Radiation-induced magnetoresistance oscillations in high-mobility two-dimensional semiconductors

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Abstract: We give a brief overview to a systematic theoretical treatment on radiation induced magnetoresistance oscillations in high-mobility two-dimensional electron systems, based on the balance-equation approach to magnetotransport which is developed for high-carrier-density systems. The model covers regimes of both inter- and intra-Landau level processes, takes full account of multiphoton-assisted electron transitions as well as radiation-induced change of the electron distribution, and naturally includes electrodynamic damping. Electron scatterings by impurities, transverse and longitudinal acoustic phonons as well as polar optic phonons are considered in GaAs-based heterosystems with realistic scattering potentials. This theoretical model reproduces the main features of magnetoresistance oscillations, predicts the appearance of the measured zero resistance, and explains the rapid temperature decay of the oscillatory photoresistance as observed in many prominent experiments.

Keywords: Magnetoresistance oscillation, two-dimensional semiconductor, THz radiation

doi: 10.11906/TST.001-014.2009.03.01

1. Introduction

Since the discovery of radiation induced magnetorersistance oscillations (RIMOs) and zero-resistance states in ultra-high mobility two-dimensional (2D) electron systems, tremendous experimental and theoretical efforts have been devoted to study this exciting phenomenon and a general understanding of it has been reached [1-10].

As one of the major theoretical treatments, the balance-equation approach to magne-totransport has been developed for high-carrier-density systems based on photon-assisted electron transition. This microscopic theoretical model has been shown to give a systematic and uniform description for radiation induced magnetoresistance oscillations in high-mobility two-dimensional electron gas (2DEG) [11-14]. It provides a quantitative and tractable approach to radiation-induced magnetotransport in Faraday geometry, which enables us not only to analyze the magnetoresistance oscillation, whose dependence is on the radiation intensity and temperature, but also to explain many newly appeared prominent experimental observations including: (1) additional peak-valley structures at $\omega/\omega_c = 1/2, 2/3, 3/2$ (ω is the radiation frequency and ω_c

is the electron cyclotron frequency) due to mulitphoton processes under enhanced radiation; (2) strong suppression 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 higher than 0.2 *THz*; (8) new peak-valley pairs and zero-resistance states under bichromatic radiation; (9) fascinating effects of a strong dc current on RIMOs.

This paper will give a brief introduction to this theoretical method [11] and present several numerical examples derived from it [12-14].

2. Formulation

2.1. Balance equations in crossed electric and magnetic fields

For a general treatment, we consider N_e electrons in a unit area of a quasi-2D system in the *x*-*y* plane with a confining potential $V(z)$ in the *z*-direction. These electrons, subjected to a uniform magnetic field $\boldsymbol{B} = (0, 0, B)$ in the *z* direction, are interacting with each other and scattered by random impurities/disorders and by phonons in the lattice. When an incident electromagnetic wave of frequency $\omega = 2\pi f$ irradiates perpendicularly on, we can assume that a uniform dc electric field $\boldsymbol{E}$ and a high-frequency (HF) ac field of frequency ω,

$$\boldsymbol{E}(t) \equiv \boldsymbol{E}_s \sin(\omega t) + \boldsymbol{E}_c \cos(\omega t), \tag{1}$$

are applied within the 2D electron system in the *x*-*y* plane,

In terms of the 2D center-of-mass momentum and coordinate of the electron system, which are defined as $\boldsymbol{P} \equiv \sum_j p_{j\|}$ and $\boldsymbol{R} \equiv N_e^{-1} \sum_j \boldsymbol{r}_{j\|}$ with $\boldsymbol{p}_{j\|} \equiv (p_{jx}, p_{jy})$ and $\boldsymbol{r}_{j\|} \equiv (x_j, y_j)$ being the momentum and coordinate of the *j*th electron in the 2D plane, and the relative electron momentum and coordinate $\boldsymbol{p}'_{j\|} \equiv \boldsymbol{p}_{j\|} - \boldsymbol{P}/N_e$ and $\boldsymbol{r}'_{j\|} \equiv \boldsymbol{r}_{j\|} - \boldsymbol{R}$, the Hamiltonian of the system can be written as the sum of a center-of-mass part H_{cm} and a relative electron part H_{er}($\boldsymbol{A}(r)$ is the vector potential of the $\boldsymbol{B}$ field),

$$H_{cm} = \frac{1}{2N_e m}\left(\boldsymbol{P} - N_e e \boldsymbol{A}(\boldsymbol{R})\right)^2 - N_e e\left(\boldsymbol{E} + \boldsymbol{E}(t)\right)\cdot \boldsymbol{R}, \tag{2}$$

$$H_{er} = \sum_j \left[\frac{1}{2m} \left(\boldsymbol{p}'_{j\|} - e\boldsymbol{A}\left(\boldsymbol{r}'_{j\|}\right) \right) + \frac{p_{jz}^2}{2m_z} + V\left(z_j\right) \right] + \sum_{i<j} V_c \left(\boldsymbol{r}'_{i\|} - \boldsymbol{r}'_{j\|}, z_i, z_j \right), \tag{3}$$

together with electron-impurity and electron-phonon interactions $H_{\rm ei}$ and $H_{\rm ep}$. Here m and m_z are respectively the electron effective mass parallel and perpendicular to the plane, and V_c stands for the electron-electron Coulomb interaction. It should be noted that the uniform electric field (dc and ac) appears only in $H_{\rm cm}$, and that $H_{\rm er}$ is just the Hamiltonian of a quasi-2D system subjected to a magnetic field. The coupling between the center-of-mass and the relative electrons exists via the electron-impurity and electron-phonon interactions. Our treatment starts with the Heisenberg operator equations for the rates of changes of the center-of-mass velocity $\dot{\boldsymbol{V}} = -i\left[\boldsymbol{V}, H\right] + \partial \boldsymbol{V}/\partial t$, with $\boldsymbol{V} = -i\left[\boldsymbol{R}, H\right]$, and of the relative electron energy $\dot{H}_{er} = -i\left[H_{er}, H\right]$, as well as proceeds with the determination of their statistical averages.

The center-of-mass coordinate $\boldsymbol{R}$ and velocity $\boldsymbol{V}$ can be treated classically, i.e. as the time-dependent expectation values of the center-of-mass coordinate and velocity, $\boldsymbol{R}(t)$ and $\boldsymbol{V}(t)$, such that $\boldsymbol{R}(t) - \boldsymbol{R}(t') = \int_{t'}^{t} \boldsymbol{V}(s) ds$. We are concerned with the steady transport state under an irradiation of single frequency and we focus on the photon-induced dc resistivity and the energy absorption of the high frequency (HF) field. These quantities are directly related to the time-averaged and/or base-frequency oscillating components of the center-of-mass velocity. Hence, it suffices to assume that the center-of-mass velocity, i.e. the electron drift velocity, consists of a dc part v and a stationary time-dependent part $v(t)$ of the form

$$\boldsymbol{V}(t) = \boldsymbol{v} + \boldsymbol{v}_1 \cos(\omega t) + \boldsymbol{v}_2 \sin(\omega t). \tag{4}$$

On the other hand, for 2D systems having electron sheet density of order of $10^{15}\ m^{-2}$, the intra-band and inter-band Coulomb interactions are so sufficiently strong that it is adequate to describe the relative-electron transport state just by using a single electron temperature $T_{\rm e}$. In this way the steady transport state of the irradiated 2D electron system can be described by the four parameters: $\boldsymbol{v}$, $\boldsymbol{v}_1$, $\boldsymbol{v}_2$, and $T_{\rm e}$. These parameters are shown to satisfy the following force and energy balance equations:

$$0 = N_e e\boldsymbol{E} + N_e e(\boldsymbol{v} \times \boldsymbol{B}) + \boldsymbol{F}, \tag{5}$$

$$\boldsymbol{v}_1 = \frac{e\boldsymbol{E}_s}{m\omega} + \frac{\boldsymbol{F}_s}{N_e m\omega} - \frac{e}{m\omega}\left(\boldsymbol{v}_2 \times \boldsymbol{B}\right), \tag{6}$$

$$-\boldsymbol{v}_2 = \frac{e\boldsymbol{E}_c}{m\omega} + \frac{\boldsymbol{F}_c}{N_e m\omega} - \frac{e}{m\omega}\left(\boldsymbol{v}_1 \times \boldsymbol{B}\right), \tag{7}$$

$$N_e e\boldsymbol{E}\cdot\boldsymbol{v} + S_p - W = 0, \tag{8}$$

in which $\boldsymbol{F} = \boldsymbol{F}_i + \boldsymbol{F}_p$ is the time-averaged damping force against the electron drift motion due to impurity and phonon scatterings:

$$\boldsymbol{F}_i = \sum_{q\|}\left|U\left(\boldsymbol{q}_\|\right)\right|^2 \sum_{n=-\infty}^{\infty} \boldsymbol{q}_\| J_n^2(\xi)\Pi_2\left(\boldsymbol{q}_\|, \omega_0 - n\omega\right), \tag{9}$$

$$\boldsymbol{F}_p = \sum_{\boldsymbol{q}\|}\left|M(\boldsymbol{q})\right|^2 \sum_{n=-\infty}^{\infty} \boldsymbol{q}_\| J_n^2(\xi)\Pi_2\left(\boldsymbol{q}_\|, \omega_0 + \Omega_{\boldsymbol{q}} - n\omega\right) \times\left[n\left(\frac{\Omega_{\boldsymbol{q}}}{T}\right) - n\left(\frac{\omega_0 + \Omega_{\boldsymbol{q}} - n\omega}{T_e}\right)\right]. \tag{10}$$

In these equations, $n(x) = 1/(e^x-1)$ is the Bose function, $U(\mathbf{q}_\|)$ is the effective impurity potential, $M(\boldsymbol{q})$ is the electron-phonon coupling matrix element, Ω_q is the energy of a wavevector-$\boldsymbol{q}$ phonon, $\Pi_2\left(\boldsymbol{q}_\|, \Omega\right)$ is the imaginary part of the electron density correlation function at electron temperature T_e in the presence of the magnetic field, and $\omega_0 = \boldsymbol{q}_\| \cdot \boldsymbol{v}$, and $J_n(\xi)$ is the Bessel function of order n with argument $\xi \equiv \sqrt{\left(\boldsymbol{q}_\|\cdot\boldsymbol{v}_1\right)^2 + \left(\boldsymbol{q}_\|\cdot\boldsymbol{v}_2\right)^2}\Big/\omega$. In Eq. (10) S_p is the time-averaged rate of the electron energy-gain from the HF field, i.e. $\frac{1}{2}N_e e\left(\boldsymbol{E}_s\cdot\boldsymbol{v}_2 + \boldsymbol{E}_c\cdot\boldsymbol{v}_1\right)$, which can be written in a form obtained from the expression of $\boldsymbol{F}$ by replacing the $\boldsymbol{q}_\|$ factor with $n\omega$, and $\boldsymbol{W}$ is the time-averaged rate of the electron energy-loss due to coupling with phonons, whose expression can be obtained from the expression of $\boldsymbol{F}_p$ by replacing the $\boldsymbol{q}_\|$ factor with Ω_q, the energy of a wavevector-q phonon.

In the high-mobility electron systems, the oscillating frictional force amplitudes $\boldsymbol{F}_s$ and $\boldsymbol{F}_c$ are small in comparison with the damping force resulting from the radiative decay, and they will be neglected from now on. In this way, velocities $\boldsymbol{v}_1$ and $\boldsymbol{v}_2$ are determined from Eqs. (6) and (7) by the incident ac field and the setup of 2D electrons in the sample [11].

Assumed that the 2D electrons would be contained in a thin sample suspended in vacuum at plane z = 0. When an electromagnetic wave illuminates the plane perpendicularly with the incident electric field $\boldsymbol{E}_i(t)=\boldsymbol{E}_{is}\sin(\omega t)+\boldsymbol{E}_{ic}\cos(\omega t)$, the HF electric field in the 2D electron system is

$$\boldsymbol{E}(t)=\frac{N_e e\boldsymbol{v}(t)}{2\varepsilon_0 c}+\boldsymbol{E}_i(t). \tag{11}$$

Using this $\boldsymbol{E}(t)$ in Eqs. (6) and (7), v_1 and v_2 are explicitly expressed in terms of incident electric fields $\boldsymbol{E}_{is}$ and $\boldsymbol{E}_{ic}$.

The incident HF field thus enters through the argument ξ of the Bessel functions in $\boldsymbol{F}_i$, $\boldsymbol{F}_p$, W and S_p. Comparing with the result that is without the HF field (only n = 0 term and $J_0^2=1$), we see that there are impurity and/or phonon scattering in an electron gas (otherwise homogeneous), and an HF field of frequency ω opens additional channels for electron transition: an electron in a state can absorb or emit one or several photons which are scattered to a different state with the help of impurities and/or phonons. The sum over $|n|\geq 1$ represents contributions of single and multiple photon processes of frequency $-\omega$ photons. These photon-assisted scatterings help to transfer energy from the HF field to the electron system and give rise to additional damping force on the moving electrons.

2.2. Landau-level broadening

The density correlation function $\Pi_2(q_\parallel,\Omega)$ of the 2D electron gas in a magnetic field can be written in the Landau representation as [15]

$$\Pi_2(\boldsymbol{q}_\parallel,\Omega)=\frac{1}{2\pi l_B^2}\sum_{n,n'}C_{n,n'}\left(l_B^2 q_\parallel^2/2\right)\Pi_2(n,n',\Omega), \tag{12}$$

$$\begin{aligned}\Pi_2(n,n',\Omega)=&-\frac{2}{\pi}\int d\varepsilon\left[f(\varepsilon)-f(\varepsilon+\Omega)\right]\\&\times\operatorname{Im}G_n(\varepsilon+\Omega)\operatorname{Im}G_{n'}(\varepsilon),\end{aligned} \tag{13}$$

where $l_B=\sqrt{1/|eB|}$ is the magnetic length,

$$C_{n,n+1}(Y) \equiv n!\left[(n+l)!\right]^{-1} Y^l e^{-Y}\left[L_n^l(Y)\right]^2 \tag{14}$$

with $L_n^l(Y)$ being the associate Laguerre polynomial, and $f(\varepsilon) = \left\{\exp\left[(\varepsilon-\mu)/T_e\right]+1\right\}^{-1}$ being the Fermi distribution function. Furthermore, $\mathrm{Im}\,G_n(\varepsilon)$ is the imaginary part of the electron Green's function, or the density of states (DOS), of the Landau level *n*.

The Landau level (LL) broadening results from impurity, phonon and electron-electron scatterings. In a high-mobility GaAs-based 2D system, the dominant elastic scattering comes from residual impurities or defects in the background rather than from remote donnors [16], and phonon and electron-electron scatterings are generally neither not long-ranged because of the screening. On the other hand, the cyclotron radii of electrons involving in transport are much larger than the correlation length of the dominant scattering potential. In this case, the broadening of the LL is expected to be a Gaussian form[17] [$\varepsilon_n = \left(n+\frac{1}{2}\right)\omega_c$ is the center of the *n*th LL],

$$\mathrm{Im}\,G_n(\varepsilon) = -\frac{\sqrt{2\pi}}{\Gamma^2}\exp\left[-\frac{2(\varepsilon-\varepsilon_n)^2}{\Gamma^2}\right] \tag{15}$$

with a $B^{1/2}$-dependent half width expressed as

$$\Gamma = \left(\frac{2\omega_c}{\pi\tau_s}\right)^{1/2}, \tag{16}$$

where τ_s, the single-particle lifetime or quantum scattering time in the zero magnetic field, depends on impurity, phonon and electron-electron scatterings and is generally temperature dependent.

Expressions (15) and (16) for the DOS of the *n*th LL will be used in both the separated and overlapping LL regimes. The total DOS of a 2D system of the unit area in the magnetic field, $g(\varepsilon) = -\sum_n \mathrm{Im}\,G_n(\varepsilon)/\pi^2 l_B^2$, can be written as the sum of the DOS without magnetic field, g_0, and a magnetic-field induced oscillatory part. When the level width 2Γ is larger than the level spacing ω_c (overlapping LLs), the oscillatory part is smaller than g_0 and one can keep only its fundamental harmonic component to give

$$g(\varepsilon) \approx g_0\left[1-2\delta\cos(2\pi\varepsilon/\omega_c)\right], \tag{17}$$

with $g_0 = m/\pi$ and $\delta = \exp\left(-\pi^2\Gamma^2/2\omega_c^2\right) = \exp\left(-\pi/\omega_c\tau_s\right)$.

A reliable evaluation of single-particle lifetime τ_s (or the LL width 2Γ), which must include effects of impurity, phonon and electron-electron scatterings, has not yet been available. We treat it as an empirical parameter, or, relate it to the zero-field linear mobility μ_0 or the transport relaxation time τ_{tr} using an empirical parameter α by $1/\tau_s = 4\alpha/\tau_{tr} = 4\alpha e/m\mu_0$.

2.3. Longitudinal and transverse resistivities

The nonlinear longitudinal and transverse resistivities in the presence of an HF field are easily obtained from the zero-order force balance equation (5). For an isotropic system where the frictional force ***F*** is in the opposite direction to the drift velocity *v*, we can write $\boldsymbol{F(v)} = F(v)\boldsymbol{v}/v$.
In the Hall configuration with velocity *v* in the *x* direction, $\boldsymbol{v} = (v, 0, 0)$ or the current density $J_x = J = N_s ev$ and $J_y = 0$, Eq. (5) yields, at given *v*,

$$R_{xx} \equiv \frac{E_x}{N_e ev} = -\frac{F}{N_e^2 e^2 v}. \tag{18}$$

$$R_{yx} \equiv \frac{E_y}{N_e ev} = -\frac{B}{N_e e}. \tag{19}$$

The linear longitudinal resistivity is the weak dc current limit ($v \to 0$) of (18):

$$\begin{aligned} R_{xx} = &-\sum_{\boldsymbol{q}_{\|}} q_x^2 \frac{\left|U\left(\boldsymbol{q}_{\|}\right)\right|^2}{N_e^2 e^2} \sum_{n=-\infty}^{\infty} J_n^2(\xi) \frac{\partial}{\partial \Omega} \Pi_2\left(\boldsymbol{q}_{\|}, \Omega\right)\Bigg|_{\Omega = n\omega} \\ &-\sum_{\boldsymbol{q}} q_x^2 \frac{\left|M(\boldsymbol{q})\right|^2}{N_e^2 e^2} \sum_{n=-\infty}^{\infty} J_n^2(\xi) \frac{\partial}{\partial \Omega} \Lambda_2\left(\boldsymbol{q}_{\|}, \Omega\right)\Bigg|_{\Omega = \Omega_{\boldsymbol{q}} + n\omega} \end{aligned} \tag{20}$$

with $\Lambda_2(\boldsymbol{q}, \Omega) \equiv 2\Pi_2\left(\boldsymbol{q}_{\|}, \Omega\right)\left[n\left(\Omega_{\boldsymbol{q}}/T\right) - n\left(\Omega/T_e\right)\right]$. On one hand, we see that the longitudinal resistivity R_{xx} is strongly affected by the irradiation through photon-assisted impurity and phonon scatterings. On the other hand, the transverse resistivity R_{xy} remains the classical form, without changing in the presence of HF radiation.

Note that although according to Eq. (20), the linear and nonlinear longitudinal magnetoresistivity R_{xx} can be formally written as the sum of contributions from various individual scattering mechanisms, all the scattering mechanism has to be taken into account simultaneously in solving the energy-balance equations to determine T_e, which enters the expression of R_{xx}.

3. Examples with GaAs-Based 2D systems

To have an idea on how the theoretical model anticipates RIMOs, we focus our attention on high mobility two-dimensional electron systems in GaAs/AlGaAs heterostructure.

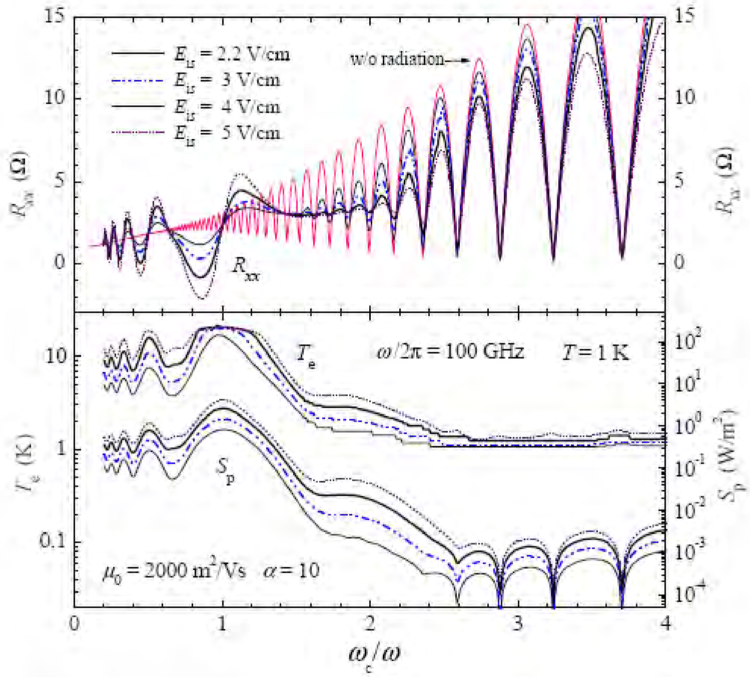

Fig. 1 The magnetoresistivity R_{xx}, electron temperature T_e and energy absorption rate S_p of a GaAs-based 2DEG with μ_0 =2000 m^2/Vs and α =10, subjected to 100 *GHz* linearly *x*-polarized incident HF fields $E_{is}\sin(\omega t)$ of four different strengths. The lattice temperature is T = 1*K*. From [12].

As indicated by experiments [16], although long range scattering due to remote donors who always exist in the 2D heterostructures, and in ultra-clean GaAs-based 2D samples having mobility of order of 10^3 m^2/Vs, the remote donor scattering is responsible for merely ~10% or less of the total momentum scattering rate. The dominant contribution to the momentum scattering rate comes from short-range scatterers such as residual impurities or defects in the background. Furthermore, even with same scattering rate, the remote impurity scattering is much less efficient in contributing to RIMOs than short-ranged background scatterers. Therefore, we assume that the elastic scatterings are due to short-range impurities randomly distributed throughout the GaAs region.

In order to obtain the energy dissipation rate from the electron system to the lattice, W, we take into account scatterings from bulk longitudinal acoustic and transverse acoustic phonons (via the deformation potential and piezoelectric couplings), as well as from longitudinal optical phonons (via the Frohlich coupling) in the GaAs-based system. The relevant matrix elements are well known [18]. The material and coupling parameters for the system are taken to be widely accepted values in bulk GaAs: electron effective mass $m = 0.068m_e$ (m_e is the free electron mass), transverse sound speed $v_{st} = 2.48\times10^3\, m/s$, longitudinal sound speed $v_{sl} = 5.29\times10^3\, m/s$, acoustic deformation potential $\Xi = 8.5\, eV$, piezoelectric constant $e_{14} = 1.41\times 10^9\, V/m$, dielectric constant $\kappa = 12.9$, and material mass density $d = 5.31 g/cm^3$.

Figure 1 shows the calculated energy absorption rate S_p, the electron temperature T_e and the longitudinal magnetoresistivity R_{xx} as functions of ω_c/ω ($\omega_c = eB/m$ is the cyclotron frequency) for a 2D system having an electron density of $N_e = 3.0 \times 10^{15}\, m^{-2}$, a linear mobility of $\mu_0 = 2000 m^2/Vs$ and a broadening parameter of $\alpha = 10$, subject to linearly x-direction polarized HF radiations of frequency $\omega/2\pi = 100$ GHz having four different incident amplitudes $E_{is} = 2.2, 3, 4$ and 5 V/cm at a lattice temperature of $T = 1\, K$. The energy absorption rate S_p exhibits a broad main peak at cyclotron resonance $\omega_c/\omega = 1$ and secondary peaks at cyclotron harmonics ω_c/ω = 1/2,1/3,1/4. The electron heating

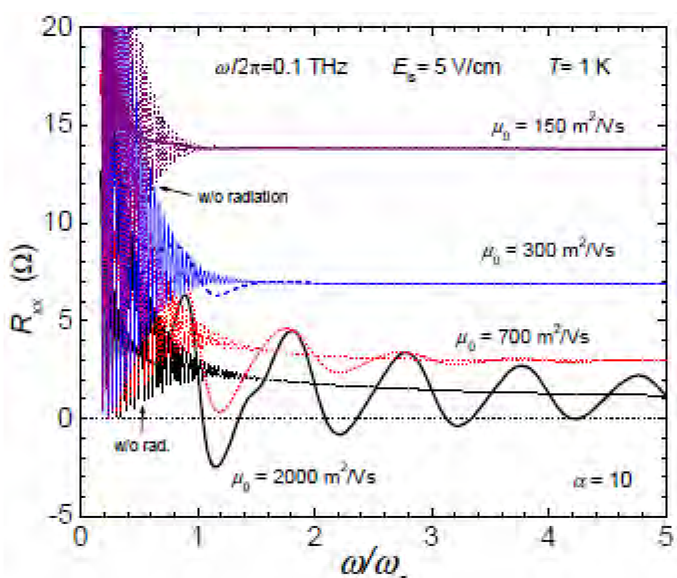

Fig. 2 Radiation-induced magnetoresistance oscillations in 2D systems having different mobilities. From [13].

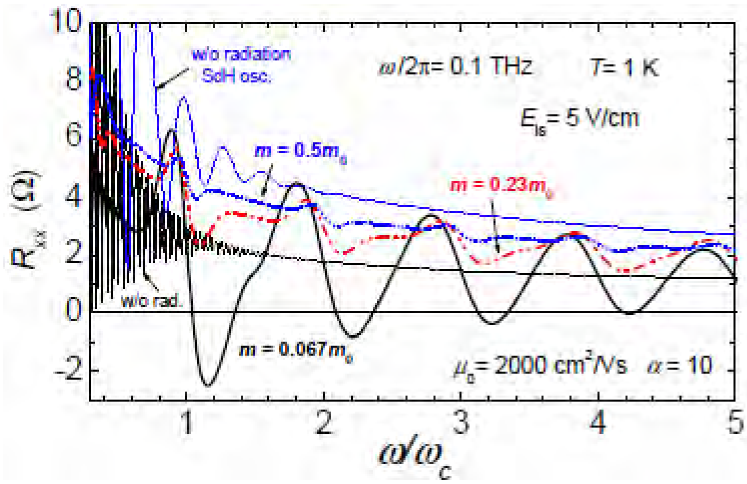

Fig. 3 RIMOs in 2D systems having different carrier effective masses. From [13].

has similar feature: T_e exhibits peaks around ω_c/ω = 1,1/2,1/3,1/4. RIMOs clearly appear at lower magnetic fields, which are insensitive to the electron heating even at T_e of order of 20 *K*. Shubnikov-de Haas oscillations (SdHOs) appearing in the higher magnetic field side, are damped due to the rise of the electron temperature $T_e > 1K$.

Figure 2 shows the longitudinal resistivity R_{xx} under linearly polarized microwave radiation of frequency $\omega/2\pi = 0.1THz$ and incident amplitude $E_{is} = 5$ *V/cm* in 2D electron systems, having same effective mass but different linear mobilities μ_0, indicating that RI-MOs can hardly appear in lower mobility samples.

Figure 3 shows the longitudinal resistivity R_{xx} versus ω/ω_c under linearly polarized microwave radiation of frequency $\omega/2\pi = 0.1THz$ and incident amplitude $E_{is} = 5$ *V/cm* for 2D systems, having same mobility but different effective mass, indicating that RIMOs are unlikely to show up in 2D systems with heavy carrier mass.

Figure 4 shows the R_{xx} oscillation of a 2D electron system is subject to linearly polarized radiations having same incident amplitude E_{is} =4*V/cm* but different frequencies $\omega/2\pi$ = 80,100,150,200,300 and 500 *GHz*, indicating that radiation of frequency higher than 0.3 *THz* may give rise to an apparent magnetoresistance oscillation quite different from that induced by lower frequency radiation.

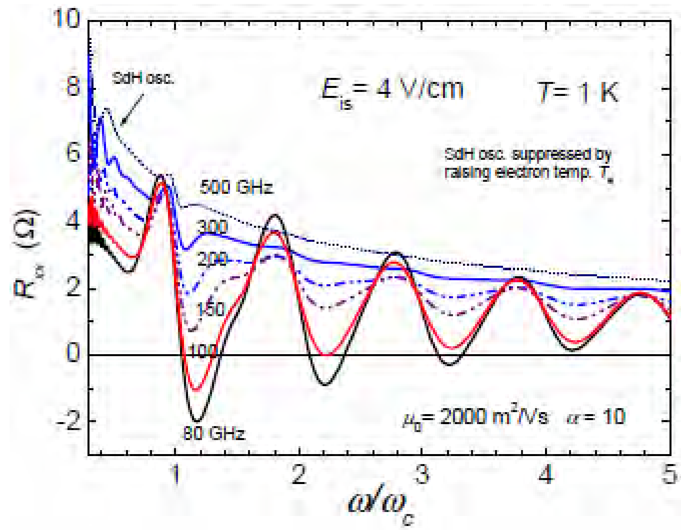

Fig. 4 R_{xx} oscillations in a 2D system induced by radiation fields of different frequencies. From [13].

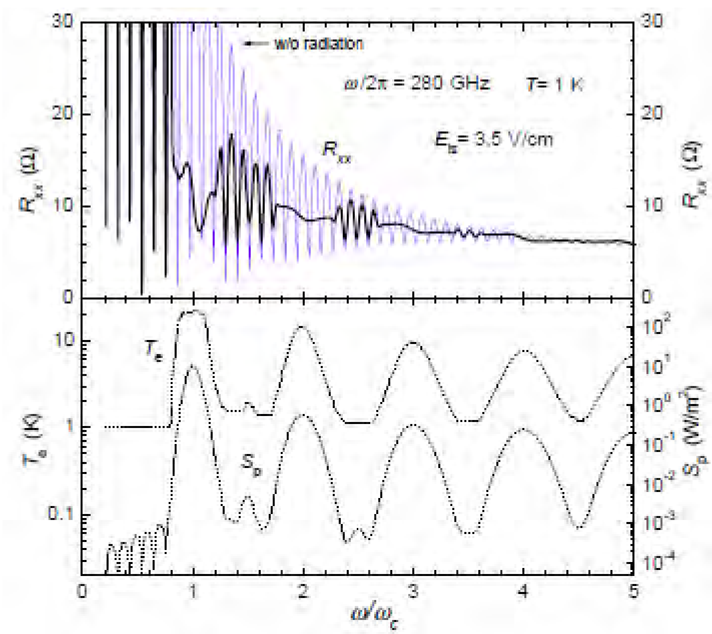

Fig. 5 The magnetoresistivity R_{xx}, electron temperature T_e and energy absorption rate S_p of a GaAs-based 2DEG with μ_0 = 1000m^2/Vs and α = 2, subject to a linearly x-polarized incident HF field of frequency 280 *GHz* and incident amplitude E_{is} = 3.5 *V/cm* at T = 1 *K*. From [12].

Figure 5 shows the energy absorption rate S_p, the electron temperature T_e, and the magnetoresistivity R_{xx} as functions of ω/ω_c for a 2D system has an electron density of N_e = 3.0×10^{15} m^{-2}, a linear mobility of μ_0 = 1000m^2/Vs, and a broadening parameter of α = 2, subject to linearly x-direction polarized incident radiations of frequency $\omega/2\pi$ = 280 *GHz* and amplitude E_{is} = 3.5 *V/cm*. The energy absorption rate S_p has broad large peaks at ω/ω_c =

1,2,3,4,5 (due to single-photon resonant process) and small peaks at ω/ω_c = 1.5,2.5 (due to two-photon resonant process), giving rise to the oscillation of the electron temperature T_e. One can clearly see the peaks of the electron temperature T_e and the nodes of SdHO modulation at ω/ω_c = 1,2,3,4 and 5, together with RIMOs.

4. Conclusions

We have briefly introduced a theoretical investigation on radiation induced magnetoresistance oscillations based on the balance-equation approach to magnetotransport in Faraday geometry. We find that for systems having zero-field linear mobility μ_0 (1 K) $\leqslant 2.4\times10^7 cm^2V^{-1}s^{-1}$ multiphoton-assisted impurity scatterings are the main mechanism responsible for radiation-induced magnetoresistance oscillations at temperature $T\leqslant 4$ K. Different from the SdHOs which are easily suppressed by a few-degree rise of the electron temperature, the radiation-induced magnetoresistance oscillations are quite insensitive to the modest electron heating as long as the lattice temperature remains the same. The growth of the Landau level broadening resulting from the enhancement of phonon and electron-electron scatterings with increasing temperature leads to the observed temperature suppression of the radiation-induced magnetoresistance oscillation.

Acknowledgement

This work was supported by the project of the National Science Foundation of China (No. 60876064), the National Basic Research Program of China (No. 2007CB310402) and the Shanghai Municipal Commission of Science and Technology (No. 06dj14008).

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