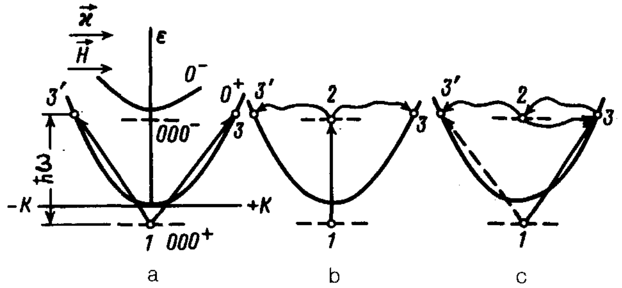

FIG. 2. Possible mechanisms for the optical transition of an electron from impurity level 000^+ to the 0^+ band; the 000^- intermediate state has been taken into account.

to state 3 (or 3′) accompanied by a simultaneous resonant scattering of the electron forward (3′→2→3) and backward (3→2→3′) (Fig. 2c). We denote the amplitude for this transition by R, while the amplitude for the corresponding transition to state 3 is R'.

All of these mechanisms obviously interfere with each other, so in calculating the total probabilities for transitions from state 1 to states 3 and 3′ we should add the corresponding amplitudes, rather than probabilities. The amplitudes P and R can be written in the form

$$P \sim P_1 + \frac{\kappa}{k} P_2 \quad ; \qquad R \sim - R_0 \frac{\kappa}{k} \frac{\Gamma}{\Delta + i\Gamma} \quad . \tag{1}$$

Here $\Delta = \hbar(\omega - \omega_0)$ is the deviation from the resonant frequency; Γ is the width of the 000^- level; k is the momentum of an electron at point 3; and P_1, P_2, and R_0 are positive quantities, similar in order of magnitude. The reason for the latter circumstance is that in the one-dimensional case the amplitude for a resonant scattering of a wave in the resonance region is close to unity, i.e., close to the amplitude of the unscattered (incident) wave. Note also that the expressions for P' and R' differ from (1) in the sign of k.

It is important to note that the amplitude R, in contrast with P, differs from zero only to the extent that κ does. The reason is that in our case the resonant scattering is a consequence of the spin-orbit coupling in the field of the impurity (the electron spin in the 0^+ band is up, while its orbital angular momentum is -1; in the 000^- state, in contrast, the orbital angular momentum is 0, and the spin is down). The matrix element for this coupling is of odd parity in the momentum of the electron. Consequently, the amplitudes of the waves which are scattered forward and backward and which thus correspond to opposite momenta have opposite signs. The total amplitude for the transition of an electron from level 000^+ to the 0^+ band, caused by the light and accompanied by a simultaneous resonant scattering, is therefore the sum of the amplitudes corresponding to forward and backward scattering. When we now take the momentum of the photon into account, we find that these contributions cancel each other out completely. Incorporating the photon momentum κ leads to a difference between these terms, which increases with κ/k. We also wish to stress that both P and R are independent of the direction of **H**. According to Ref. 6, the amplitude for the 1→2→3 transition, which is related to the k^3 terms, should be of odd parity in H. The effect seen in the present experiments, however, does not depend in any substantial way on the magnetic field direction. This result means that the contribution of the $1 \rightarrow 2 \rightarrow 3$ transition is comparatively small.

The total amplitude (M) for the transition induced by the light to state 3 is thus $M = P + R$, and the amplitude for the transition to state 3′ is $M' = P' + R'$. The electron current of interest here is $j \sim (\langle k \rangle / m)(|M|^2 - |M'|^2)$, where $\langle k \rangle = k[\Delta^2/(\Delta^2 + \Gamma^2)]$ is the momentum of an electron in the band, m is the effective mass, and n is the electron density. Using (1), we find the following expression for the resonant component of the photocurrent:

$$j - j_b \sim - \frac{\Delta^3 \Gamma}{(\Delta^2 + \Gamma^2)^2}, \tag{2}$$

where j_b is the nonresonant background photocurrent.

This functional dependence gives a good description of the experimental curve in Fig. 1a, in particular, its bipolar nature and the relatively gently sloping decay ($\sim 1/\Delta$) far from the resonance.

In our situation, the optical absorption coefficient α, which (in contrast with j) is proportional to the sum of the squares of matrix elements M and M', is described by a Lorentzian lineshape. There is no asymmetric Fano increment[8] because in our case the leading interference terms in $\alpha \sim |M|^2 + |M'|^2$ cancel each other out.

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