Nonequilibrium transport in very high Landau levels

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Abstract. Low temperature transport properties of high mobility two-dimensional electron systems placed in a weak perpendicular magnetic field can be modified dramatically by microwave or dc electric fields. This paper surveys recent experimental developments which include zero-differential resistance states, Hall field-induced resistance oscillations in tilted magnetic fields, nonlinear response of the Shubnikov-de Haas Oscillations, and a novel microwave photoconductivity peak near the second harmonic of the cyclotron resonance.

1. Introduction
Over the past decade it was realized that high mobility two-dimensional electron systems (2DESs) exhibit an array of fascinating transport phenomena occurring in very high Landau levels where the Shubnikov-de Haas oscillations (SdHOs) are not yet resolved. Among these are several classes of magnetooscillations, namely, microwave-(MIROs) [1; 2], phonon-[3–11], Hall field-(HIROs) [12–15] induced resistance oscillations, and their combinations [16–25]. In a clean 2DES the minima of MIROs can evolve into zero-resistance states (ZRSs) [26–39], which are currently explained in terms of the absolute negative resistance and its instability with respect to formation of current domains [40–43]. Transport in irradiated 2DESs was extensively studied both experimentally [44–67] and theoretically [68–105] but open issues remain. Among these are experimental confirmation of domains, apparent insensitivity of MIROs to the sense of circular polarization of microwaves [37], and suppression of MIROs [33] by in-plane magnetic fields.

More recent experiments on non-irradiated 2DESs have revealed further intriguing phenomena which remain poorly understood. Among these are zero-differential resistance states (ZdRSs), which emerge from the SdHO maxima in quantizing magnetic fields (B ∼ 10 kG) [106–108] and from the HIRO minimum [109] in much lower magnetic fields (B ∼ 1 kG). It was suggested [106] that ZdRSs are analogous to the radiation-induced ZRSs in a sense that they can also be explained by the domain model. As such, ZdRSs offer an alternative playground for exploring instabilities which proved to be difficult to access in irradiated 2DESs.

This paper describes some of the recent and ongoing experimental developments in the field of nonlinear transport in very high Landau levels and is organized as follows. After a brief review of MIROs and HIROs (Sec. 2), we discuss the temperature evolution of the HIRO-originated ZdRS (Sec. 3), HIROs in tilted magnetic fields (Sec. 4), nonlinear transport in the SdHO regime (Sec. 5), and the anomalously large microwave photoconductivity effect near the second harmonic of the cyclotron resonance which appears in addition to MIROs (Sec. 6).

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2. Microwave- and Hall field-induced resistance oscillations

MIROs appear in magnetoresistivity under microwave irradiation and are controlled by a dimensionless parameter $\epsilon_{ac} = \omega / \omega_c$, where $\omega = 2\pi f$ is the microwave frequency and $\omega_c = eB/m^*$ is the cyclotron frequency of an electron with an effective mass $m^*$. The resistivity of an irradiated 2DES can be expressed as $\rho_\omega = \rho + \delta \rho_\omega$, where $\rho$ is the resistivity of the non-irradiated 2DES and $\delta \rho_\omega(\epsilon_{ac})$ is the photoresistivity which is a sign-alternating function of $\epsilon_{ac}$.

According to the displacement model [68; 69; 71; 79; 101; 104], $\delta \rho_\omega$ originates from the microwave-induced impurity-assisted transitions between the disorder-broadened Landau levels. In another mechanism, known as inelastic [75; 91; 101; 104], microwaves create a nonequilibrium distribution of electron states which, in turn, translates to the oscillating distribution of electron states which leads to a resistance drop. Since both models were developed from the inelastic [91] mechanism. In this approach a dc field creates a nonequilibrium microwave-induced impurity-assisted transitions between the disorder-broadened Landau levels. The maxima and minima are pushed towards cyclotron resonance harmonics and occur at $\epsilon_{ac}^{\pm} = n \mp 1/4$ ($n = 1, 2, 3, \ldots$). However, in many experiments using high mobility 2DES the condition of overlapping Landau levels is violated at sufficiently high $B$ and the maxima and minima are pushed towards cyclotron resonance harmonics and occur at $\epsilon_{ac}^{\pm} = n \mp \delta$, where $\delta$ can be considerably smaller than $1/4$ [31; 79; 91].

HIROs appear in differential magnetoresistivity $r = dV/dI$ when a direct current $I$ is passed through a Hall bar-shaped 2DES. HIROs are explained by the displacement model [22; 24; 110; 111] owing to the impurity-mediated transitions between Landau levels tilted by the Hall electric field, $E_{dc} = \rho_H j$, where $\rho_H$ is the classical Hall resistivity and $j = I/w$ ($w$ is the sample width). In this scenario, the dominant scattering process involves an electron which is backscattered off an impurity. The guiding center of such an electron is displaced by a distance equal to the cyclotron diameter, $2R_c$, in a single scattering event. When $2R_c$ matches an integral multiple of the real-space Landau level separations the probability of such events is enhanced. This enhancement leads to a maximum in the differential resistivity occurring whenever the dimensionless parameter $\epsilon_{dc} = eE_{dc}(2R_c)/\hbar\omega_c$ is equal to an integer [14; 110]. At $2\pi\epsilon_{dc} \gtrsim 1$, HIROs are described by

$$\frac{d\rho_{\omega}}{\rho} \simeq -\eta P_\omega \epsilon_{ac} \lambda^2 \sin 2\pi\epsilon_{ac}. \quad (1)$$

Here, $\lambda = \exp(-\pi/\omega_c\tau_q)$ is the Dingle factor, $\tau_q$ is the quantum lifetime, $\eta$ is the model-dependent scattering parameter, and $P_\omega$ is the dimensionless parameter proportional to the microwave power. Away from the cyclotron resonance $P_\omega$ decays rapidly with increasing frequency, roughly as $\omega^{-4}$. According to Eq. (1), maxima and minima of MIROs should occur at $\epsilon_{ac}^{\pm} = n \mp 1/4$ ($n = 1, 2, 3, \ldots$). However, in many experiments using high mobility 2DES the condition of overlapping Landau levels is violated at sufficiently high $B$ and the maxima and minima are pushed towards cyclotron resonance harmonics and occur at $\epsilon_{ac}^{\pm} = n \mp \delta$, where $\delta$ can be considerably smaller than $1/4$ [31; 79; 91].

At weak dc fields, $2\pi\epsilon_{dc} \ll 1$, the theory [110] predicts another source of nonlinearities originating from the inelastic [91] mechanism. In this approach a dc field creates a nonequilibrium distribution of electron states which leads to a resistance drop. Since both models were developed in the limit of strongly overlapping Landau levels, a condition which is not always satisfied in experiments [14; 106; 107; 112], the relative importance of these mechanisms at $2\pi\epsilon_{dc} \ll 1$ remains poorly understood.

Both MIROs and HIROs are best observed at $T \lesssim 1$ K and quickly decay at higher $T$. In high mobility 2DESs, the decay originates primarily from the electron-electron interaction effects which modify the single particle lifetime $\tau_q$ entering the Dingle factor $\lambda$ [15; 61; 104; 113]. However, in 2DESs with larger impurity contribution to $1/\tau_q$, with different type of disorder, and/or at sufficiently low temperatures, the decay of MIROs can also originate from $\eta \sim \tau_{in} \simeq E_F/T^2$ [66; 91; 104] within a framework of the inelastic mechanism. Here, $\tau_{in}$ is the inelastic relaxation time and $E_F$ is the Fermi energy.
developed ZdRS, which is formed between which extends over a finite current range, \( I \) and \( V \) longitudinal voltage \( T \). At clean 2DESs. Integrating the data in Fig. 1(a) yields the increase is likely due to increased scattering on acoustic phonons which reduces the mobility of step of 0.5 K. At \( T \) the quantum lifetime entering the Dingle factor and thus play an important role in the work. On one hand, recent studies [7] have shown that electron-electron interactions modify represent the linear response regime (Ohm’s law) at 1.5 K and 4.0 K. the effect appears in the separated Landau levels, a regime which remains poorly understood. 3. Zero-differential resistance state in high Landau levels Recent experiments [109] have shown that when a high mobility 2DES is subject to weak electric and magnetic fields, its current-voltage characteristic exhibits a plateau signaling a formation of a state with zero differential resistance. In contrast to the ZdRS originating from the SdHO maxima (and thus appearing only at the discrete values of \( B \) corresponding to odd filling factors) [106], the ZdRS discussed here originates from a HIRO minimum and is observed over a continuous range of magnetic fields extending well below the onset of the SdHOs.

In Fig. 1(a) we present differential resistivity \( r(I) \) measured at \( B = 1.5 \) kG and at different \( T \) from 1.5 K to 4.0 K, in step of 0.5 K. ZdRS is observed at \( I_1 \lesssim I \lesssim I_2 \) where \( I_1 \) and \( I_2 \) can be associated with currents inside the domains [114]. These data were obtained on a Hall bar sample (width \( w = 100 \) \( \mu \)m) with density \( n_e \sim 3.8 \times 10^{11} \) \( \text{cm}^{-2} \) and mobility \( \mu \approx 1.0 \times 10^7 \) \( \text{cm}^2/\text{Vs} \).

![Image](468x333 to 491x333)

**Figure 1.** (a) \( r \) and (b) \( V \) vs \( I \) measured at \( B = 1.5 \) kG and at different \( T \) from 1.5 K to 4.0 K, in step of 0.5 K. ZdRS is observed at \( I_1 \lesssim I \lesssim I_2 \) where \( I_1 \) and \( I_2 \) can be associated with currents inside the domains [114]. These data were obtained on a Hall bar sample (width \( w = 100 \) \( \mu \)m) with density \( n_e \sim 3.8 \times 10^{11} \) \( \text{cm}^{-2} \) and mobility \( \mu \approx 1.0 \times 10^7 \) \( \text{cm}^2/\text{Vs} \).
Figure 2. Differential magnetoresistivity $r(B)$ at $I = 100 \, \mu\text{A}$ and $T = 1.0 \, \text{K}$ measured at different tilt angles $\theta$ (as marked). HIRO peaks at $\epsilon_{dc} = 1$ and $\epsilon_{dc} = 2$ are marked by ↓ and ↑, respectively. These data were obtained on a Hall bar sample ($w = 100 \, \mu\text{m}$) with $n_e \simeq 3.6 \times 10^{11} \, \text{cm}^{-2}$ and $\mu \simeq 1.1 \times 10^7 \, \text{cm}^2/\text{Vs}$.

4. Hall field-induced resistance oscillations in tilted magnetic fields

The effect of an in-plane magnetic field, $B_{\parallel}$, on MIROs has been studied in two experiments [33; 34]. In one experiment [34] the 2DES was tilted with respect to the total field $B$ by an angle $\theta$ as $B$ was varied. In this setup the ratio of $B_{\parallel} = B \sin \theta$ to $B_{\perp} = B \cos \theta$ remains fixed, $B_{\parallel}/B_{\perp} = \tan \theta$, and, as a result, lower order (higher $B_{\perp}$) MIROs experience larger $B_{\parallel}$ than the higher order (lower $B_{\perp}$) MIROs. Another experiment [33] employed a two-axis magnet so that MIROs of all orders, occurring at different $B_{\perp}$, were subject to the same $B_{\parallel}$. While both experiments agreed that the oscillation period is governed by $B_{\perp}$, Ref. [33] found that MIROs disappear under $B_{\parallel} \simeq 5 \, \text{kG}$ while in Ref. [34] MIROs were essentially unchanged up to $\theta \simeq 80^\circ$ (or $B_{\parallel} \lesssim 12 \, \text{kG}$). Obviously, the role of $B_{\parallel}$ remains poorly understood and it is interesting and timely to examine how other classes of magneto-oscillations respond to $B_{\parallel}$.

In what follows, we present the results of our experiment studying the effect of $B_{\parallel}$ on HIROs.

Figure 2 shows differential resistivity $r$ vs $B_{\perp}$ measured at $I = 100 \, \mu\text{A}$ and $T = 1.0 \, \text{K}$ for various tilt angles up to $\theta = 82.9^\circ$ (as marked). Similar to MIROs [33; 34], Fig. 2 clearly demonstrates that the HIRO period is controlled by $B_{\perp}$, as the corresponding peak positions coincide with each other for all tilt angles. At $\theta = 0$ (bottom curve) the data reveal at least three well developed oscillations which gradually decay away with increasing $\theta$. Careful examination of the data reveals that the the decay is nonuniform; the strongest, fundamental HIRO peak (cf., ↓) is much more sensitive to the tilt than the higher order peaks; it disappears completely at $\theta \simeq 82.9^\circ$ ($B_{\parallel} \simeq 1.3 \, \text{T}$), while the second (cf., ↑) and the third HIRO peaks are still clearly observed. The second HIRO peak eventually also disappears, at $\theta \simeq 85.9^\circ$, while the third HIRO peak still remains visible at this $\theta$.

Our analysis [115] of the HIRO decay with increasing tilt angle shows that it can be understood in terms of a $B_{\parallel}$-induced correction to the single particle scattering rate which scales roughly as $B_{\parallel}^2$. While the exact mechanism of such an increase remains subject of future theoretical and experimental studies, this scenario is qualitatively consistent with the observations of Ref. [33] where $B_{\parallel}$ was held constant and MIROs of higher orders decayed faster than the lower orders. Therefore, it appears plausible that suppressions of MIROs [33] and HIROs originate from the same physical mechanism.
5. Effect of dc electric field on Shubnikov-de Haas oscillations

When a direct current is passed through a 2DES, one can naively expect that SdHOs will smoothly decay with increasing current due to increased Joule heating. Recent experiments [116], however, revealed far more intriguing evolution of the SdHOs with current which could not be explained by conventional heating effects. In particular, it was found that the SdHO frequency doubles at certain currents suggesting significant redistribution between the first and the second Fourier components of the SdHOs. This behavior was analyzed and interpreted within a framework of the inelastic mechanism [91; 110] which leads to a filling factor-dependent spectral diffusion of electrons.

In Fig. 3 we illustrate another experimental aspect of the nonlinear transport in the SdHO regime. Here, we plot the differential magnetoresistivity $r(B)$ measured at different currents $I$, from 0 $\mu$A (bottom) to 6 $\mu$A (top), in step of 1 $\mu$A. As one would expect, SdHOs initially decay with increasing $I$. However, at still higher $I$ SdHOs reappear but with the opposite phase. Indeed, comparison of the bottom ($I = 0$) trace to the top ($I = 6 \mu$A) trace shows that the SdHO maxima have evolved into the minima and vice versa. At such low currents, HIROs remain confined to lower magnetic fields (cf. peaks marked by 1 and 2 at the top trace) so that the SdHOs appear in the regime of $\epsilon_{dc} < 1$. Therefore one cannot explain the observed phase reversal of the SdHOs by the inter-Landau level scattering processes which give rise to HIROs.

As discussed in Sec. 2, both the inelastic and the displacement contributions may play an important role in the regime of $2\pi\epsilon_{dc} \ll 1$. However, in both cases calculations predict that the characteristic current at which SdHOs would change a phase should increase roughly linearly with the magnetic field. As evidenced by Fig. 3 this is clearly not the case as all of the SdHOs evolve together; the sudden phase change occurs simultaneously at roughly the same $I$ regardless of the magnetic field (which varies by a factor of three in this measurement). One should note, however, that existing calculations assumed overlapping Landau levels and therefore might not be directly applicable to experiments. Unfortunately, a comprehensive theory of nonlinear transport in the separated Landau levels is not currently available. To explain the observed phase change of the SdHOs, the theory might also have to examine if and how the applied electric field modifies relative contributions of short- and long-range disorder potentials.
6. Photoresistance near the second harmonic of the cyclotron resonance

As discussed in the introduction, MIRO minima evolve into the radiation-induced ZRSs in sufficiently clean 2DESs and therefore the negative photoresistivity never exceeds the dark resistivity by absolute value. In contrast, positive photoresistivity responsible for the MIRO maxima has no associated instabilities and was routinely found to exceed the dark resistivity (but usually no more than 2-3 times). In addition to MIROs, Smet et al. [37] reported a remarkably strong and narrow photoresistivity peak in close proximity to the cyclotron resonance, which showed threshold-like dependence on the radiation intensity. In Fig. 4(a) we present the magnetoresistivity \( \rho(B) \) measured in a moderate mobility 2DES under microwave irradiation of frequency \( f = 38 \) GHz at \( T \approx 1.5 \) K which shows a giant photoresistivity peak. Similar to the peak reported in Ref. [37], the peak shown in Fig. 4(a) occurs near the cyclotron resonance and is only observed at microwave intensities above some critical value. While this peak can be phenomenologically linked to the bolometric effect [37], due to the resonant heating at the cyclotron resonance, its exact nature was not theoretically considered.

In Fig. 4(b) we present another example of an unusually large microwave photoresistance which is observed in addition to MIROs but occurs only near the second harmonic of the cyclotron resonance [117–119]. Here we plot magnetoresistivity \( \rho(B) \) measured under microwave irradiation of frequency \( f = 190 \) GHz at \( T \approx 1.2 \) K. The data show a very sharp peak at \( B \approx 2 \) kG which appears superimposed on the second MIRO maximum. More detailed analysis of the oscillation waveform [31] reveals that the peak appears between the second harmonic of the cyclotron resonance and the second MIRO maximum. Frequency dependence studies shows that in contrast to MIROs, which are known to decay with microwave frequency, this peak is observed only above certain microwave frequency (about 100 GHz in our 2DES). We also find that the peak exhibits roughly linear dependence on microwave intensity, disappears with increasing temperature in a way similar to MIROs [118], and can be more than an order of magnitude stronger than MIROs. Due to an unusually strong negative magnetoresistivity effect in our 2DES, which has yet to be understood, the peak can also be more than two orders of magnitude larger than the dark resistivity. Based on the above, we conclude that such a dramatic effect cannot be explained by existing theories of microwave photoconductivity and understanding its nature remains a subject of future theoretical and experimental work. In particular, it would be interesting to examine possible role of quasiclassical memory effects [84; 102] and to investigate the effects of dc electric field and in-plane magnetic field.
7. Summary
Owing to both experimental and theoretical advances over the past few years our understanding of nonequilibrium transport in high Landau levels has improved dramatically but questions remain. Among the long standing issues are apparent immunity of MIROs to the sense of circular polarization [37], suppression of MIROs/HIROs by modest in-plane magnetic fields [33; 115], the nonlinear resistivity in the SdHO regime [108; 116] and in the regime preceeding zero-differential resistance states [109], and the novel photoresistivity peak recently discovered near the second harmonic of the cyclotron resonance [117; 118].

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