CYCLOTRON RESONANCE IN GaAs/AlGaAs SUPERLATTICES

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The cyclotron resonance of the GaAs/AlGaAs superlattice is studied by the generalized quantum Langevin equation approach to electronic transport. Divergences are eliminated from the conventional forms for the memory functions by inclusion of the effects of the fluctuation of the center of mass. In our theory there exists two resonance peaks in the CR absorption spectrum: the conventional magnetoplasmon absorption peak at the frequency $\omega > \omega_c$, and another peak at $\omega < \omega_c$ due to the fluctuation effect. The positions, amplitudes, and the relative spacing of these two peaks depend mainly on the magnetic field, the electron density, the mobility of the sample and the temperature. Our results for the CR spectrum of a single layer GaAs/AlGaAs heterojunction are consistent with the experiments of Schlesinger et al. and of Muro et al. In calculating the CR spectrum of an infinite layer GaAs/AlGaAs superlattice, we find that the peak shift becomes larger and the peak width is almost unchanged when the superlattice periodicity is reduced.

1. Introduction

Superlattices possess unusual electron properties of quasi two-dimensional (2D) character. In recent years, many aspects of the GaAs/AlGaAs superlattices have been studied [1-3]. However, cyclotron resonance (CR) in superlattices is far from understood, since a lot of CR phenomenon in a single layer of 2D electrons remains unexplained [4]. It is well known that in the presence of a perpendicular magnetic field, each energy band of an ideal two dimensional (2D) electron gas is quantized into a series of discrete Landau levels [4], and the corresponding free electron polarization function has a divergence problem. Even though a lot of theoretical efforts dealing with this problem were made in the literature [4], a rigorous cyclotron resonance (CR) theory, which also agrees with the experimental results, is still lacking. Here we report our theoretical study of CR in GaAs/AlGaAs superlattices.

Recently, we have shown that there is a physical effect which can eliminate the divergence viz. fluctuations, and that then a CR theory can be formulated [5]. In Ref. 5 we applied our theory to the short range impurity case, and obtained a good fit to the heretofore unexplained CR experimental data of Si(001) for the cyclotron effective mass and the scattering time, for a range of electron densities [4,6]. In this paper, we apply our theory to an interacting 2D electron long-range impurity system, and we study the CR phenomenon for the low temperature and high magnetic field (quantum limit) case, with application to the GaAs/AlGaAs heterojunction, in particular to an infinite system of superlattices. The formulation is based on the use of the generalized quantum Langevin equation (GLE) of the center of mass of electrons, which is obtained by eliminating the heat bath variables (relative electrons, phonons) in the Heisenberg equation of the center of mass momentum [7]. The center of mass is a massive quantity with a negligible non-commutativity to its coordinates. In our approach, the dynamical conductivity $\sigma(\omega)$ is obtained in terms of the memory function $M(\omega)$, which is essentially the Fourier transform of the memory function appearing in the GLE. When the fluctuation effect of the center of mass is included, a divergence free calculation for the CR can be performed.

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2. Formulation

Our model for the GaAs/AlGaAs superlattice is that of infinitely many parallel 2D electron layers (density n_s) with a separation length d between adjacent layers. The electrons are scattered by the electron-electron interactions

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in the random phase approximation (RPA) and by the electron-impurity interactions with the impurity sheets (doped layers) separated from the 2D electrons by a distance a. By incorporating into our GLR the standard procedure of treating the superlattice effect of the 2D electrons [2,3], we obtain the memory function of the superlattice in the RPA approximation as

$$M(\omega) = \omega_c \frac{n_i}{n_s} \frac{e^2}{\kappa_{sc} \ell_o \omega_c} \int dx \frac{x^2}{y\, H(x) S(xd/\ell_o)} \left| \frac{1}{\varepsilon(x,o)} - \frac{1}{\varepsilon(x,y)} \right|^2 \left| e^{-ax/2} + [S(xd/\ell_o)-1] \cosh \frac{ax}{2} \right|^2 , \quad (1)$$

where $x = q\ell_o$, $y = \omega/\omega_c$, $\omega_c = eB/mc$, $\ell = (\hbar/m\omega)^{1/2}$, $a = 2\alpha/\ell$, n_i is the impurity density, κ_{sc} is the dielectric constant of the static lattice and $\varepsilon(q,\omega)$ is the RPA dielectric function of wave vector q, which contains the Coulomb potential treated by the standard Fang-Howard-Stern (FHS) variational scheme for the 2D electron gas [4] and the zero mode (i.e. $k_z = 0$ in Eq. (39) of [4]) superlattice structure factor

$$S(q) = \frac{\sinh qd}{\cosh qd - 1} . \quad (2)$$

In addition, $H(x)$ is the result for the structure factor resulting from the standard FHS variational treatment of the electron-electron and electron-impurity interactions.

The superlattice a.c. conductivity tensor element $\sigma_+ = \sigma_{xx} + i\sigma_{yx}$ (electric field is in x-direction) is expressed in the familiar form

$$\sigma_+(\omega) = \frac{in_s e^2/m}{\omega - \omega_c + M(\omega)} . \quad (3)$$

The evaluation of the memory function $M(\omega)$ of (1) remains a controversial question, arising from the proper handling of the well-known divergence of the free electron polarization function associated with the RPA dielectric function $\varepsilon(q,\omega)$. In a recent paper [5], we have demonstrated that there is a physical effect which can eliminate the divergences viz. fluctuations, and that the electron polarization function associated with the dielectric function $\varepsilon(q,\omega)$ is

$$\pi_{nn'}(q,\omega) = \frac{f(\varepsilon_n) - f(\varepsilon_{n'})}{\hbar\omega - (\varepsilon_{n'} - \varepsilon_n) + i\, Dq^2} , \quad (4)$$

where $\varepsilon_n = (n + 1/2)\hbar\omega_c - \varepsilon_F$, ε_F is the Fermi energy of the electron gas, $f(x)$ is the Fermi distribution function, and D is the diffusion constant defined in terms of the ensemble average of the coordinate fluctuations $\delta R^2(t)$ of the center of mass

$$D = \ell \lim_{t\to\infty} \frac{1}{2t} \overline{\delta R^2(t)} . \quad (5)$$

As we have shown elsewhere [7], D is proportional to the inverse of the number of particles N and thus the fluctuation effects are most pronounced for small systems with low-electron concentrations. Since D is difficult to evaluate numerically, we will treat it as a parameter (while retaining the property of being inversely proportional to N) in the following calculation.

3. Numerical Results and Discussion

The memory function (1) is the key quantity in our theory. Our numerical calculation reveals that the real part $M_1(y)$ is an oscillating function of ω, which is positive at the low frequency side and has its first zero at $\omega \gtrsim \omega_c$, while the imaginary part is a positive function. On the other hand, from (3), the absorption peak position is mainly determined by the solution of $M_1(y)/\omega_c = 1-y$. Thus, due to the oscillating behavior of $M_1(y)$, there may exist two resonance peaks in the CR absorption spectrum in our theory. One is the conventional magnetoplasmon absorption peak at the frequency $\omega > \omega_c$ (where $M_1(y) < 0$), and the other peak is at $\omega < \omega_c$ due to fluctuation effects. The positions, magnitudes, half widths, and the separation of these two peaks depend on the B, n_s and the mobility of the sample. Our results for the CR spectrum of a single GaAs/AlGaAs heterojunction (i.e. $d=\infty$, $S(x)=1$ in (1)) are very consistent with the experiments of Schlesinger et al. [8] and Muro et al. [9]. Fig.1 is an example of comparison between our numerical results, where the fitting parameter $D^* = mD/\hbar = 0.2$ is used, and the experimental result of Muro et al., which was performed for a GaAs/AlGaAs FET system.

Based on the agreement between our calculated CR spectrum and that of the experimental results for the single layer 2D electrons, we now extend our theory to the case of an infinite layer of superlattice, in particular to study the influence of the periodicity d of the superlattice on the CR spectrum as compared to the single layer case. We take standard values as in the single layer case: $m=0.07m_e$, $\kappa_{sc}=13.1$, $a = 50\text{Å}$, and $n_i=n_s$, and calculate the memory function (1) and the CR absorption spectrum (4) at different superlattice periodicities d. Our study reveals that when d is in the physical region, the memory function and the CR spectrum of the superlattice will have the same qualitative behavior as that of the single heterojunction discussed in the previous paragraph. Quantitatively, our numerical results show that while the imaginary part of the memory function $M_2(\omega)$ is not very sensitive to d, $M_1(\omega)$ will

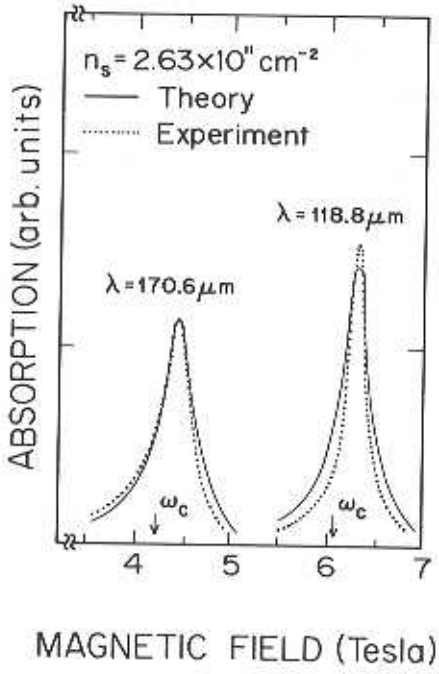

Fig. 1. A comparison between the theoretical and experimental [9] CR spectrum of the GaAs/AlGaAs heterojunction at two infrared frequencies. D* = 0.2 is used to obtain the best fit for the theoretical curves.

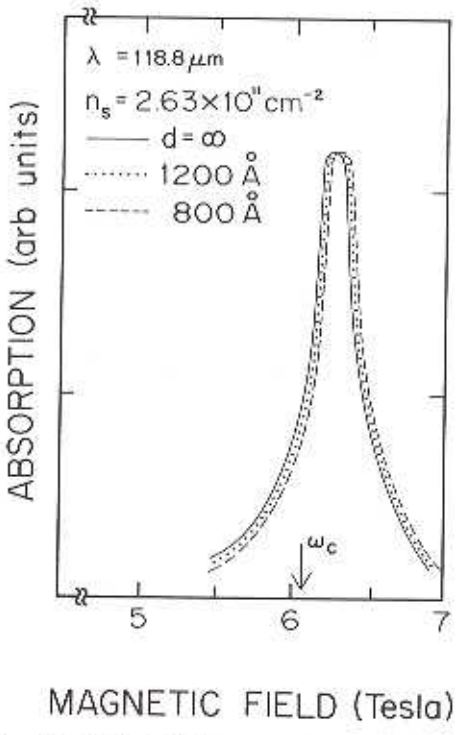

Fig. 2. Theoretical CR spectrum for the GaAs/AlGaAs superlattice, with an infinite number of layers, at three different periodicities d. D* = 0.2 is used.

increase if d is decreased when it is of the order of 10^3 Å. As a result, the CR peak shift which is found for the single layer ($d=\infty$) case, will become larger when d becomes smaller but the peak width is almost unchanged. This is illustrated by Fig. 2, where we have plotted our calculated CR spectrum as a function of magnetic field at three different d values. To our knowledge no experimental data has been published in this respect. We hope the present calculation will stimulate more experimental interest.

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