Oscillations of Nonlinear Magnetoresistance in Microwave-Irradiated 2D Semiconductors

X. L. Lei
Department of Physics, Shanghai Jiao Tong University, Shanghai, China
Email: xllei@sjtu.edu.cn

***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 $\nu = \varepsilon_F/\omega_c$ (ε_F is the Fermi energy and ω_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 ω in the submillimeter wave range, the magnetoresistance of a 2D electron system oscillates periodically with changing parameter $\epsilon_\omega = \omega/\omega_c$, exhibiting peak-valley structures around $\omega/\omega_c = k$ ($k = 1, 2, 3, 4, ...$), 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 $J = N_s ev$ (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 $T \sim 2\,\mathrm{K}$ 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 magnetoresitance 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 ω, ω_j, ω_s, or $\omega \pm \omega_j \pm \omega_s$, in the frequency argument of the electron density correlation function $\Pi_2(\boldsymbol{q}_\|, \Omega)$ 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, $\Pi_2(\boldsymbol{q}_\|, \Omega) \sim \Pi_2(\boldsymbol{q}_\|, \Omega + \omega_c)$, change of ω, ω_j, ω_s, or $\omega \pm \omega_j \pm \omega_s$ will lead to oscillation of related physical quantities. When ω, ω_j, ω_s, or $\omega \pm \omega_j \pm \omega_s$ varies by a value of ω_c, the related quantities

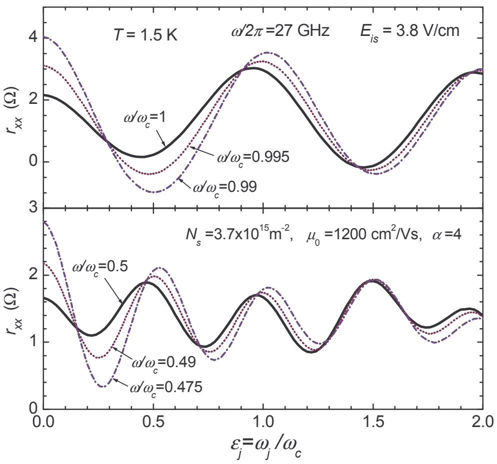

Fig. 1. Magnetoresistivity r_{xx} vs $\epsilon_j = \omega_j/\omega_c$ subject a microwave of $\omega/2\pi = 27\,\text{GHz}$ at $\omega/\omega_c = 1$, 0.995, 0.99, 0.5, 0.4878 and 0.4762 [24].

will experience a change of one oscillation period, suggesting ϵ_ω, ϵ_j, ϵ_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 mulitphoton 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 ϵ_j of phonon resistance maximum best emerges; (13) why under a ω-microwave driving the frequency of the resistance oscillation with ϵ_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 $T = 1.5\,\text{K}$ [24].

Acknowledgment

The author thank NSF (Nos. 10734021 and 60866064) and NBRP (No. 2007CB310402) of China for support.

References

[1] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayanamurti, W. B. Johnson, and V. Umansky, "Zero-resistance states induced by electromagnetic-wave excitation in GaAs/AlGaAs hetrostructures", *Nature* **420**, 646 (2002);

[2] M. A. Zudov, R. R. Du, L.N. Pfeiffer, and K. W. West, "Evidence for a new dissipationless effect in 2D electron transport", *Phys. Rev. Lett.* **90**, 046807 (2003);

[3] M. A. Zudov, R. R. Du, J. A. Simmons, and J. L. Reno, "Shubnikov-de Haas-like oscillations in millimeterwave photoconductivity in a high-mobility two-dimensional electron gas", *Phys. Rev. B* **64**, 201311(R) (2001).

[4] P. D. Ye, L. W. Engel, D. C. Tsui, J. A. Simmons, J. R. Wendt, G. A. Vawter, and J. L. Reno, "Giant microwave photoresistance of two-dimensional electron gas", *Appl. Phys. Lett.* **79**, 2193 (2001).

[5] S. I. Dorozhkin, "Giant magnetoresistance oscillations by cyclotron resonance harmonics", *JETP Lett.* **77**, 577 (2003).

[6] R. L. Willett, L.N. Pfeiffer, and K. W. West, "Evidence for current-flow anomalies in the irradiated 2D electron system at small magnetic field", *Phys. Rev. Lett.* **93**, 026804 (2004).

[7] A. T. Hatke, M. A. Zudov, L.N. Pfeiffer, and K. W. West, "Temperature dependence of microwave photoresistance in 2D electron systems", *Phys. Rev. Lett.* **102**, 066804 (2009).

[8] V. I. Ryzhii, "Photoconductivity characteristics in thin films subjected to crossed electric and magnetic fields", *Sov. Phys. Solid State* **11**, 2078 (1970).

[9] A. C. Durst, S. Sachdev, N. Read, and S. M. Girvin, "Radiation-induced magnetoresistance oscillations in a 2D electron gas", *Phys. Rev. Lett.* **91**, 086803 (2003).

[10] I. A. Dmitriev, A. D. Mirlin, and D. G. Polyakov, "Cyclotron-resonance harmonics in the ac response of a 2D electron gas with smooth disorder", *Phys. Rev. Lett.* **91**, 226802 (2003).

[11] X. L. Lei and S. Y. Liu, "Radiation-induced magnetoresistance oscillation in a two-dimensional electron gas in Faraday geometry", *Phys. Rev. Lett.* **91**, 226805 (2003).

[12] M. G. Vavilov and I. L. Aleiner, "Magnetotransport in two-dimensional electron gas at large filling factors", *Phys. Rev. B* **69**, 035303 (2004).

[13] C. L. Yang, J. Zhang, R. R. Du, J. A. Simmons, J. L. Reno, "Zener tunneling between Landau orbits in a high-mobility two-dimensional electron gas", *Phys. Rev. Lett.* **89**, 076801 (2002).

[14] W. Zhang, H. -S. Chiang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, "Magnetotransport in a two-dimensional electron system in dc electric fields", *Phys. Rev. B* **75**, 041304(R) (2007).

[15] W. Zhang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, "Resistance oscillations in two-dimensional electron systems induced by both ac and dc fields", *Phys. Rev. Lett.* **98**, 106804 (2007).

[16] A. T. Hatke, H. -S. Chiang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, "Nonlinear magnetotransport in microwave-illuminated two-dimensional electron systems", *Phys. Rev. B* **77** , 201304(R) (2008).

[17] M. A. Zudov, I. V. Ponomarev, A. L. Efros, R. R. Du, J. A. Simmons, and J. L. Reno, "New class of magnetoresistance oscillations: Interaction of a two-dimensional electron gas with leaky interface phonons", *Phys. Rev. Lett.* **86**, 3614 (2001).

[18] A. A. Bykov, A. K. Kalagin and A. K. Bakarov, "Magnetophonon resonance in a GaAs quantum well with AlAs/GaAs superlattice barriers at high filling factors", *JETP Lett.* **81**, 523 (2005).

[19] W. Zhang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, "Resonant Phonon Scattering in Quantum Hall Systems Driven by dc Electric Fields", *Phys. Rev. Lett.* **100**, 036805 (2008).

[20] X. L. Lei and S. Y. Liu, "Radiation-induced magnetotransport in high-mobility two-dimensional systems: Role of electron heating", *Phys. Rev. B* **72**, 075345 (2005).

[21] X. L. Lei, "Current-induced magnetoresistance oscillations in two-dimensional systems", *Appl. Phys. Lett.* **90**, 132119 (2007).

[22] X. L. Lei, "Low-temperature electron-phonon resonance in dc-current-biased two-dimensional electron systems", *Phys. Rev. B* **77**, 20753409 (2008).

[23] X. L. Lei and S. Y. Liu, "Nonlinear magnetoresistance of an irradiated two-dimensional electron systems", *Appl. Phys. Lett.* **93**, 082101 (2008).

[24] X. L. Lei, "Nonlinear theory of fractional microwave-induced magnetoresistance oscillations in a dc-driven two-dimensional electron system", *Phys. Rev. B* **79**, 115308 (2009).