Pseudo-Open-Orbit in Disordered Quantum-Wire Array: Disappearance of Cyclotron Resonance

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Abstract

The dynamical conductivity of a lateral superlattice with disorder in period, etc., in magnetic fields are calculated using the Boltzmann equation. In a weak magnetic field, the normal cyclotron resonance disappears and the multi-peak structure appears due to the resonance associated with the formation of a pseudo-open-orbit caused by diffuse Bragg scattering. The normal cyclotron resonance is recovered in sufficiently high magnetic fields due to magnetic breakthrough.

Key words: lateral superlattice, anisotropic mobility, disordered period, Bragg scattering, cyclotron resonance

PACS: 73.21.Hb, 72.10.-d

1. Introduction

A GaAs/AlAs quantum well grown on a GaAs (775)B substrate has a corrugated heterointerface which is of a periodic zigzag shape in one direction and uniform in the other direction [1–3]. In transport experiments, a huge anisotropic electron mobility was observed, i.e., the mobility perpendicular to the zigzag direction is 30 – 70 times as large as that in the parallel direction [4,5]. This anisotropy is not caused by the band gap associated with the corrugation, however [6]. Actually, the zigzag corrugation has some fluctuations in its period, height, direction, etc. Effect of such disorder has been considered to the lowest order using a Boltzmann transport equation and the large anisotropy was successfully explained [7,8].

The key ingredient lies in the presence of diffuse Bragg scattering in the vicinity of the zone boundary because of a broadened Bragg peak present in the correlation function of the corrugation (see Fig. 2(b)) [7,8]. This diffuse Bragg scattering was shown to lead to a pseudo-band-structure [9] and corresponding pseudo-interband optical absorption [10]. In this paper, we demonstrate the disappearance of cyclotron resonance and the appearance of multi-peak structure in weak magnetic fields due to the formation of pseudo-open-orbits.

2. Model and method

A schematic illustration of a quantum wire array with period \( a \) and minimum and maximum well width \( d_1 \) and \( d_2 \) respectively is shown in Fig. 1. We choose the \( x \) and \( y \) directions in the direction perpendicular and parallel to quantum wires, respectively, and the \( z \) direction perpendicular to the plane. The effective potential associated with corrugation \( \Delta(\mathbf{r}) \) is well approximated by

\[
V_{\text{eff}}(\mathbf{r}) = F_{\text{eff}} \Delta(\mathbf{r}),
\]

(1)

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Preprint submitted to Physica E 7 July 2007
characterized by the correlation function
\[ \langle \Delta(r) \rangle = \frac{1}{2} \left( \frac{x}{a_1} + 1 \right), \quad 0 \leq x < a_1 \]
\[ \Delta(a - x, a_2) = 1, \quad a_1 \leq x < a \]  
\( \Delta = d_2 - d_1, \)  
where \( a_1 + a_2 = a \) and \( a_1/a_2 = 1/2. \)

The Fourier transform of \( \langle \Delta(r) \rangle \) vanishes and therefore the corrugation is characterized by four parameters, \( a, \lambda, \Delta_0, \) and \( \lambda. \)

\[ D(q) = \Delta^2 \int \left[ \frac{\nabla^2 q^2}{2\pi} \right]^{-1/2} \]
\[ \times \exp \left[ -\frac{1}{2} \left( \frac{q^2}{\Delta^2} + \nabla^2 q^2 \right) \right] \frac{a}{\sqrt{2\pi} |\nabla \xi|} \]
\[ \times \exp \left[ -\frac{1}{2} \left( \frac{a}{\Delta} \right) \frac{\nabla \xi^2}{\nabla^2 q^2} \right], \]  
with
\[ g(q) = \frac{4a}{q^2} \sin^2 \frac{qa}{2}. \]  

This correlation function is characterized by four parameters, \( a, \lambda, \Delta_0, \) and \( \lambda. \)

\[ \alpha : \text{fluctuations of the corrugation period} \]
\[ \nabla \xi : \text{fluctuations of the local quantum-wire direction} \]
\[ \Delta_0 : \text{fluctuations of the height of the corrugation averaged locally} \]
\[ \lambda : \text{correlation length of fluctuations of the height of the corrugation averaged locally in the quantum-wire direction} \]

The electron scattering probability
\[ W_{k,k'} = \frac{2\pi}{\hbar} |\langle V_{k,k'}|^2 \rangle \delta(\epsilon_k - \epsilon_{k'}), \]  
is proportional to \( D(k - k') [7], \) where \( V_{k,k'} \) is the matrix element of \( V_{\text{eff}}(r) \) and \( \epsilon_k = \hbar^2k^2/2m^* \) with effective mass \( m^*. \) The Boltzmann transport equation for the distribution function \( f_k \) is given by
\[ \frac{df_k}{dt} = -\int \frac{dE'}{(2\pi)^2} \left[ f_k(1 - f_k') - f_k'(1 - f_k) W_{k,k'} \right]. \]  

Let \( E e^{-i\omega t} \) be the applied electric field with frequency \( \omega. \) Within the liner response to \( E, \) \( f_k \) is written as
\[ f_k = f_k^0 + g_k(\omega) e^{-i\omega t}, \]  
where \( g_k(\omega) \) is the nonequilibrium and \( f_k^0 \) is the equilibrium part of the distribution function. Define \( g_k^x(\omega) \) and \( g_k^y(\omega) \) as \( g_k(\omega) \) for the electric field in the \( x \) and \( y \) direction, respectively. Define further
\[ \frac{1}{\tau_k} = \int \frac{dk'}{(2\pi)^2} \frac{2\pi}{\hbar} |\langle V_{k,k'}|^2 \rangle \delta(\epsilon_k - \epsilon_{k'}); \]
\[ g_k^x(\omega) = (-\epsilon) E h_k^x(\omega) - \frac{\partial f_k^0}{\partial \lambda}. \]

Then, Eq. (7) is rewritten as
\[ \nu^x = \left( \epsilon - \frac{1}{\tau_k} \right) h_k^x(\omega) - \omega \epsilon \frac{\partial h_k^x(\omega)}{\partial \theta} \]
\[ + \int \frac{dk'}{(2\pi)^2} \frac{2\pi}{\hbar} |\langle V_{k,k'}|^2 \rangle | \delta(\epsilon_k - \epsilon_{k'}). \]  

where \( v = \partial \epsilon_k/\hbar \partial k, \) and \( \omega_c \) is the cyclotron frequency.

### 3. Numerical Results

Figure 2(a) shows \( \delta_{xx}(\omega) \) for \( \omega_f = \omega_0 = (\hbar^2/2m^*)(\pi/a)^2 \) and for \( D(q) \) shown in Fig. 2(b). When the magnetic field is small, the dynamical conductivities have peaks at \( \omega/\omega_c = 2n \) (\( n = 1, 2, \cdots \)) and the usual cyclotron resonance at \( \omega = \omega_c \) is absent. With the increase of the field, these peaks disappear and the cyclotron resonance appears.

Figure 2(c) shows a schematic illustration of the path of the electron in the momentum space. Because of the strong diffuse Bragg scattering, the electron moves along a half circle. In the real space, this corresponds to an open orbit moving in the \( x \) direction. The resonance occurs for \( \omega/2\omega_c = n \) with \( n = 1, 2, \cdots \) for this orbit. When the magnetic field is sufficiently strong,
the probability of this Bragg scattering decreases and the cyclotron resonance is recovered due to the magnetic breakdown.

In summary, the dynamical conductivity has been calculated in a disordered quantum-wire array. Although the band structure is absent due to disorder, the strong diffuse Bragg scattering causes the formation of a pseudo open orbit and the conventional cyclotron motion disappears in magnetic fields. In a sufficiently strong magnetic field, the normal circular cyclotron motion is recovered due to the magnetic breakdown.

Acknowledgments

This work was supported in part by a 21st Century COE Program at Tokyo Tech “Nanometer-Scale Quantum Physics” from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References


