Direct Observation of Depolarization Shift of the Intersubband Resonance

S. Graf and H. Sigg
Paul Scherrer Institut, Labor für Mikro- und Nanotechnologie, CH-5232 Villigen-PSI, Switzerland

K. Köhler
Fraunhofer Institut für angewandte Festkörperforschung, Tullastrasse 72, D-79108 Freiburg i.Br., Germany

W. Bächtold
Laboratory for Electromagnetic Fields and Microwave Electronics, ETHZ, CH-8092 Zürich, Switzerland
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We have studied the intersubband resonance of GaAs/AlGaAs multi-quantum-well systems by comparing photon drag and absorption spectra obtained by in-plane photocurrent and photoconduction measurements. The peak absorption at room temperature is found to be blueshifted from the photon drag resonance by as much as 33 cm^{-1}. We argue that this difference gives directly the depolarization shift, since the resonant photon drag current is driven by the Doppler effect, which is a k-vector dependent single particle process.

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It is by now commonly accepted that the intersubband resonance (ISR) in doped semiconductor quantum well (QW) systems is not a single particle process but a collective phenomenon designated as a plasmon or charge-density excitation [1]. As a consequence, the resonance energy observed, for example, in a far infrared (FIR) transmission or absorption experiment does not occur at the energy given by the single particle energy level separation. Also, the linewidth and line form of the resonance may be affected by collective effects. This has been demonstrated recently by ISR experiments performed on a QW made of InAs/AlSb, which is a system with a strongly nonparabolic conduction band structure [2]. In simple systems like GaAs QWs, with nearly parabolic and parallel subbands, collective effects such as dynamical screening lead to a blueshift of the resonance—the so-called *depolarization shifted* or *dressed* ISR.

Numerous works have been devoted to the determination of these collective effects by studying the dependence of the ISR on temperature [3,4], intensity [5], and carrier density [6–8]. The drawback of these methods is that the single particle effects are distinguished from the many-body effects using model calculations, which require knowledge of sample parameters such as the electron concentration, effective mass, QW width, barrier heights, etc. The experimental situation is more comfortable for the case of low temperature light scattering, because the energy difference between spin density and charge density excitations can be used for the determination of the direct Coulomb interaction terms [9]. This technique cannot be applied to the FIR absorption, since spin flip excitations are not allowed, except for systems with strongly nonparabolic bands, which complicate the evaluation of collective effects [10]. The only FIR based method which, to our knowledge, seems to give the undressed intersubband energy is the study of the coupled intersubband Landau level transitions in the limit of high in-plane magnetic fields [11]. The single particle transition energy is then obtained by a proper extrapolation of the high field data to zero magnetic field [12].

The purpose of this paper is to show that the photon drag (PD) effect yields a new method to directly observe the depolarization shift. In contrast to all above methods, our measurement can also be performed at room temperature. The basic idea is the following: While the optical properties are related to the plasmon excitation with a virtually negligible propagation vector, the photon drag is a current which is driven by the transfer of momentum from the photon to the electron system. Because of the subband level dependent momentum relaxation rate, as has been shown theoretically [13–15] and experimentally [16], this current in general is different for excitation at opposite sides of the single particle dispersion. Since the transition energy for these excitations differs by the Doppler effect, an antisymmetric current response is obtained, and the transition energy at the electron propagation vector $k = 0$ (which is by definition the single particle transition energy in a system with parallel subbands) is apparent from the zero crossing of the resonant photon drag current [17].

The samples were grown by molecular-beam epitaxy and consist of a 30 period modulation doped multi-QW system made of 82 Å GaAs wells and 260 Å $Al_{0.35}Ga_{0.65}As$ barriers, with surface electron concentrations of 0.87×10^{12} cm^{-2} and 0.93×10^{12} cm^{-2} per well for samples A and B, respectively. The top and bottom layers adjacent to the multi-QW structure were designed to properly compensate for surface charge and the background doping in the buffer layer and substrates, respectively. The Fermi energy lies between the first two subbands, and, therefore, also at room temperature (RT), a single ISR is observed. The signal detection scheme relies on the integration of the active QW layer into a microstrip,

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forming a microwave transmission line [19]. The incoupling of the light is accomplished using a Ge prism placed on top of the sensitive area. The microstrip arrangement with total reflection incoupling provides some important experimental advantages. First, at the critical total reflection angle, the electric field of p-polarized light is exactly perpendicular to the quantum layers, providing optimal coupling to the ISR. Second, due to the illumination through the surface, the FIR field strength is constant along the propagation direction of the light, which avoids (electron) temperature gradient induced currents. Third, measurements of the signal transients are possible over a bandwidth which exceeds 30 GHz. This is essential when working with pulsed FIR sources as, e.g., the free electron laser of the FOM Institute for plasma physics (FELIX) used here. All of the ISR experiments were performed at RT.

In order to have the same conditions, for an accurate comparison between the PD and the ISR absorption, pulsed photocurrent and photoconduction (PC) measurements have been performed under, respectively, zero and positive or negative bias; cf. inset of Fig. 1(a). For better signal-to-noise ratios, we integrated over the entire macropulse of FELIX [20]. The mechanism of the in-plane PC can be understood as a simple electron heating effect. This has been checked for different QW structures by comparing the strength and sign of the PC signal with, respectively, the absorbed power and the temperature dependence of the conductivity as obtained from Hall measurements. As electron heating is directly related to the absorbed power, tedious transmission measurements are circumvented with this method. The PC spectrum, shown in Fig. 1(a) (open circles), has a Lorentzian line shape with the peak position at 866 cm^{-1}, in good agreement with the resonance position obtained by attenuated total reflection (ATR) measurements with a Fourier transform spectrometer. The constant offset visible far from the resonance stems from the inequality of the conductivity for the two bias polarities. The PD signal has been obtained from the same measurements by adding the signals of each polarity. The spectral response obtained in this way is corrected for offset and plotted in Fig. 1(a) (diamonds) together with the direct measurement of the photon drag (solid circles) at zero bias. The direct signal is stronger, since losses in the biasing electronic network (bias-Tee) were omitted. Unfortunately, some measurement points are missing in the spectrum due to a temporary blackout of the IR source. Aside from this difference in strength, the deviation in the line shape and position is negligible.

In order to determine the PD resonance position, the PD signal must be decomposed into its so-called direct and resonant parts. We first discuss the situation in the case of parallel subbands. The direct part is a consequence of the direct momentum transfer from the photon to the electron system and is thus proportional to the absorption and

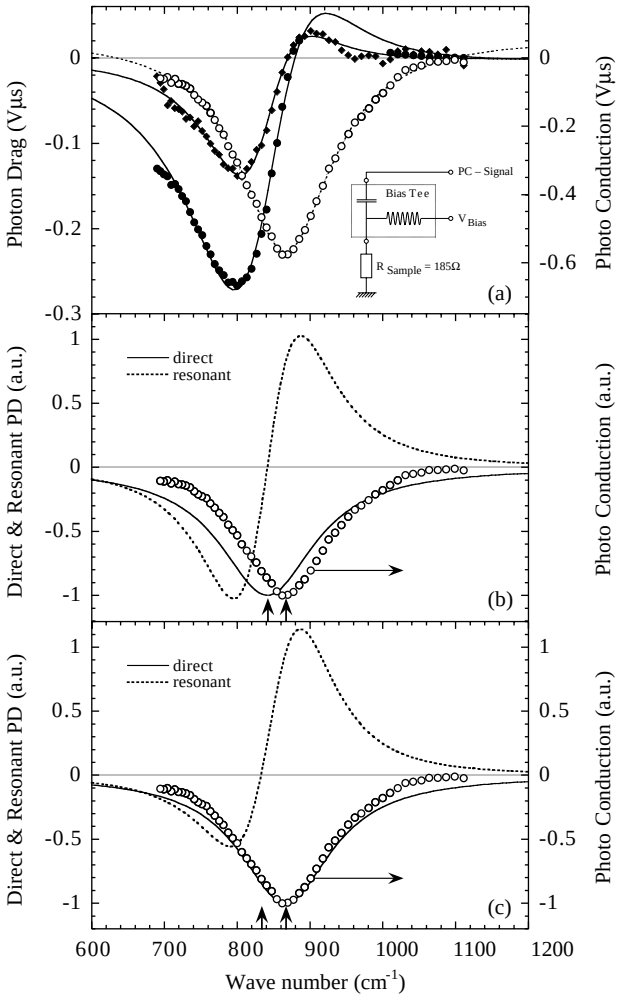

FIG. 1. (a) Intersubband spectra at RT of a 30 period, 82 Å $GaAs/Al_{0.35}Ga_{0.65}As$ multi-QW system obtained under positive, zero, and negative bias. The photoconduction measurement (open circles) performed at ± 0.3 V bias is shown with the photon drag spectra (diamonds), obtained by adding the signals of either polarity and the immediate (no bias) PD (solid circles). The inset shows the schematic of the biasing electronic network. (b) The decomposition spectra of the simple PD fit to the data shown in (a). The direct (solid line) and resonant (dotted line) parts of the PD are depicted for comparison with the scaled PC spectra. (c) The decomposition spectra of the PD fit using the Załużny model to the data shown in (a). The resonance position of the PC spectra (right arrow) and the direct PD part are blueshifted from the zero crossing of the resonant PD part (left arrow).

the photon wave vector $q = 2\pi\nu n/c$, where n is the refractive index in GaAs. The second, more complex contribution is due to the Doppler effect and the difference in the subband momentum relaxation rates, $\tau_1 - \tau_2$. An ISR excited electron with wave vector $\mathbf{k}_2$ leaves an empty state (hole) in the ground subband with $\mathbf{k}_1 = \mathbf{k}_2 - \mathbf{q}$. The thereby excited currents are proportional to the corresponding relaxation time. Since, due to the Doppler effect, the absorption energy for a transition at any negative k (measured with respect to the light propagation direction) is

smaller than the corresponding transition at positive k by $2\hbar^2\mathbf{k}\cdot\mathbf{q}/m^*$, this second contribution to the PD signal is proportional to $\mathbf{k}\cdot\mathbf{q}$ and $\tau_1 - \tau_2$. Summing over all k states shows that the Doppler effect leads to a spectral response which is proportional to the derivative of the absorption, i.e., the spectrum is antisymmetric with respect to the energy of the single particle excitation. The two contributions lead to the following frequency dependence of the photon drag effect [21]:

$$i_{\mathrm{PD}} \propto \alpha(\omega)\tau_2 + \frac{\partial\alpha(\omega)}{\partial\omega}\frac{\langle E\rangle}{\hbar}(\tau_1 - \tau_2), \qquad (1)$$

where $\alpha(\omega)$ is the frequency dependent absorption coefficient, and $\langle E\rangle$ is the mean value of the electron energy in the ground subband. In particular, at $T = 0$ K, we obtain $2\langle E\rangle = E_F$, with E_F the Fermi energy.

Applying the PD formula of Eq. (1) as a fit to the measured PD curves in Fig. 1(a) yields a center position of the photon drag based $\alpha(\omega)$ at 841 cm^{-1}, which corresponds to a shift from the peak resonance of the PC measurement by as much as 25 cm^{-1} [cf. the two arrows in Fig. 1(b)].

Inherent in the above simple model is that both the direct and resonant PD signals are related to the individual excitations in $\mathbf{k}$ space. However, since the direct part is of classical origin, one would expect this part to be fully dressed. A theoretical treatment of the problem, employing the self-consistent field method, is given by Załużny [17]. He shows that the direct and resonant terms are indeed affected differently by the resonant screening. The ω dependence of the direct part coincides with the spectral dependence of the IS absorption coefficient. The resonant component is more complicated and, for a Lorentzian absorption line form, is given by the expression

$$i_{\mathrm{res}} \propto \frac{(\tau_1 - \tau_2)}{(\omega - \tilde{\omega}_{12})^2 + \tau^{-2}}\,\frac{2\langle E\rangle(\omega - \omega_{12})}{(\omega - \omega_{12})^2 + \tau^{-2}}, \qquad (2)$$

where $\tilde{\omega}_{12}$ is the depolarization shifted resonance frequency, and τ is the dephasing time. The spectral shape of i_{res} is no longer exactly antisymmetric, but the sign change still occurs at the undressed resonance frequency ω_{12}. In the case of a nonparallel dispersion the integral leading to Eq. (2) cannot be performed analytically [17]. However, since the zero crossing of i_{res} practically coincides with the redshifted single particle transition energy, ω_{12} [18], the same formula, Eq. (2), can still be employed without affecting our results and interpretations in an essential way.

Shown in Fig. 1(c) are the direct and resonant parts of the PD, extracted from the fitted experimental PD spectra using Eq. (2). The thus obtained single particle excitation energy ω_{12} is found to be 833 cm^{-1} [left arrow in Fig. 1(c)]. The agreement of the fit with the experimental curve is as good as with the simple equation, and the values for the relaxation time ratio are found to be similar, i.e., 1.4 compared to 1.5 [22]. The blueshift increases to 33 cm^{-1}, illustrating the importance of screening even at RT. This value is comparable to the shift of 50 cm^{-1} predicted by Załużny in his recent paper [17]. In his calculation, a slightly narrower QW system has been used, and the temperature has been set to $T = 0$ K. According to a previous paper of Załużny [23], the depolarization shift for comparable QW systems is reduced by approximately 10% at $T = 300$ K, in fair agreement with our experiment.

In the paper of Craig *et al.* [5], the redshift of the ISR position for increasing intensities, measured in a transmission experiment, has been attributed to the reduction of the dynamical screening due to the population of excited subbands. In Fig. 2, we show experimental results of sample B, where the peak positions of the ATR measurements are plotted as a function of the FIR intensity. The intensity has been corrected for reflection losses at the Ge prism and refers to the condition of total reflection. As in Ref. [5], a redshift of the peak position is observed for increasing intensity. The undressed resonance positions, also depicted in Fig. 2, are obtained as above, from the simultaneously measured PD spectra fitted with the Załużny model, Eq. (2). The blueshift is found to be smaller than in the experiment on sample A, where the absorption is obtained by in-plane PC. We explain this by systematical errors due to the background subtraction in the ATR measurements. The trends, however, are not affected, since the same correction is applied for all of the spectra. In the linear regime, we expect no change in the undressed energy, which is in good agreement with the obtained data. In this limit, our results support the findings of Ref. [5]. Towards the saturation intensity, which we define as the intensity at which the minimum peak reflection strength attains half of its low intensity value, the PD resonance energies exhibit a pronounced drop. We presently have no detailed understanding of the involved mechanisms, since close to saturation some of the assumptions in the employed self-consistent field approach are no longer fulfilled. Also, the influence of the inhomogeneous electrical field penetration within the QWs additionally complicates the interpretation

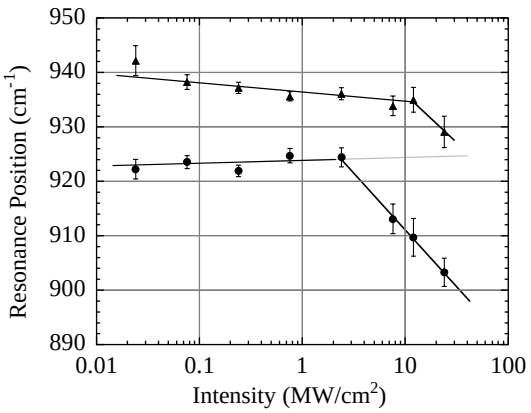

FIG. 2. Resonance positions of the ATR (triangles) and the photon drag spectra (circles) as a function of intensity in a 82 Å $GaAs/Al_{0.35}Ga_{0.65}As$ multi-quantum-well sample. The saturation intensity of the ATR is $\approx$15 $\mathrm{MW/cm}^{-2}$. The lines are drawn as guides to the eye.

of the PD spectra in the saturation regime, as can be anticipated from the asymmetric and shifted ATR line form, calculated by Załużny *et al.* [25], for a 50 period QW system. Nevertheless, we attribute part of the frequency down-shift to nonparabolicity and the larger effective mass in the first excited subband. This leads to a decrease of the single particle transition energy with increasing intensity due to a redistribution towards larger **k** of electrons in the ground subband. In contrast to the ATR, the PD is expected to be strongly influenced by this effect. It is worthwhile to note that this result and the extrapolated tendencies of the low intensity regime imply an almost complete screening effect close to optical saturation.

In conclusion, the role of collective effects in the ISR has been demonstrated by the comparison of the absorption with the photon drag effect. While the absorption process is basically a zero wave vector collective excitation, the PD effect, in particular the resonant part of the PD, can only be understood as a consequence of single particle excitations, with k extending from zero up to the Fermi wave vector. Our combined ISR experiments on GaAs/AlGaAs QW systems show, for the first time, that the undressed resonance position, which is related to the single particle excitations, is apparent from a direct experiment, providing a benchmark for testing the validity of many-body interaction models. This technique has been applied to study the depolarization shift dependence on excitation intensity. An unexpectedly strong screening effect has been found at room temperature, up to intensities close to saturation.

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