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CYCLOTRON-INTERSUBBAND COUPLING IN PERIODICALLY MODULATED QUASI-TWO-DIMENSIONAL ELECTRON GAS

M. ZALUŻNY AND T. STAŃKO

Institute of Physics, M. Curie-Skłodowska University
Pl. M. Curie-Skłodowskiej 1, 20-031 Lublin, Poland

The problem of the coupling between the Landau levels originating from the ground and first excited subband in laterally modulated quasi-two-dimensional systems in the presence of the tilted magnetic field is discussed in the framework of the one-electron perturbation theory. It was found that the tilting of the superlattice potential leads to the strong dependence of this coupling on the orientation of the magnetic field with respect to the lateral confinement direction.

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Cyclotron-resonance-intersubband (CRI) coupling in quantum well structures induced by tilted configuration of the magnetic field was considered by many groups [1]. Recently, Huant et al. [2, 3] have shown experimentally and theoretically that, in laterally modulated quasi-two-dimensional systems, CRI can also be observed when not magnetic field but a lateral potential is tilted. The purpose of this note is to extend their theoretical treatment by considering the case when simultaneously, magnetic field $\boldsymbol{B}=(B_x,B_y,B_z)$ and lateral modulation potential $U(x,z)$, are tilted with respect to the surface normal $\boldsymbol{n}=(0,0,1)$. We will show that in this case the change in the energy splitting induced by parallel component of the magnetic field $\boldsymbol{B}_{\|}$ $[=(B_x,B_y)=(B_{\|}\sin\varphi,B_{\|}\cos\varphi)]$ depends strongly on the orientation of $\boldsymbol{B}_{\|}$ i.e., the energy splitting is different for "longitudinal" tilting ($B_x=0$) and "transverse" tilting ($B_y=0$).

Let us assume that the electron (with effective mass m^* and charge $-e$) moving in the rectangular quantum well [with quantizing potential $V(z)$] is subject to a strong magnetic field $\boldsymbol{B}$ and a weak lateral potential $U(x,z)$. If we choose the vector potential $\boldsymbol{A}$ in the form $\boldsymbol{A}=(B_yz,-B_xz+B_zx,0)$ then the effective mass Hamiltonian can be written as

$$H=H_0+H_1+H_2, \tag{1}$$

with

$$H_0=H_{\|}+H_{\perp}=\frac{1}{2m^*}[p_x^2+(p_y+eB_zx)^2]+\left[\frac{1}{2m^*}p_z^2+V(z)\right], \tag{2}$$

and

$$H_1 = H^{(\mathrm{t})} \sin\varphi + H^{(\mathrm{l})} \cos\varphi + U(x,z) \tag{3}$$

where $H^{(\mathrm{t})} = -\frac{ez}{m^*}(p_y + eB_z x)B_{\|}$, $H^{(\mathrm{l})} = \frac{ez}{m^*}p_x B_{\|}$ and $H_2 = e^2 z^2 B_{\|}^2/2m^*$. (The spin dependent term in Eq. (1) is neglected for simplicity.)

Following Huant et al. [2, 3] we assume that the tilted lateral potential $U(x,z)$ can be approximated by $U(x,z) = V_0[1 + \lambda\cos(2\pi x/L_x + 2\pi\epsilon z/L)]$, where V_0 is the amplitude of the modulation, L_x is the period of the modulation, λ is the lateral growth-ordering parameter, ϵ is the parameter determining the tilting of the lateral potential and L is the thickness of the quantum well (QW).

In the gauge used here the Hamiltonian has translational symmetry in the y-direction and the y-component of the electron wave vector (k_y) is a good quantum number. The Landau ($|M,k_y\rangle$) and subband ($|N\rangle$) levels are the exact eigenfunctions of $H_{\|}$ and $H_{\perp}$, respectively. The eigenvalues of H_0 are given by $E_{NM}^{(0)} = E_N^{(0)} + (M + 1/2)\hbar\omega_{\mathrm{c}}^{\mathrm{2D}}$, where $\omega_{\mathrm{c}}^{\mathrm{2D}} = eB_z/m^*$ and $E_N^{(0)}$ is the energy of the N-th electric subband when $B = V_0 = 0$.

The second term in Eq. (1) couples the levels $|N=1, M=1, k_y\rangle$ and $|N=2, M=0, k_y\rangle$ removing the degeneracy at the crossover i.e., when subband separation $E_{21}^{(0)} = E_2^{(0)} - E_1^{(0)}$ is close to the cyclotron energy $\hbar\omega_{\mathrm{c}}^{\mathrm{2D}}$. When $\tan\theta = B_{\|}/B_z \ll 1$ and $\lambda V_0 \ll E_{21}^{(0)}$ the first-order perturbation theory for the degenerate levels $|N=2, M=0, k_y\rangle$ and $|N=1, M=1, k_y\rangle$ can be used. In this limit the energy splitting is given by

$$\Delta_{\mathrm{tot}} = 2|\langle 1,1,k_y|H^{(\mathrm{t})}\sin\varphi + H^{(\mathrm{l})}\cos\varphi + U|2,0,k_y\rangle|. \tag{4}$$

Employing the well known relations [1]

$$\langle 1,k_y|p_x|0,k_y\rangle = \mathrm{i}\frac{\hbar\omega_{\mathrm{c}}^{\mathrm{2D}} m^* l_{\perp}}{\sqrt{2}}, \tag{5}$$

$$\langle 1,k_y|p_y + eB_z x|0,k_y\rangle = \frac{\hbar\omega_{\mathrm{c}}^{\mathrm{2D}} m^* l_{\perp}}{\sqrt{2}}, \tag{6}$$

we get the following expressions for the matrix element of $H^{(\mathrm{t})}$ and $H^{(\mathrm{l})}$:

$$\langle 1,1,k_y|H^{(\mathrm{l})}|2,0,k_y\rangle = \mathrm{i}\Delta_B, \tag{7}$$

$$\langle 1,1,k_y|H^{(\mathrm{t})}|2,0,k_y\rangle = -\Delta_B, \tag{8}$$

where $\Delta_B = 16eL\hbar^2\tan(\theta)/9\pi^2 m^* l_{\perp}^3$, $l_{\perp} = \sqrt{\hbar/eB_z}$. Deriving Eqs.(7) and (8) we have assumed, following Huant et al. [2, 3], that QW is infinitely deep i.e., $|N\rangle = \sqrt{2/L}\sin(N\pi/L)$.

In the above limit the matrix element of the lateral potential $U(x,z)$ is given by [3]:

$$\langle 1,1,k_y|U|2,0,k_y\rangle \equiv U_{11,20} = \Delta_U \cos(\pi\epsilon + 2\pi X/L_x), \tag{9}$$

with

$$\Delta_U = \frac{V_0\lambda l_{\perp}}{\sqrt{2}L_x}\frac{32\epsilon\cos(\pi\epsilon)}{(1-4\epsilon^2)(9-4\epsilon^2)}\exp\left(-\pi^2\frac{l_{\perp}^2}{L_x^2}\right), \tag{10}$$

where $X = k_y l_{\perp}^2$ is the coordinate of the cyclotron orbit center.

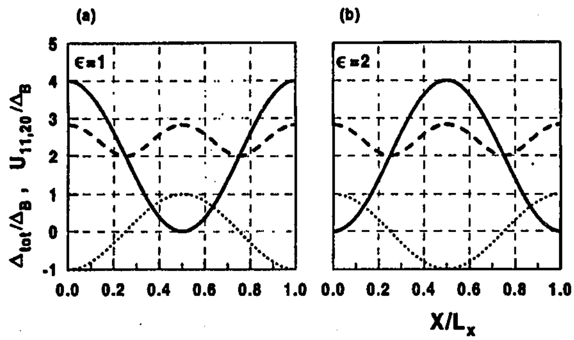

Fig. 1. Plot of Δ_{tot} as function of the dimensionless parameter X/L_x for the system with $\Delta_B = \Delta_U$ and different values of ϵ; longitudinal tilting (dashed curves), transverse tilting with $\sin\varphi = 1$ (solid curves). For comparison the variation of $U_{11,20}$ is also presented (dotted curves).

Since matrix element of $H^{(1)}$ is imaginary, the expression for Δ_{tot} takes the following form:

$$\Delta_{\text{tot}} = 2\{(\Delta\cos\varphi)^2 + [-\Delta_B \sin\varphi + \Delta_U \cos(\pi\epsilon + 2\pi X/L_x)]^2\}^{1/2}. \tag{11}$$

We have calculated (see Fig. 1) the X-dependence of Δ_{tot} for the transverse and longitudinal tiltings assuming that $\Delta_U = \Delta_B$ and taking $\epsilon = 1$ and $\epsilon = 2$. For comparison we present also X-dependence of $U_{11,20}$. Since $U_{11,20}$ is an oscillatory function of the position of the cyclotron centre X, the energy splitting Δ_{tot} also depends on X. However, the character of the above dependence is sensitive on the orientation of $\boldsymbol{B}_{\|}$. Particularly interesting is the case of transverse tilting ($\sin\varphi = \pm 1$). In this geometry, we observe the constructive and destructive interferences between corrections induced by B_x and the "tilting" of the lateral potential. When, like in systems studied by Huant et al. [2, 3], the Fermi level is low in the $M = 0$ Landau band we can take $X \approx L_x/2$ (and neglect inhomogeneous broadening of the cyclotron and intersubband resonance spectra). Then Eq. (11) (see also Fig. 1 and Ref. [1]) predicts the vanishing of the coupling between cyclotron and intersubband modes for $\Delta_B \sin\varphi = \Delta_U \cos[\pi(\epsilon + 1)]$. Note that in the case of the longitudinal tilting Δ_{tot} is always larger than Δ_B.

Acknowledgments

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References

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