Transport properties of two dimensional electrons in periodically modulated magnetic fields

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Abstract

We study both classical and quantum transports in two dimensional electron gas (2DEG) numerically, where magnetic fields are applied perpendicular to the plane of 2DEG and are periodically modulated. Due to the non-homogeneous magnetic fields, the system becomes chaotic. In the classical model, we show the commensurability oscillation of magnetoresistance in periodic magnetic fields. The negative magnetoresistance is observed when the conductivity σ_{xx} is small. The quantum transport is also investigated, and the universal conductance fluctuations as well as the fractal behavior of the magnetoconductance are observed.

Key words: ballistic transport; periodic magnetic field; quantum chaos; UCF

1. Introduction

We numerically investigate both classical and quantum transport properties in the presence of periodically modulated magnetic fields. The system with periodic modulation of magnetic fields is a kind of chaotic system, and various interesting phenomena which originate from the chaoticity are observed [1]. Applying periodic fields is an easier way to realize chaotic systems than fabricating the geometry of samples, and furthermore, we can observe peculiar effects which are different from systems in chaotic geometries. In the classical model, we adopt and use the Kubo formula to obtain the transport coefficients. We found the commensurability effect similar to the antidot systems [2]. In ref.3, the average of the modulated fields B_{M} is positive. New features appear when the average of B_{M} is vanishing, which is discussed below. In the quantum model, we use tight-binding model and study the energy level statistics and the two terminal conductance. To calculate energy level statistics, we diagonalize the Hamiltonian by the Householder method. The distribution function $P(s)$ of adjacent level spacing shows peculiar behavior different from disordered systems in uniform magnetic fields. The two terminal conductance given by Landauer formula is calculated using recursive Green's function method [4].

2. Classical Transport

Besides an external uniform magnetic field B_{U}, the periodically modulated magnetic fields B_{M} are applied perpendicular to the plane of 2DEG. We assume modulated magnetic fields B_{M} to be

$$B_{\mathrm{M}}(x,y) = B_{\mathrm{M}}^{0}[\sin(\pi x/a_0)\sin(\pi y/a_0)]^{\alpha}, \qquad (1)$$

where α controls the steepness of modulation. The factor B_{M}^{0} in eq.(1) determines the maximum value of the modulated magnetic field, a_0 is periodicity of modulation. We ignore inelastic scattering mechanism in this system. We use Kubo formula

$$\sigma_{ij} \propto \int_0^{\infty} e^{-t/\tau}\langle v_i(t_0+t)v_j(t_0)\rangle \mathrm{d}t \qquad (2)$$

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to obtain the conductivity. In Fig. 1 results in the case of $\alpha = 1$ for the longitudinal resistance ρ_{xx} as a function of the externally applied field $B_{\rm U}$ are shown. When the resistance at $B_{\rm U} = 0$ is large, we observe negative magnetoresistance.

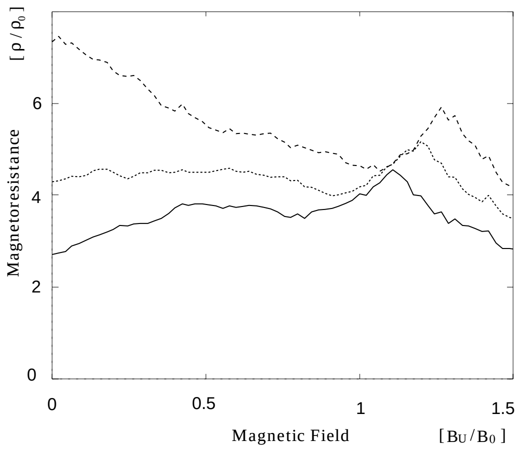

Fig. 1. Magnetoresistance ρ_{xx} in the case of $\alpha = 1$. The solid line corresponds to $B_{\rm M}^0 = 1.4$, the dotted $B_{\rm M}^0 = 1.6$, and the dashed $B_{\rm M}^0 = 1.8$. The magnetoresistance is normalized by the longitudinal resistance ρ_0 in zero field and the magnetic field is normalized by commensurability magnetic field $B_0 = 2m^* v_{\rm F}/ea_0$, m^* being the effective mass and $v_{\rm F}$ the Fermi velocity.

3. Quantum Transport

The quantum transport in a chaotic system has been attracting great interests. We now discuss the quantum transport in the presence of periodic magnetic fields. To describe the two dimensional electron system with periodically modulated magnetic fields, we use the following tight-binding Hamiltonian.

$$H = -\sum_{\langle i,j \rangle} V_{i,j} C_i^\dagger C_j, \quad V_{i,j} = t \exp[i\theta_{i,j}] \tag{3}$$

We assume a square lattice periodically modulated magnetic field $B_{\rm M}$ as in eq.(1) and use two approaches to study this system. One is the energy level statistics in the isolated system obtained by the direct diagonalization of the Hamiltonian matrices. The $P(s)$ shows GOE behavior in the presence of spatial symmetry and GUE in the absence of it. We also study the two terminal conductance in open systems. Leads with width W are attached at opposite corner of the square region. To calculate conductance in this system, we use Landauer formula given by

$$G = \frac{e^2}{\pi\hbar} \sum_{\mu\nu} |t_{\mu\nu}|^2 \tag{4}$$

Fig.2 shows conductance $G(B_{\rm M})$ calculated by eq.(4) as a function of $B_{\rm M}$ in units of the correlation field B_ξ. We obtain universal conductance fluctuations in periodically modulated magnetic field. The variance of the conductance in the chaotic system is ${\rm Var}G/G_0 = 1/8\beta$. Our results are consistent with this. With spatial symmetry, the system belongs to the orthogonal class, while the system belongs to the unitary class when the modulation field is no longer symmetric.

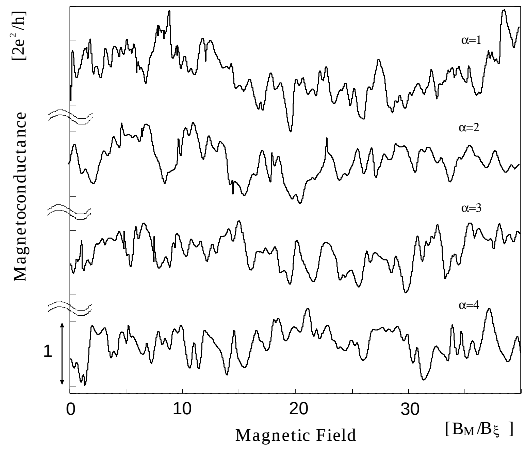

Fig. 2. Conductance fluctuation as a function of $B_{\rm M}$. The system size $L = 100$, width of lead $W = 10$, and $E_{\rm F}/t = 0.95$. The conductance is scaled by conductance quantum $2e^2/h$ and the magnetic field is scaled by correlation field B_ξ. The modulated magnetic fields are not symmetric.

4. Summary

To summarize, we have studied the transport properties in two dimensional periodically modulated magnetic fields by numerical simulation. In the classical model, we show the commensurability oscillation of magnetoresistance and the negative magnetoresistance at low external field. In the quantum model, we have examined the conductance fluctuations. The parity of the modulation parameter α and the spatial symmetry of the modulated fields characterizes the transport properties of this system.

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