Cyclotron Resonance Study of the Two-Dimensional Electron Layers and Bilayers in Tilted Magnetic Fields

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The cyclotron resonance in absorption of far-infrared radiation in two-dimensional electron single-layers and double-layers occurs when its frequency ω coincides with the frequency ω_c of the periodic motion of electrons subjected to a magnetic field $\vec{B}$. In strictly 2D electron systems, a single *constant* cyclotron mass, $m_c^* = \omega_c/|e|B_\perp$, characterizes the cyclotron motion of electrons, where $B_\perp$ denotes the component of the field perpendicular to the plane of electron layers. The situation becomes more complicated if we consider more realistic systems, quasi-two-dimensional electron layers or bilayers, in magnetic fields of general orientation. Due to the finite width, their electronic structure is strongly affected by the in-plane component of the field, $B_\parallel$. Then the cyclotron mass is not longer a constant and becomes a function of both $B_\parallel$ and $B_\perp$, $m_c^* = m_c^*(B_\parallel, B_\perp)$, as demonstrated by recent experiments (see e.g.[1]).

We have studied this problem theoretically, employing simple parabolic quantum wells to model single-layer systems. Bilayer systems are represented by a pair of tunnel-coupled strictly two-dimensional quantum wells, located at the distance d. These simple models allow to carry out most calculations analytically and yet are able to capture the essence of physics of single-layers and bilayers.

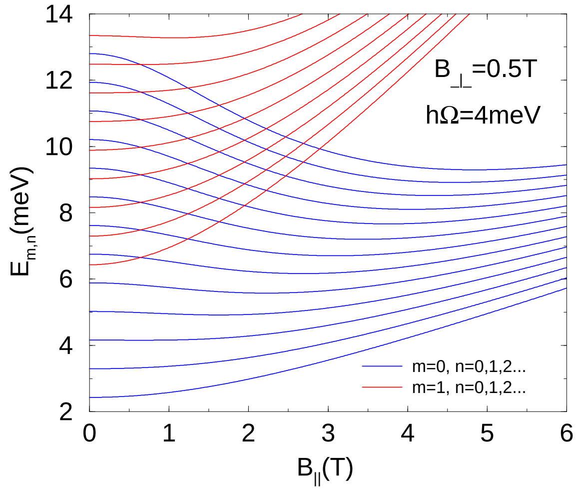
The linear response theory (Kubo formula) is used to evaluate diagonal components of the magnetoconductivity tensor responsible for determination of the dissipated power. In both systems we consider the ground and excited subbands which yield two fans of Landau levels, each level is denoted by a subband index m, and a level index n. Corresponding wave functions determine probabilities of transitions between levels via the dipole matrix elements in the Kubo formula.

The separation of Landau levels varies with increasing $B_\parallel$ for fixed $B_\perp$. In both types of systems the eigenenergies in excited subbands sharply grow. Behaviour of levels from the ground subbands is more complicated and different for single layers and bilayers. In parabolic quantum wells the energy of levels with the higher indices at first decreases, reaches the minimum and increases again with $B_\parallel$. In our oversimplified model all possible transitions between levels are characterized by a single cyclotron mass which is a function of $B_\parallel$ only, $m_c^* = m_c^*(B_\parallel)$.

In bilayers the in-plane component of the field reduces the coupling of wells and in the high field limit they can be considered as completely independent. As a result, the energy spectrum is quantized by $B_\perp$ in each well separately and levels become degenerated in the well index. Adjacent even and odd states corresponding to $B_\parallel = 0$ give rise to a pair of degenerate levels at very high $B_\parallel$. The cyclotron mass corresponding to transitions between these two levels diverges.

In perpendicular magnetic fields only the intrasubband transitions ($\delta m = 0$, $\delta n = \pm 1$) are allowed, i.e. only the adjacent Landau levels from the same subband contribute. As the in-plane field increases, the intersubband transitions become possible and also the transitions between more separated Landau levels. The brightness of transitions is governed by the transition matrix elements. In general, the intrasubband transitions become dark and the intersubband transitions bright at high $B_\parallel$.

[1] H. Aikawa, S. Takaoka, K. Oto, K. Murase, T. Saku, Y. Hirayama, S. Shimomura and S. Hiyamizu, Physica E 12(2002) 578



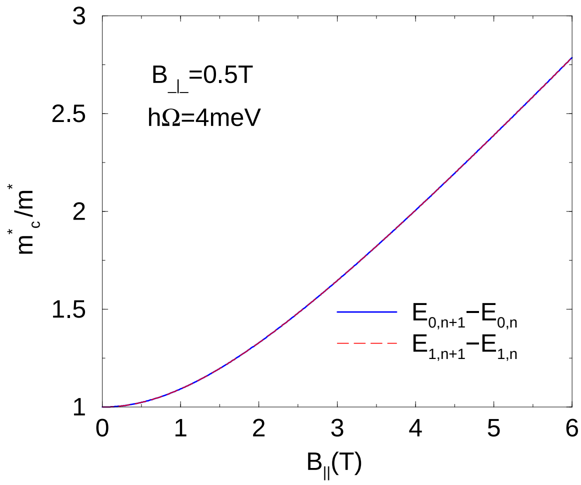
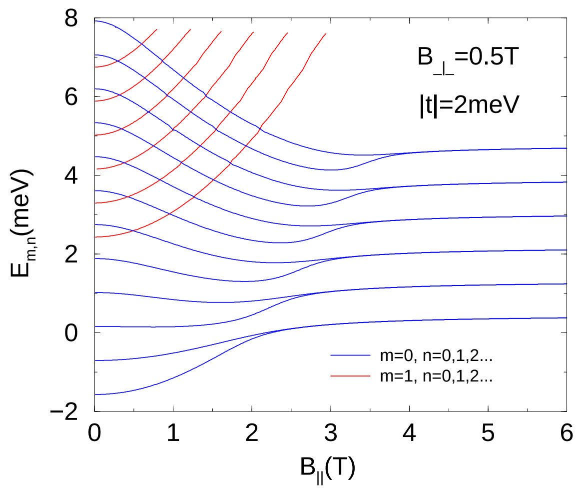


Figure 1: (left) Fan diagram of eigenenergies against the in-plane $B_{\|}$ component of magnetic field at fixed $B_{\perp} = 0.5$ T corresponding to the energy of subband separation $\hbar\Omega = 4$ meV for the model of 2D electron single-layer systems.

Figure 2: (right) Cyclotron effective masses m_c^* calculated from the difference between Landau levels of the eigenenergy spectrum (Figure 1) for two types of transitions $\delta m = 0$, $\delta n = \pm 1$ and $\delta m = \pm 1$, $\delta n = 0$ as the function of an in-plane magnetic field.



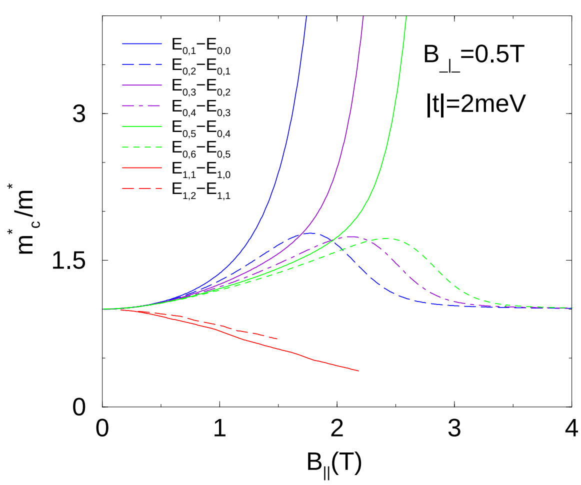


Figure 3: (left) Eigenenergies of bilayer systems as a function of $B_{\|}$ at fixed $B_{\perp} = 0.5$ T and the interwell hopping energy $2|t| = 4$ meV. Blue and red lines denote Landau levels from the bonding and antibonding subbands, respectively.

Figure 4: (right) Cyclotron effective masses m_c^* calculated from energy difference between adjacent Landau levels of the band structure spectrum (Figure 3) as the function of an in-plane magnetic field.