Drag photocurrent in a 2D electron gas near the cyclotron resonance and its first subharmonic

A. P. Dmitriev, S. A. Emel'yanov, S. V. Ivanov, P. S. Kop'ev, Ya. V. Terent'ev, and I. D. Yaroshetskiĭ
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, 194021, St. Petersburg (formerly Leningrad)

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The current due to the photon momentum $\hbar\kappa$ in a GaSb/InAs/GaSb semimetallic quantum well has been studied in a magnetic field perpendicular to the 2D layer. The photocurrent was detected in the plane of the 2D layer, either along the direction of the light or in the perpendicular direction. In each case, clearly expressed resonances of the photocurrent were detected, both in the region of the cyclotron resonance and in the region of its first subharmonic. The resonance in the absorption, in contrast, was observed only at the fundamental frequency. A classical theoretical description of the experimental results is offered. In a model of quantum transitions, the resonant currents at $H = (1/2)H_c$ are interpreted as yet another manifestation of an effect which was recently discovered: a resonant interference photocurrent {A. P. Dmitriev *et al.*, Zh. Eksp. Teor. Fiz. **99**, 619 (1991) [Sov. Phys. JETP **72**, 347 (1991)]}.

In this letter we are reporting the observation of some strong resonances, comparable in magnitude, in the drag current near the cyclotron resonance and near its first harmonic. We will show that the resonance at the fundamental frequency stems from a drag effect,[2] which in turn is a consequence of the radiation pressure accompanying the strong resonant absorption of light. The resonance near the first subharmonic can be interpreted as resulting from a quantum interference of a resonant quadrupole transition and a nonresonant level-skipping dipole transition. The latter transition is allowed to the extent that the electrons interact with the impurity field.

The GaSb/InAs/GaSb test samples with a single quantum well were grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The structures had the following basic characteristics: $d_z = 200$ Å, $n_s = 1.1\times10^{12}$ cm^{-2}, and $\mu = 5\times10^4$ cm^2/(V·s) at $T = 77$ K (Ref. 3). The experimental geometry is shown in the inset in Fig. 1. The light was coupled into the sample at an acute angle ($\sim 10°$) with the help of a prism in optical contact with the sample. The sample was placed in the cavity of a superconducting solenoid at $T = 4.2$ K. The light source was an optically pumped pulsed D_2O laser (the design is described in Ref. 4). The wavelength of the light was 385 μm (the photon energy was $\hbar\omega = 3.2$ meV); the length of the pulse was 100 ns; and the intensity of the unpolarized light inside the sample was $I = 3$ kW/cm^2. We measured the photocurrents flowing in the plane of the 2D layer: either the longitudinal current with respect to the light, j_y (contacts *a–a* in the inset in Fig. 1), or the transverse current, j_x (contacts *b–b*).

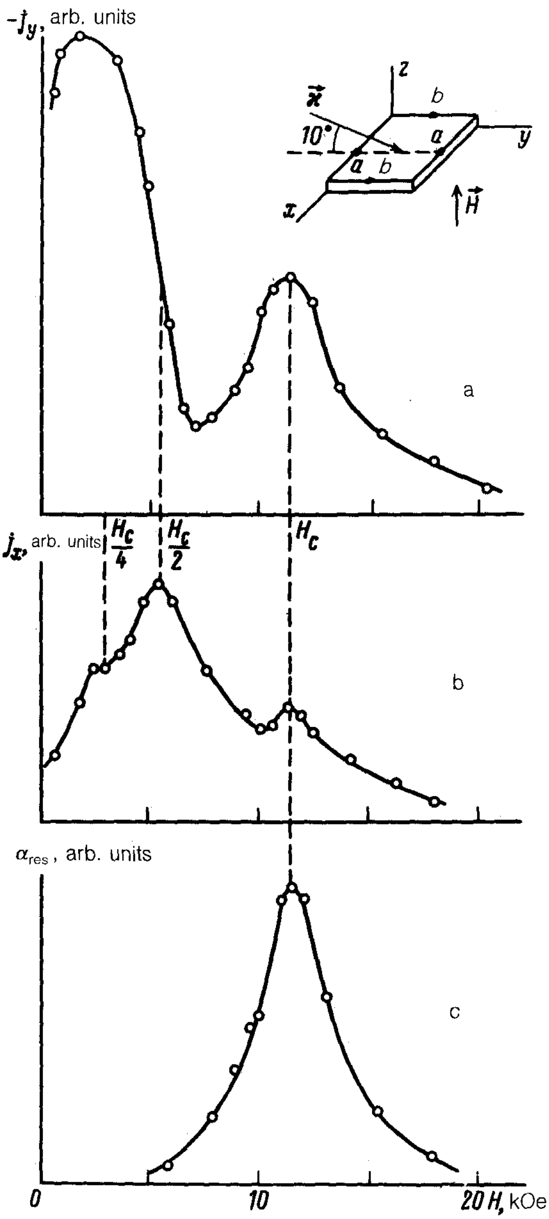

FIG. 1. a—The photocurrent which is longitudinal with respect to the direction of the light, j_y (contacts a–a), versus the magnetic field; b—the transverse photocurrent j_x (contacts b–b), also versus the magnetic field; c—resonant absorption coefficient versus the magnetic field for the case of normally incident light. The inset shows the experimental geometry in the measurements of the photocurrents j_y and j_x. The signs shown for the photocurrents here correspond to the directions of the axes and of the magnetic field in the inset.

Parts a and b of Fig. 1 show the results of these j_y and j_x measurements. Shown for comparison is a plot of the resonant optical absorption coefficient, measured on the same sample (part c). The position of the cyclotron-resonance line along the magnetic-field scale agrees with the positions found by other authors.[5,6] It can be seen from this comparison that the photocurrents j_y and j_x have clearly defined structural features not only near the cyclotron resonance but also near the first subharmonic of the cyclotron resonance, where there is no absorption resonance. In addition, the resonant current j_y is bipolar in the subharmonic region. Both currents are odd in the wave vector of the light. When the magnetic field H is reversed, the current j_x changes sign, while j_y does not.

To explain these results, we will work from the classical kinetic equation, since the Fermi energy satisfies $\epsilon_F \gg \hbar\omega$ under these experimental conditions. For simplicity we will also restrict the anslysis to the τ approximation for the collision integral. We ignore heating.

The calculations show that each current attains resonances not only at the fundamental cyclotron-resonance frequency (at $H = H_c$, where $H_c = \omega m^* c/e$) but also near its first subharmonic (at $H = H_c/2$). For the resonant contributions to the photocurrents j_y and j_x in a sample of finite dimensions (under short-circuiting conditions) we find

$$j_{y0} = -\kappa \frac{eE^2c^2n_s}{8\omega d_z} \frac{1}{H_\tau^2 + \delta_0^2}; \quad H_\tau = \frac{mc}{e\tau}; \quad \delta_0 = |H| - H_c , \tag{1}$$

$$j_{x0} = -\kappa \frac{H}{|H|} \frac{eE^2c^2n_s}{16\omega_\tau d_z} \frac{H_\tau^2}{H^2} \frac{1}{H_\tau^2 + \delta_0^2}; \quad \frac{1}{\omega_\tau} = \epsilon_F \frac{d\tau}{d\epsilon}\Big|_{\epsilon_F} , \tag{2}$$

$$j_{y1} = \kappa \frac{eE^2c^2n_s}{32\omega_\tau d_z} \frac{1}{H^2} \frac{H_\tau \delta_1}{\frac{1}{4}H_\tau^2 + \delta_1^2}; \quad \delta_1 = |H| - \frac{1}{2}H_c , \tag{3}$$

$$j_{x1} = \kappa \frac{H}{|H|} \frac{eE^2c^2n_s}{64\omega_\tau d_z} \frac{H_\tau^2}{H^2} \frac{1}{\frac{1}{4}H_\tau^2 + \delta_1^2}, \tag{4}$$

where E is the electric field amplitude of the light wave, and τ is the momentum relaxation time. An important point is that τ increases with increasing energy ϵ, since scattering by charged impurities is dominant in our case.

It can be seen from (1)–(4) that the longitudinal photocurrents are even in H, while the transverse photocurrents are odd. The resonances of j_{y0}, j_{x0}, and j_{x1} have a Lorentzian lineshape ($j \propto 1/\delta^2$), in contrast with the photocurrent $j_{y1} \propto 1/\delta$. All the currents are linear in κ.

Note that in these experiments the j_{x0} resonance not only is relatively small but also has the sign opposite that predicted theoretically. The apparent reason for this result is that Eqs. (1)–(4) ignore the heating of the electrons; i.e., these equations were derived in the approximation linear in the intensity. The contribution to j_{x0}, which is quadratic in I, makes a contribution of the opposite sign, so at a sufficiently high excitation intensity ($I \sim 3$ kW/cm^2 in these experiments) the sign of the resonance may change. On the other hand, it can be shown that heating effects do not influence the signs of the other resonances. We might also note that a weak resonance in the current j_x is observed experimentally at $H = H_c/4$ (Fig. 1b). It is possible that this is a manifestation of a third subharmonic, but it, like the second, is proportional to κ^3. On the other hand, we do not rule out the possibility that nonlinear mechanisms are having a significant effect here. A detailed analysis of such mechanisms goes beyond the scope of this paper.

The photocurrent j_{y0} stems from an effect of radiation pressure. It is proportional to the resonant absorption coefficient. The physical meaning of resonances in the current in the region of the first subharmonic can be explained more conveniently in terms of quantum transitions between Landau levels. Clearly, these resonances correspond to level-skipping transitions, i.e., to $N \to N+2$ transitions. If we ignore the interaction of the electrons with impurities, we conclude that this transition is possible only in the quadrupole approximation.[1)] Its amplitude is proportional to κ, so the probability is proportional to κ^2. As a result, we find $j_{y1}, j_{x1} \propto \kappa^3$.

When the interaction with the impurity is taken into account, the picture changes qualitatively. In this case, there is an admixture of wave functions of level $N+1$ in the wave functions of levels N and $N+2$. This admixture is particularly noticeable in relatively weak magnetic fields.[5] As a result, a nonresonant dipole transition $N \to N+2$ becomes possible. The interference of this transition with the resonant quadrupole transition gives rise to a photocurrent whose magnitude is proportional to κ.

It can be seen from this discussion that the formation of photocurrents linear in κ in the region of the first subharmonic of the cyclotron resonance is essentially a manifestation of an effect which was recently discovered: a quantum-interference resonant photocurrent.[1] The discussion in that previous study was of an interference photocurrent proportional to $1/\Delta$, where Δ is the detuning from resonance. However, an interference of optical transitions can also lead to a photocurrent with a Lorentzian lineshape: $j \sim 1/\Delta^2$. To demonstrate the point, we denote by P the amplitude of the nonresonant transition, and we denote by $R/\Delta + i\Gamma$ the amplitude of the resonant transition which is interfering with the nonresonant one (Γ is the width of the level). The interference part of the total transition probability, W_I, is

$$W_I = \frac{P^* R}{\Delta + i\Gamma} + \frac{P R^*}{\Delta - i\Gamma}.$$

Let us assume that the phase of the matrix elements P and R is shifted relative to each other by the amount φ. We can then write

$$W_I = |R| \cdot |P| \cdot \left(\frac{e^{i\varphi}}{\Delta + i\Gamma} + \frac{e^{-i\varphi}}{\Delta - i\Gamma} \right) = |R| \cdot |P| \frac{2\Delta \cos\varphi + 2\Gamma \sin\varphi}{\Delta^2 + \Gamma^2}.$$

We see that we have $W_I \propto 1/\Delta$ only if $\varphi = 0, \pi, \ldots$. In the cases $\varphi = \pi/2, 3\pi/4, \ldots$, in contrast, we find $W_I \sim 1/(\Delta^2 + \Gamma^2)$. In all other cases, both terms are present. At a sufficient distance from the center of the line ($\Delta \gg \Gamma$), the asymmetric contribution will of course be predominant if $\cos\varphi$ is not too small.

In the experiments described above, Γ was comparatively large, and both terms could have been important. As can be seen from the classical calculation presented above, the asymmetric term proportional to $1/\Delta$ is the leading term in the case of the current j_{y1}, while the Lorentzian term proportional to $1/\Delta^2$ is the leading term for the current j_{x1}.

[1)] Mechanisms which would allow such a transition in the dipole approximation (e.g., nonparabolic bands) are negligible here, as can be seen from the absence of a corresponding resonance in the absorption.

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