Resistance Oscillations in Two-Dimensional Electron Systems Induced by Both ac and dc Fields

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We report on magnetotransport measurements in a high-mobility two-dimensional electron system subject simultaneously to ac (microwave) and dc (Hall) fields. We find that dc excitation affects microwave photoresistance in a nontrivial way. Photoresistance maxima (minima) evolve into minima (maxima) and back, reflecting strong coupling and interplay of ac- and dc-induced effects. Most of our observations can be explained in terms of indirect electron transitions using a new, combined resonant condition. Observed quenching of microwave-induced zero resistance by a dc field cannot be unambiguously linked to a domain model, at least before a systematic theory treating both excitation types within a single framework is developed.

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Over the past few years, nonequilibrium transport in very high Landau levels (LLs) of two-dimensional electron systems (2DES) has become a subject of strong interest. A large body of theoretical effort has been directed toward microwave-irradiated 2DES, aiming to explain microwave-induced resistance oscillations (MIRO) [1,2]. At the same time, it has become known that a phenomenologically similar effect, Hall field-induced resistance oscillations (HIRO) [3–5] emerges in a 2DES driven by a pure dc excitation.

Experimentally, microwave- (ac-) and dc-induced effects exhibit many similar features. MIRO appear in microwave photoresistance (MWPR), which is a periodic function of $\epsilon^{ac} \equiv \omega/\omega_C$, where $\omega = 2\pi f$ and $\omega_C = eB/m^*$ (m^* is the effective mass) are microwave and cyclotron frequencies, respectively. HIRO occur in a dc-driven 2DES, owing to the commensuration of two length scales, the cyclotron diameter $2R_C$ and the spatial separation between Hall field-tilted LLs $\Delta Y = \hbar\omega_C/eE$ (E is the Hall field). As a result, the differential resistance $r \equiv dV/dI$ is periodic in $\epsilon^{dc} = \gamma R_C/\Delta Y = \omega_H/\omega_C$, where $\gamma \simeq 2$ and $\hbar\omega_H = (\gamma R_C)eE$ is the energy associated with the Hall voltage drop across the cyclotron orbit. Both MIRO and HIRO rely on transitions between high LLs and show similar sensitivity to the sample mobility. Finally, strong suppression in resistance occurs in the regime of separated LLs at small ϵ^{ac} [6–8] or small ϵ^{dc} [5,9].

Theoretically, our understanding of these phenomena rests upon different microscopic mechanisms. While MIRO [10] were originally discussed in terms of microwave-induced impurity scattering [11–14], it was then argued that the dominant contribution comes from inelastic processes leading to a nontrivial distribution function [15,16]. Conversely, HIRO seem to rely on a large momentum transfer, suggesting the importance of short-range disorder, and are believed to stem from inter-LL elastic scattering [17,18]. It is interesting to note that the same momentum transfer, but provided by acoustic phonons, was employed to explain oscillations due to magnetophonon resonance [19,20]. Introducing additional parameters into ac-driven 2DES can, in principle, help to distinguish between contributions from different mechanisms and even lead to new effects. In this regard, magnetotransport in 2DES subject to microwave radiation and periodic modulation was recently studied both theoretically [21,22] and experimentally [23].

As far as dc excitation is concerned, of particular interest is its effect on microwave-induced zero-resistance states (ZRS) [24,25] which are formed in high-quality 2DES at the MIRO minima. ZRS are currently understood in terms of absolute negative resistance and its instability, which leads to current domains [26,27]. Recent experiments with bichromatic microwaves seem to support negative resistance [28,29], but so far there exists no direct evidence for the domain structure. The theory, however, predicts that domains, and hence ZRS, can exist only below some characteristic current, suggesting dc excitation as a convenient probe. Despite the apparent simplicity of such an experiment, we will see that its interpretation is not straightforward due to dc-induced effects, i.e., HIRO, which were not theoretically discussed in relation to domains.

In this Letter, we report on magnetotransport studies in a 2DES subject to both ac and dc excitations. Remarkably, we observe that resistance oscillations are governed by a new parameter $\epsilon = \epsilon^{ac} + \epsilon^{dc}$, reflecting strong coupling of the excitations. We can qualitatively explain most of the observations in terms of *indirect* electron transitions, viewed as combinations of a jump in energy (microwave absorption) and a jump in space (Zener tunneling) between Hall field-tilted LLs. These results are suggestive of a deep relation between ac- and dc-induced effects and might provide valuable information about the microscopic origin of the MWPR phenomena, given further theoretical input.

Our Hall bar sample (width $w = 100\ \mu$m) was fabricated from a symmetrically doped GaAs/$Al_{0.24}Ga_{0.76}As$ 300-Å-wide quantum well. High-quality Ohmic contacts were made by evaporation of Au/Ge/Ni. After brief illumination, the electron mobility μ and the density n_e were $\simeq 1.2 \times 10^7$ cm^2/V s and 3.7×10^{11} cm^{-2}, respectively. The experiment was performed at a constant coolant temperature $T \simeq 1.5$ K and under continuous microwave radiation. While similar results were obtained at other frequencies and intensities, all of the data reported here were acquired at frequency $f = 69$ GHz at maximum available power. The differential resistance r was measured using a quasi-dc (a few hertz) lock-in technique.

Before presenting the experimental data under combined (ac/dc) excitation, we briefly review the resonant conditions for MIRO and HIRO. MIRO maxima$_{(+)}$ and minima$_{(-)}$ are usually found at $\epsilon^{ac}_{n\pm} \simeq n + \phi^{ac}_{n\pm}$, where $n = 1, 2, \ldots$ and $\phi^{ac}_{n\pm} \simeq \mp \phi^{ac}_{n}$. In the regime of overlapped LLs, ϕ^{ac}_{n} is close to 1/4, but when LLs get separated ϕ^{ac}_{n} decreases with increasing B [30,31]. HIRO, as measured in r, obey a similar relation $\epsilon^{dc}_{m\pm} \simeq m + \phi^{dc}_{m\pm}$, with $m = 0, 1, \ldots$, $\phi^{dc}_{m+} \simeq 0$, $\phi^{dc}_{m-} \simeq 1/2$ [5]. With increasing B, ϕ^{dc}_{0-} also decreases [5,9]; in our sample, $\phi^{dc}_{0-} \simeq 0.12$ at $B = 1.75$ kG.

In Fig. 1, we present typical magnetotransport data $r/r_0 \equiv r(B)/r(0)$ acquired under ac excitation and different dc excitations. The zero-bias ($I = 0$) trace (black curve), included in each panel for reference, shows MIRO and two well-developed ZRS: ϵ^{ac}_{1-} (cf. 1 −) and ϵ^{ac}_{2-} (cf. 2 −). In addition, Fig. 1(a) shows data acquired at 6 μA [light (blue)] and 9 μA [dark (red)]. One immediately observes that MWPR is strongly modified even by modest currents. As far as ZRS are concerned, ϵ^{ac}_{2-} ZRS disappears at 9 μA (cf. 2 −), while ϵ^{ac}_{1-} ZRS remains essentially unaffected (cf. 1 −). Quite surprisingly, a fundamental ϵ^{ac}_{1+} peak develops a deep local minimum (cf. 1 +) giving rise to a "camelback" structure, while the ϵ^{ac}_{2+} peak (cf. 2 +) survives.

In Fig. 1(b), we continue with the data taken at higher I, 12 μA [light (blue)] and 21 μA [dark (red)]. Examination of the 12 μA trace reveals that high-order MIRO, which were already absent at 9 μA, reappear but with the opposite phase (cf. ↑). At 21 μA, the "phase flip" progresses into the ZRS regime, and ϵ^{ac}_{2-} ZRS evolves into a peak (cf. 2 −). Most remarkably, the ϵ^{ac}_{2+} peak is transformed into a *new* "ZRS" (cf. 2 +), which coexists with the persisting, but about to disappear, ϵ^{ac}_{1-} ZRS (cf. 1 −). This new ZRS is a result of a combined (ac/dc) excitation.

Data at still higher I, 33 μA [light (blue)] and 51 μA [dark (red)], are shown in Fig. 1(c). The new "ZRS" disappears and evolves back to a peak at 51 μA (cf. 2 +). The peak also develops at the ϵ^{ac}_{1-} ZRS (cf. 1 −). We thus conclude that dc excitation strongly modifies MWPR and affects not only ZRS, as predicted by the domain model [26], but also the peaks. In fact, ϵ^{ac}_{1-} ZRS sustains much higher I than the ϵ^{ac}_{1+} peak.

We now examine the regime of low I, where the intriguing camelback structure was observed at ϵ^{ac}_{1+}. In Fig. 2(a), we present microwave magnetoresistance about $\epsilon^{ac}_{1\pm}$ under dc current excitation from 1 to 7 μA, in 1 μA steps. A deep local minimum emerges at the ϵ^{ac}_{1+} peak position (cf. 1 +), while the ϵ^{ac}_{1-} ZRS remains essentially unchanged (cf. 1 −). The evolution of MWPR near $\epsilon^{ac}_{2\pm}$ is shown in Fig. 2(b), where the current was varied from 2 to 14 μA, in 2 μA steps. A considerably larger I is needed to destroy the ϵ^{ac}_{2+} peak, but one also discerns a local minimum at ϵ^{ac}_{2+} (cf. 2 +). At the same time, the ϵ^{ac}_{2-} ZRS appears far less

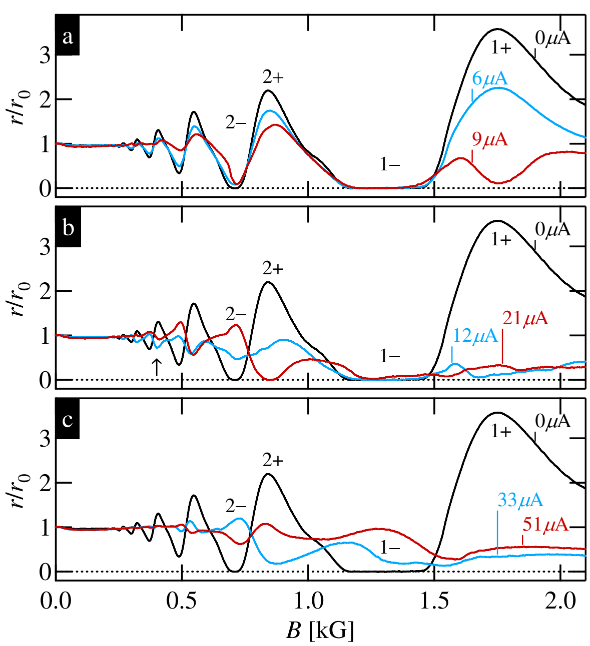

FIG. 1 (color online). Microwave magnetoresistance r/r_0 under dc excitations: $I = 0$ μA (black curve) in (a)–(c); 6 μA [light (blue)] and 9 μA [dark (red)] in (a); 12 μA [light (blue)] and 21 μA [dark (red)] in (b); 33 μA [light (blue)] and 51 μA [dark (red)] in (c).

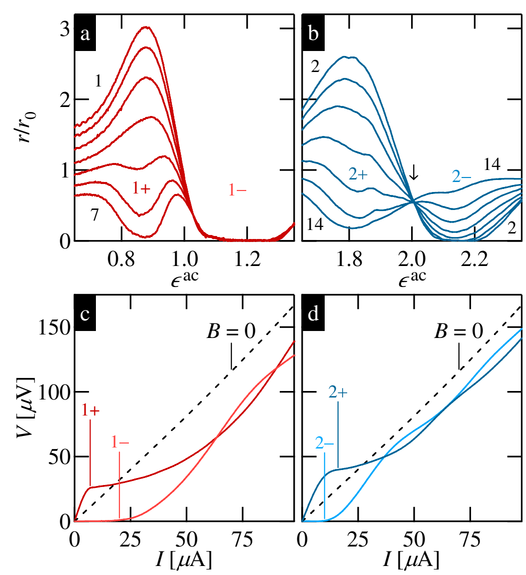

FIG. 2 (color online). (a) [(b)] Microwave magnetoresistance r/r_0 about $\epsilon^{ac}_{1\pm}$ [$\epsilon^{ac}_{2\pm}$] at I from 1 [2] to 7 [14] μA, in 1 [2] μA steps. (c) [(d)] CVCs at ϵ^{ac}_{1+} [ϵ^{ac}_{2+}] and ϵ^{ac}_{1-} [ϵ^{ac}_{2-}]. Dashed lines: CVC at $B = 0$.

persistent (cf. $2-$) in comparison with the ϵ^{ac}_{1-} ZRS; it disappears at $\simeq 6$ μA and is already a peak at $\simeq$14 μA. In light of dramatic changes seen in the MWPR extrema, it is rather strange to observe that zero-response nodes, e.g., $\epsilon^{ac} = 2$ [cf. ↓ in Fig. 2(b)], remain virtually immune to dc excitation in this range of I. This observation becomes even more puzzling if one recalls that without microwave radiation r would already be suppressed by about a factor of 5 [5].

Evolution of the MWPR peaks and ZRS can also be examined in current-voltage characteristics (CVCs), recorded at $\epsilon^{ac}_{1\pm}$ and $\epsilon^{ac}_{2\pm}$ and shown in Figs. 2(c) and 2(d), respectively. Indeed, the kink in the CVC, linked to a deep minimum at ϵ^{ac}_{1+} (cf. $1+$), happens much earlier than that for ϵ^{ac}_{2+} (cf. $2+$). This indicates that the strongest, first-order MWPR peak is actually the "weakest" with respect to dc excitation. On the other hand, ZRS disappearance follows the expected trend, with the strongest ϵ^{ac}_{1-} ZRS persisting to still higher I (cf. $1-$) than ϵ^{ac}_{2-} ZRS (cf. $2-$). At higher I, CVCs, while crossing each other, are roughly parallel to the CVC measured at $B = 0$ (dashed lines).

To further study the effect of dc excitation on MWPR, we perform B sweeps at different I up to 100 μA, in 1–2 μA steps. The results of these measurements are presented in Fig. 3(a) as a false-color plot in the (B, I) plane, where red (blue) represents high (low) values of r. The maximum of the color scale was limited to 3.2Ω, roughly twice the equilibrium resistance value. This limitation affects only the ϵ^{ac}_{1+} peak ($\approx$5.3Ω) but greatly helps to improve contrast for other features. In addition, the white color now approximately represents the zero-response contours surrounding resistance peaks (cf. $+$). Periodic patterns of highs and lows are observed if one follows vertical lines (fixed B) or some inclines, such as that marked "3/4." Observed periodicity suggests resonant coupling of ac and dc excitations.

In Fig. 3(b), we focus on the MIRO regime and replot the lower portion of Fig. 3(a), converting B to ϵ^{ac}. For a given $n \gtrsim 3$, the first switch from a maximum (minimum) to a minimum (maximum) occurs almost at the same I (cf. $3+$, $3-$). On the other hand, a similar image for the ZRS regime, shown in Fig. 3(c), reveals that there exists a range of I where the switch has already occurred for the peak but not for the adjacent minimum. This is best observed at $\epsilon^{ac}_{1\pm}$ (cf. $1+$, $1-$) but is also evident at $\epsilon^{ac}_{2\pm}$, further confirming the dramatically smaller effect of I on the ZRS than on the peaks.

To arrive at the resonant condition under ac/dc excitation, we plot in Fig. 4(a) the maxima (circles) and minima (squares) positions in the (I, ϵ^{ac}) plane. At small I, the maxima and minima appear as prescribed by $\epsilon^{ac}_{n\pm} = n \mp \phi^{ac}_n$. With increasing I, the maxima do not shift up to $I_{n+} \simeq 6\mu$A, which is roughly independent on n (cf. horizontal dotted line). The minima, on the other hand, do not change positions up to I_{n-}, which grows with decreasing n. In the ZRS regime $I_{n-} > I_{n+}$, but in the MIRO regime $I_{n-} \simeq I_{n+}$. At higher I, all extrema move toward lower ϵ^{ac} jumping across n or $n + 1/2$ (cf. ⟵). The solid curve, drawn at $\epsilon^{dc} = 1$, crosses the maxima positions at $\epsilon^{ac} = n$ and correlates with the jumps of the minima (cf. ⟵).

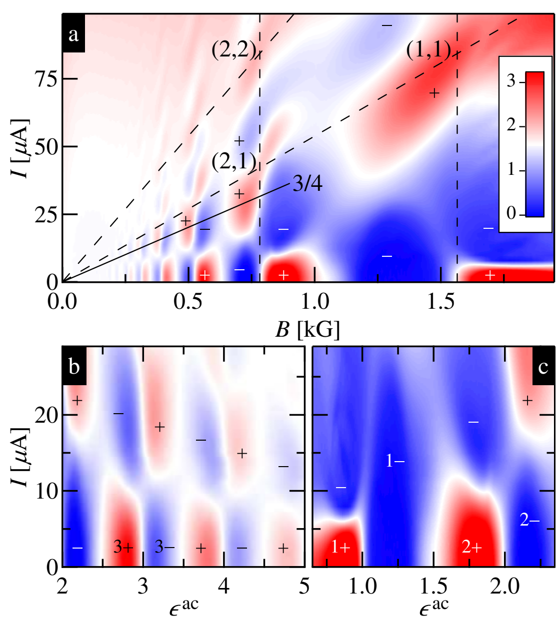

FIG. 3 (color online). (a) False-color intensity plot of r in the (B, I) plane. White contours separate the maxima ($+$) and the minima ($-$) (see text). Crossings of vertical ($\epsilon^{ac} = 1, 2$) and inclined ($\epsilon^{dc} = 1, 2$) dashed lines are marked by (ϵ^{ac}, ϵ^{dc}). Solid line: $\epsilon^{dc} = 3/4$. (b) [(c)] The lower portion of (a) in the MIRO [ZRS] regime, with B changed to ϵ^{ac}.

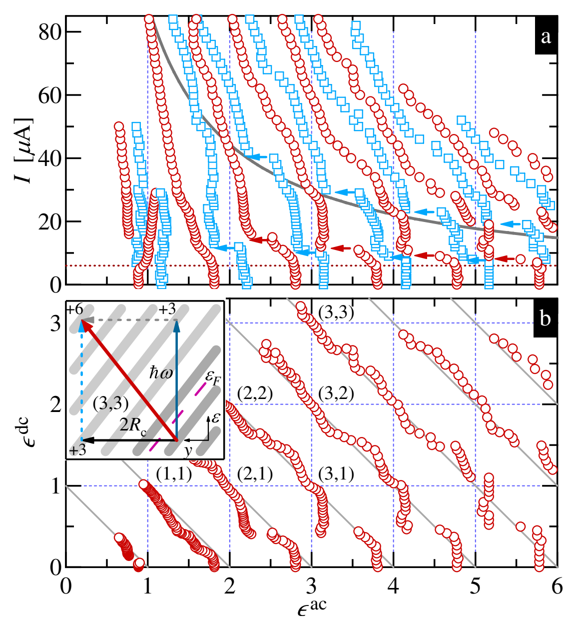

FIG. 4 (color online). (a) Positions of the r maxima (circles) and minima (squares) in the (I, ϵ^{ac}) plane. Solid curve: $\epsilon^{dc} = 1$. (b) Positions of the r maxima in the $(\epsilon^{ac}, \epsilon^{dc})$ plane. Solid lines: $\epsilon^{ac} + \epsilon^{dc} = k$, $k = 1, 2, \ldots$. Inset: LLs at $(\epsilon^{ac}, \epsilon^{dc}) = (3, 3)$. Horizontal, vertical, and inclined arrows mark electron transitions due to dc, ac, and ac/dc excitations, respectively.

We now convert I to $\epsilon^{\rm dc} = \omega_H/\omega_C$, with $\omega_H = \gamma\sqrt{2\pi/n_e}I/ew$ and $\gamma = 1.9$ [5], and replot maxima positions in Fig. 4(b). Remarkably, the data roughly fall onto parallel lines, $\epsilon^{\rm ac} + \epsilon^{\rm dc} \simeq k$, $k = 1, 2, \ldots$, apart from deviations associated with the jumps and at very small currents. We notice that the deviation is usually small when $\epsilon^{\rm ac}$ and $\epsilon^{\rm dc}$ are both integers, as marked by (n, m) pairs. This is consistent with the maxima in Fig. 3(a) being observed at the crossing points of $\epsilon^{\rm ac} = 1, 2$ (vertical dashed lines) and $\epsilon^{\rm dc} = 1, 2$ (inclined dashed lines), as marked by (1, 1), (2, 1), and (2, 2).

As suggested by Fig. 4(b), we introduce the new parameter $\epsilon = \epsilon^{\rm ac} + \epsilon^{\rm dc}$, somewhat analogous to that used in multiphoton, bichromatic MWPR [8]. The resonant condition under ac/dc excitation takes a remarkably simple form:

$$\epsilon_{k+} \simeq k, \qquad \epsilon_{k-} \simeq k + 1/2, \tag{1}$$

We propose a phenomenological interpretation based on "combined" resonances. As illustrated in the inset in Fig. 4(b), the characteristic electron transition can be viewed as a combination of a jump in energy due to microwave absorption and a jump in space due to elastic scattering by impurities under dc excitation. Note that Eq. (1) does not require $\epsilon^{\rm ac}$ and $\epsilon^{\rm dc}$ to be integers but only their sum.

Equation (1) is sufficient to qualitatively understand the stronger effect of dc excitation on MWPR maxima in the ZRS regime. With increasing I at fixed $\epsilon^{\rm ac} = n$ (MIRO zero-response nodes), the first dc-induced minimum (maximum) should appear at $\epsilon^{\rm dc}_{0-} \simeq \phi^{\rm dc}_{0-}$ ($\epsilon^{\rm dc}_{1+} \simeq 1$). The MWPR maxima (minima), being offset by the phase, will switch to minima (maxima) at $\epsilon^{\rm dc}_{+} \simeq \phi^{\rm dc}_{0-} + \phi^{\rm ac}_{n}$ ($\epsilon^{\rm dc}_{-} \simeq 1 - \phi^{\rm ac}_{n}$). In the MIRO regime, $\phi^{\rm ac}_{n} \simeq 1/4$ and $\phi^{\rm dc}_{0-} \simeq 1/2$, which gives $\epsilon^{\rm dc}_{+} \simeq \epsilon^{\rm dc}_{-} \simeq 3/4$. Indeed, the corresponding line, marked 3/4 in Fig. 3(a), passes through the maxima and minima centers. However, in the ZRS regime, both $\phi^{\rm ac}_{n}$ and $\phi^{\rm dc}_{0-}$ are reduced, yielding $\epsilon^{\rm dc}_{+} < \epsilon^{\rm dc}_{-}$, in qualitative agreement with the fact that ZRS can sustain higher I than the neighboring peaks.

In summary, we have studied magnetotransport of a high-quality 2DES under both ac and dc excitations. We have found that dc excitation modifies MWPR in a nontrivial way, reflecting strong coupling of two excitation types and hinting at a deep relation between ac- and dc-induced effects. We have observed the evolution of the MWPR maxima (minima) into minima (maxima) and back and the concurrent formation of new local minima and new "ZRS." While the observed disappearance of ZRS is consistent with the domain picture [26], we emphasize the even stronger effect of dc excitation on the MWPR maxima and that both maxima and minima are described equally well by Eq. (1). We can qualitatively understand most of our observations in terms of indirect electron transitions which rely on both inter-LL microwave absorption and dc-induced inter-LL elastic scattering. On the other hand, the physics behind the deep local minima, the immunity of the zero-response nodes, and the existence of domains remains unclear. Since the current understanding of the ac- and dc-induced effects is based on different mechanisms, it is very desirable to develop a systematic theory which would consider both excitation types simultaneously.

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