

# Oscillations of Nonlinear Magnetoresistance in Microwave-Irradiated 2D Semiconductors

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**Abstract**—This presentation gives an introduction to the magnetoresistance oscillations recently discovered in high-mobility two-dimensional semiconductors at low temperatures, which are induced by a microwave radiation, a dc current, an acoustic phonon, or a combination of them, and a comprehensive review of a nonlinear magnetotransport model, which enables a unified description for all these oscillations.

## I. MAGNETORESISTANCE OSCILLATIONS

The electron transport of a two-dimensional (2D) semiconductor subjected to a magnetic field exhibits a great many fascinating phenomena especially at low temperatures. Besides the most famous quantum Hall effect appearing in strong magnetic fields, different types of magnetoresistance oscillations can emerge in relatively weak magnetic fields.

Among them the Shubnikov-de Haas oscillation (SdHO) in the linear longitudinal magnetoresistivity has long been well known. SdHOs are periodic in inverse magnetic field  $1/B$  and controlled by the filling factor  $\nu = \varepsilon_F/\omega_c$  ( $\varepsilon_F$  is the Fermi energy and  $\omega_c$  is the cyclotron frequency of the electron system in the magnetic field) having a period  $\Delta\nu = 1$ . It exists only at fairly low temperature when the thermal broadening of the electron distribution is much smaller than the energy of Landau quantization, and is quickly suppressed by the rising temperature.

Over the past few years, several other types of magnetoresistance oscillations have been discovered in high-mobility 2D electron systems subject to a weak perpendicular magnetic field. These resistance oscillations all are periodic in  $1/B$ , show up in magnetotransport of 2D electrons occupying high Landau levels and persist to a considerably higher temperature at which SdHO has been fully smeared out. But when temperature further increases to above a few kelvin, most of them decay rather rapidly.

First of them is the radiation-induced magnetoresistance oscillation (RIMO), which has become a central focus of many experimental [1], [2], [3], [4], [5], [6], [7] and theoretical [8], [9], [10], [11], [12] studies, since the surprising observation of the accompanied zero-resistance states [1], [2]. Under the influence of a modest irradiation of frequency  $\omega$  in the sub-millimeter wave range, the magnetoresistance of a 2D electron system oscillates periodically with changing parameter  $\epsilon_\omega = \omega/\omega_c$ , exhibiting peak-valley structures around  $\omega/\omega_c = k$  ( $k = 1, 2, 3, 4, \dots$ ), i.e. a maximum at  $\omega/\omega_c = k - \delta_k^-$ , a minimum at  $\omega/\omega_c = k + \delta_k^+$ , and a node at  $\omega/\omega_c = k$  ( $\delta_k^\pm = 0.15 \sim 0.25$ ).

Further investigations demonstrate that in the case without radiation the nonlinear magnetoresistance can also oscillate when a finite dc current  $J = N_s e v$  ( $N_s$  and  $v$  are the density and drift velocity of electrons) flows in the 2D system [13], [14]. This current-induced magnetoresistance oscillation is controlled by a parameter  $\epsilon_j = 2k_F v/\omega_c$  ( $k_F$  is the Fermi wavevector), proportional to the ratio of the current density to the cyclotron frequency. In the presence of both a radiation and a finite current, the combined parameter  $\epsilon_\omega + \epsilon_j$  is found to control the main magnetoresistance oscillations [15], [16].

Recently, the magnetophonon resonance in semiconductors, previously known to result from electron coupling with optic phonons and can be observed only at high temperatures and high magnetic fields, has been demonstrated to occur in the linear resistivity at temperatures as low as  $T \sim 2$  K and lower magnetic fields in GaAs-based heterosystems [17], [18]. This resonant linear magnetoresistance was referred to as electron scatterings by acoustic phonons. The positions of resonant peaks are also periodic in  $1/B$ , and controlled by a parameter  $\epsilon_p = \omega_s/\omega_c$ , with  $\omega_s = 2k_F v_s$ , the energy of a wavevector- $2k_F$  acoustic phonon having velocity  $v_s$ . Furthermore, these phonon-induced resistance resonances are dramatically enhanced in the nonlinear dc response and when the electron drift velocity (current density) increases to the speed of sound, additional and prominent phonon resonance peaks emerge [19].

## II. A UNIFIED MODEL

A nonlinear magnetotransport model is developed with a unified microscopic treatment for all these magnetoresistance oscillations [11]. The mechanism of these magnetooscillations is referred to an additional energy  $\Delta\varepsilon$  obtained (or released) by an electron during its transition from a Landau state to another state due to impurity and phonon assisted scatterings. This energy can be provided by a microwave radiation ( $\Delta\varepsilon = \omega$ ), by a dc current ( $\Delta\varepsilon \approx \omega_j$ ), by an acoustic phonon ( $\Delta\varepsilon \approx \omega_s$ ), or by a combination of them, resulting in an extra frequency  $\omega$ ,  $\omega_j$ ,  $\omega_s$ , or  $\omega \pm \omega_j \pm \omega_s$ , in the frequency argument of the electron density correlation function  $\Pi_2(\mathbf{q}_\parallel, \Omega)$  in the damping force against the electron drift motion. Since in a magnetic field the density correlation function is frequency periodic due to periodical Landau level structure,  $\Pi_2(\mathbf{q}_\parallel, \Omega) \sim \Pi_2(\mathbf{q}_\parallel, \Omega + \omega_c)$ , change of  $\omega$ ,  $\omega_j$ ,  $\omega_s$ , or  $\omega \pm \omega_j \pm \omega_s$  will lead to oscillation of related physical quantities. When  $\omega$ ,  $\omega_j$ ,  $\omega_s$ , or  $\omega \pm \omega_j \pm \omega_s$  varies by a value of  $\omega_c$ , the related quantities

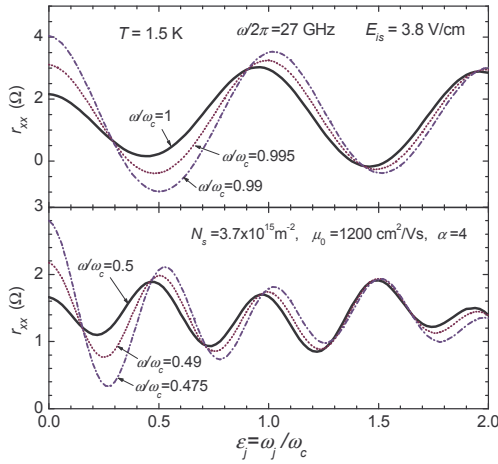


Fig. 1. Magnetoresistivity  $r_{xx}$  vs  $\epsilon_j = \omega_j/\omega_c$  subject a microwave of  $\omega/2\pi = 27$  GHz at  $\omega/\omega_c = 1, 0.995, 0.99, 0.5, 0.4878$  and  $0.4762$  [24].

will experience a change of one oscillation period, suggesting  $\epsilon_\omega$ ,  $\epsilon_j$ ,  $\epsilon_p$ , or  $\epsilon_\omega \pm \epsilon_j \pm \epsilon_p$ , to serve as the parameter to control the oscillation. Thus achieves a unified explanation for microwae-induced magnetoresistance oscillations [20], dc current-induced magnetoresistance oscillations [21], acoustic phonon-induced magnetoresistance oscillations [22], and those induced by a combination of them [23], [24].

This theoretical model not only reproduces the main features of RIMOs, predicts the appearance of the measured zero resistance, but also explains the other prominent experimental observations, including: (1) additional peak-valley structures at fractional  $\omega/\omega_c = 1/2, 2/3, 3/2$  due to multiphoton processes under enhanced radiation; (2) strong sppression of the average dissipative resistance by the irradiation; (3) remarkable amplitude modulation of SdH oscillations; (4) rapid diminution of RIMOs by a few degree rise of temperature; (5) why RIMOs do not appear in lower mobility samples; (6) why RIMOs are unlikely to show up in 2D hole systems; (7) what may happen when the radiation frequency is higher than 0.3 THz; (8) new peak-valley pairs and zero-resistance states under bichromatic radiation; (9) why the amplitude of current-induced resistance decreases with increasing current density for fixed magnetic field; (10) why phonon resonances are dramatically enhanced by the application of a finite current; (11) why new magnetophonon resonance peaks emerge when the electron drift velocity  $v$  gets to the supersonic regime ( $v \geq v_s$ ); (12) why there exists an optimal temperature at which a given order  $\epsilon_j$  of phonon resistance maximum best emerges; (13) why under a  $\omega$ -microwave driving the frequency of the resistance oscillation with  $\epsilon_j$  at subharmonics  $\omega/\omega_c = 1/2$  is twice that at cyclotron resonance and its harmonics [24].

Fig. 1 shows the differential resistivity  $r_{xx}$  as a function of  $\epsilon_j = \omega_j/\omega_c$  for a GaAs-based semiconductor irradiated by a 27 GHz microwave at  $T = 1.5$  K [24].

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