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Differential Resistance of two dimensional electron gas subject to microwave radiation

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We present the expression for differential resistance of a disordered two-dimensional electron gas placed in a perpendicular magnetic field and subject to microwave irradiation. We demonstrate that in strong dc electric fields the current oscillates as a function of the strength of the applied constant electric field. We demonstrate that the amplitude of oscillations of the differential resistivity is characterized by the back-scattering rate off disorder. We argue that the dominant contribution to the non-linearity in strong electric fields originates from the modification of electron scattering off disorder by electric fields, or so-called "displacement" mechanism. The non-equilibrium mechanism, which is related to modification of electron distribution function by electric fields turns out to be inefficient in strong electric fields, although it describes current in weak electric fields. We further analyze the positions of maxima and minima of the differential resistance as a function of the applied electric field and frequency of microwave radiation.

Keywords: Quantum Hall system; differential resistance; magnetotransport.

1. Introduction

The measured transport coefficients of the two-dimensional electron systems (2DES) formed in high-mobility GaAs/AlGaAs heterostructures are strongly non-linear functions of external parameters. One manifestation of such non-linear behavior is the effect of the microwave radiation on dc conductivity of 2DES, which results in giant magnetooscillations¹ and an appearance of the zero resistance states (ZRS)^{2,3}. This phenomenon was also observed by many other experimental groups^{4,5,6} and was the focus of numerous theoretical publications^{7,8,9,10,11,12,13,14}. Similar oscillatory dependence on magnetic field of the differential resistivity of 2DES in static electric fields was discovered^{15,16,17,18}. Further experiments^{19,20} demonstrated even more complicated behavior of 2DES in combined dc and microwave electric fields. All these observations call for further theoretical work in this area. Quantitative theory will help to extract various microscopic parameters of 2DES from experimental

data.

In this paper we discuss the behavior of current in mixed constant and oscillating electric fields. We focus on the limit of strong electric fields, the regime where the current oscillations develop. In this limit, we can neglect the non-equilibrium contribution to current¹², which arises due to the modification of electron distribution function by electric fields. The non-equilibrium contribution is characterized by the inelastic rate of electron distribution function, and this rate is typically small at low temperatures and in weak electric fields²¹. However, the electron scattering off disorder in strong electric fields also leads to suppression of the non-equilibrium distribution function and therefore, the contribution to current due to non-equilibrium mechanism turns out to be smaller than the contribution, arising from the displacement mechanism^{22,7,11}.

2. Differential resistivity

We present the expressions for the differential resistance

$$\rho = \partial E_{\parallel} / \partial j, \quad (1)$$

where E_{\parallel} is the electric field in the direction parallel to the current in the 2DES, details of calculations will be presented elsewhere²³. We consider the effect of interplay between electron motion in crossed magnetic and electric fields and scattering off disorder. We assume that disorder is completely characterized by electron scattering rate $1/\tau_{\theta}$ on angle θ . In particular, the quantum scattering rate and the transport scattering rate, which appear below, are determined by $1/\tau_{\theta}$ through standard expressions

$$\frac{1}{\tau_{\text{tr}}} = \int \frac{1 - \cos \theta}{\tau_{\theta}} \frac{d\theta}{2\pi}, \quad \frac{1}{\tau_{\text{q}}} = \int \frac{1}{\tau_{\theta}} \frac{d\theta}{2\pi}. \quad (2)$$

Within this model, the differential resistivity in the limit of large constant currents can be represented as a sum of the Drude resistivity ρ_{D} and the non-linear correction $\delta\rho$, i.e.

$$\rho = \rho_{\text{D}} + \delta\rho; \quad \rho_{\text{D}} = \frac{2}{e^2 \nu_0 v_{\text{F}}^2 \tau_{\text{tr}}}, \quad \frac{\delta\rho}{\rho_{\text{D}}} = \frac{(4\lambda)^2 \tau_{\text{tr}}}{\pi \tau_{\pi}} F(\epsilon_{\text{dc}}, \epsilon_{\text{ac}}, \mathcal{P}_{\omega}). \quad (3)$$

Here ν_0 is the electron density of states in zero magnetic field and v_{F} is the Fermi velocity. The non-linear correction to the resistivity is proportional to the rate of backscattering off disorder $1/\tau_{\pi}$ and the square of parameter λ . Parameter $\lambda = \exp(-\pi/\omega_c \tau_{\text{q}})$ gives the amplitude of oscillations in the density of states for overlapping Landau levels, $\nu(\epsilon) = \nu_0 [1 - 2\lambda \cos(2\pi\epsilon/\omega_c)]$, when $\omega_c \tau_{\text{q}} \lesssim 1$. Function $F(\epsilon_{\text{dc}}, \epsilon_{\text{ac}}, \mathcal{P}_{\omega})$ is defined as

$$F(\epsilon_{\text{dc}}, \epsilon_{\text{ac}}, \mathcal{P}_{\omega}) = \cos 2\pi \epsilon_{\text{dc}} J_0 \left(4\sqrt{\mathcal{P}_{\omega}} \sin \pi \epsilon_{\text{ac}} \right) - \frac{2\epsilon_{\text{ac}}}{\epsilon_{\text{dc}}} \sin 2\pi \epsilon_{\text{dc}} \cos \pi \epsilon_{\text{ac}} \sqrt{\mathcal{P}_{\omega}} J_1 \left(4\sqrt{\mathcal{P}_{\omega}} \sin \pi \epsilon_{\text{ac}} \right), \quad (4)$$

where $J_n(x)$ are the Bessel functions. Here we introduced dimensionless parameters

$$\epsilon_{dc} = \frac{4\pi j}{en\lambda_F\omega_c}, \quad \epsilon_{ac} = \frac{\omega}{\omega_c}, \quad \mathcal{P}_\omega = \frac{v_F^2 e^2 E_\omega^2}{\omega^2 (\omega \pm \omega_c)^2}. \quad (5)$$

These parameters are proportional to the magnitude of constant current j , the frequency ω and the power of microwave radiation, respectively.

The above result, Eq. (3), is applicable when the following conditions are met: (i) Landau levels overlap, or $\omega_c\tau_q \lesssim 1$; (ii) the electron temperature T is large, $T \gg \max\{\omega_c, \omega\}$; (iii) constant electric current is large, $\epsilon_{dc} \gg 1$. The latter inequality allows us to neglect contribution to current from the formation of the non-equilibrium distribution function. We also note that the expression for the microwave power is written for a circular polarization of microwave radiation, the sign in the denominator should be chosen according to the orientation of magnetic field and sense of microwave polarization.

In the absence of microwave radiation $F(\epsilon_{dc}, \epsilon_{ac}, 0) = \cos 2\pi\epsilon_{dc}$, we recover the previous result of ²¹. Figure 1 shows $F(\epsilon_{dc}, \epsilon_{ac}, \mathcal{P}_\omega)$ as a function of ϵ_{dc} for several values ϵ_{ac} and \mathcal{P}_ω . We now analyze behavior of $F(\epsilon_{dc}, \epsilon_{ac}, \mathcal{P}_\omega)$ at small values of

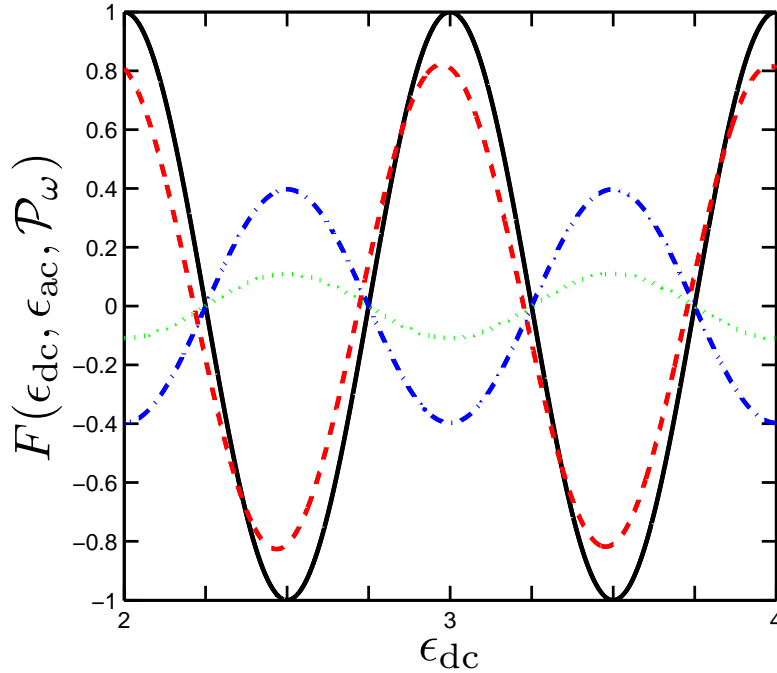


Fig. 1. (Color online) The function $F(\epsilon_{dc}, \epsilon_{ac}, \mathcal{P}_\omega)$ as defined by Eq. (4) for (a) $\epsilon_{ac} = 2.25$, $\mathcal{P}_\omega = 0$, solid line (black); (b) $\epsilon_{ac} = 2.25$, $\mathcal{P}_\omega = 0.1$, dashed line (red); (c) $\epsilon_{ac} = 2.5$, $\mathcal{P}_\omega = 1$ dashed dotted line (blue); (d) $\epsilon_{ac} = 2.5$, $\mathcal{P}_\omega = 8$, dotted line (green).

microwave power, $\mathcal{P}_\omega \ll 1$. Using the series expansion of Bessel functions, $J_0(x) \simeq 1 - x^2/4$ and $J_1(x) \simeq x/2$, we obtain

$$F(\epsilon_{\text{dc}}, \epsilon_{\text{ac}}, \mathcal{P}_\omega) = (1 - 2\mathcal{P}_\omega) \cos 2\pi\epsilon_{\text{dc}} + 2\mathcal{P}_\omega \left[\cos 2\pi\epsilon_{\text{dc}} \cos 2\pi\epsilon_{\text{ac}} - \frac{\epsilon_{\text{ac}}}{\epsilon_{\text{dc}}} \sin 2\pi\epsilon_{\text{dc}} \sin 2\pi\epsilon_{\text{ac}} \right]. \quad (6)$$

We briefly investigate the position of maxima and minima of the differential resistance as a function of ϵ_{dc} and ϵ_{ac} at small powers of microwave radiation, $\mathcal{P}_\omega \lesssim 1$. In this case, $F(\epsilon_{\text{dc}}, \epsilon_{\text{ac}}, \mathcal{P}_\omega) \propto (\epsilon_{\text{dc}} + \epsilon_{\text{ac}}) \cos(\epsilon_{\text{dc}} + \epsilon_{\text{ac}}) + (\epsilon_{\text{dc}} - \epsilon_{\text{ac}}) \cos(\epsilon_{\text{dc}} - \epsilon_{\text{ac}})$. The resistance reaches the maximum when both terms of the last expression are at their maximum. For $\epsilon_{\text{ac}} > \epsilon_{\text{dc}}$ this gives $(\epsilon_{\text{ac}}, \epsilon_{\text{dc}})^{\text{max}} = (m \pm 1/4, n \mp 1/4)$, with m, n being integers. The condition for the minimum of the resistance reads $(\epsilon_{\text{ac}}, \epsilon_{\text{dc}})^{\text{min}} = (m \pm 1/4, n \pm 1/4)$. In particular, if $\epsilon_{\text{dc}} \simeq \epsilon_{\text{ac}}$, function $F(\epsilon_{\text{dc}}, \epsilon_{\text{ac}}, \mathcal{P}_\omega)$ can be written in the form

$$F(\epsilon_{\text{dc}}, \epsilon_{\text{ac}}, \mathcal{P}_\omega) \approx (1 - 2\mathcal{P}_\omega) \cos 2\pi\epsilon_{\text{dc}} + 2\mathcal{P}_\omega \cos [2\pi(\epsilon_{\text{dc}} + \epsilon_{\text{ac}})] . \quad (7)$$

We notice that a direct addition of two different parameters ϵ_{dc} and ϵ_{ac} has no physical meaning. However, we believe that, in the considered region $\epsilon_{\text{dc}} \simeq \epsilon_{\text{ac}}$, it is the second term which is responsible for experimentally observed structure¹⁹ of the differential resistance as a function of the sum $\epsilon_{\text{ac}} + \epsilon_{\text{dc}}$.

3. Conclusions

We calculated the differential resistivity of two dimensional electron gas at large values of magnitude of direct current. We found that the differential resistivity indeed exhibits magneto-oscillations and the phase of these oscillations is affected by the frequency of microwave radiation. The amplitude of magnetooscillations of the resistivity is proportional to the rate of electron backscattering off impurities, and therefore, measurements of the differential resistivity can be used to characterize the structure of disorder in two-dimensional electron systems in heterostructures.

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