Magneto-transport characteristics of a 2D electron system driven to negative magneto-conductivity by microwave photoexcitation

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Abstract. The magneto-transport characteristics of the negative conductivity/resistivity state in the microwave photo-excited two-dimensional electron system (2DES) is examined through a numerical solution of the associated boundary value problem. The results suggest, surprisingly, that a bare negative diagonal conductivity/resistivity state in the 2DES under photo-excitation should yield a positive diagonal resistance along with a sign reversal in the Hall voltage.

1. Introduction

Microwave-induced zero-resistance states arise from "1/4-cycle-shifted" microwave radiation-induced magnetoresistance oscillations in the high mobility GaAs/AlGaAs system as a reduction in T leads to the saturation of the resistance minima at zero resistance.[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. These zero-resistance states exhibit activated transport similar to the quantum Hall situation although the Hall resistance, R_{xy}, does not exhibit plateaus or quantization in this instance.[1] The observations have led to some theoretical interest in understanding associated phenomena.[22, 23, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38]

Some theories have utilized a two step approach to model the observations. (There do exist alternate approaches which directly realize zero-resistance states, see for example [27, 33, 36]) In the first step, theory identifies a mechanism that helps to realize large oscillations in the diagonal magneto-photo-conductivity/resistivity, where the minima of the oscillatory diagonal conductivity/resistivity can even take on negative values.[22, 23, 25, 29] The next step invokes an instability in the zero-current-state at negative resistivity (and conductivity),[24] which favors the appearance of current domains with a non-vanishing current density,[24] and zero-resistance.

Naively, one believes that negative magneto-resistivity/conductivity should lead to observable negative magneto-resistance/conductance, based on expectations for the zero-magnetic-field situation. At the same time, the existence of the magnetic field is no doubt an important additional feature because $\rho_{xy} >> \rho_{xx}$ for $\omega_c\tau >> 1$, the typical situation in these experiments. Here, ρ_{xy} and ρ_{xx} are the Hall off-diagonal and diagonal resistivities, respectively, ω_c is the cyclotron frequency and τ is the relaxation time. Thus, one wonders if the magnetic field, and the extremely strong Hall effect, are sufficiently important to overcome nominal expectations, based on the zero-magnetic-field analogy, for an instability in a negative magneto-

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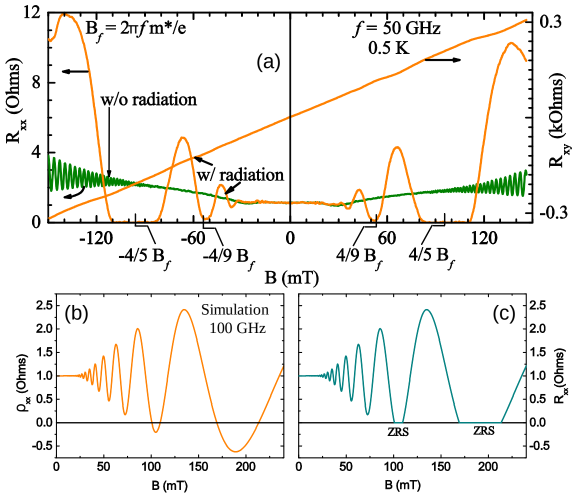

Figure 1. (a) The dark- and photo-excited-diagonal- (R_{xx}) and the photo-excited-Hall-resistance (R_{xy}) vs. the magnetic field B for a GaAs/AlGaAs device. R_{xx} exhibits a non-vanishing resistance in the dark. Under photo-excitation (red traces), R_{xx} exhibits large oscillations with vanishing resistance in the vicinity of $\pm(4/5)B_f$, where $B_f = 2\pi f m^*/e$, without concurrent Hall quantization. (b) Theory predicts negative diagonal resistivity, i.e., $\rho_{xx} < 0$, at the oscillatory minima, observable here in the vicinity of $B \approx 0.19$ Tesla and $B \approx 0.105$ Tesla. (c) Theory asserts that current domain formation leads to zero-resistance states (ZRS).

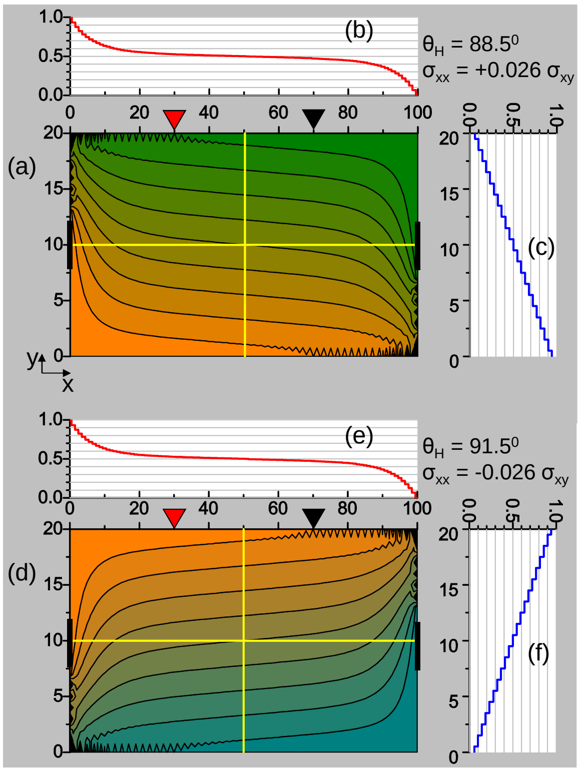

Figure 2. Numerical simulation of the potential within a Hall bar device. Panel (a) shows the potential profile at $\sigma_{xx} = +0.026\sigma_{xy}$. Panel(b) shows the potential variation from the left to the right end at $y = 10$. Panel(c) suggests a large Hall voltage between the bottom and top edges. Panel (d) shows the potential profile at $\sigma_{xx} = -0.026\sigma_{xy}$. Here, the potential profile is reflected with respect panel (a) about the line at $y = 10$ when the σ_{xx} shifts from a positive to a negative value. Panel (e) shows that the potential still decreases from left to right, implying a positive R_{xx}. Panel (f) shows a sign reversal in the Hall voltage in going from positive conductivity to negative conductivity

conductivity/resistivity state. Indeed, a related question of interest is: what are the magneto-transport characteristics of a bare negative conductivity/resistivity state?

To address this last question, we examine here the transport characteristics of the photo-excited 2DES at negative diagonal conductivity/resistivity through a numerical solution of the associated boundary value problem. The results suggest, rather surprisingly, that negative conductivity/resistivity in the 2DES under photo-excitation should generally yield a positive diagonal resistance, i.e., $R_{xx} > 0$. The simulations also identify an associated, unexpected sign reversal in the Hall voltage under these conditions.

2. Experiments and results

Figure 1(a) exhibits measurements of R_{xx} and R_{xy} at $T = 0.5K$ with and without microwave photoexcitation. The green curve represents the R_{xx} in the absence of photo-excitation (w/o radiation). Microwave photo-excitation of this specimen at 50GHz, see orange traces in Fig. 1, produces radiation-induced magnetoresistance oscillations in R_{xx}, and these oscillations grow in amplitude with increasing $|B|$. At the deepest minimum, near $|B| = (4/5)B_f$, where $B_f = 2\pi f m^*/e$, the R_{xx} saturates at zero-resistance.[1]

Both the displacement theory,[22] and the inelastic model,[29] for the radiation-induced magnetoresistivity oscillations suggest that the magnetoresistivity can take on negative values over the B-spans where experiment indicates zero-resistance states. For illustrative purposes, such theoretical expectations are sketched in Fig. 1(b), which presents the simulated ρ_{xx} at $f = 100$ GHz. This figure shows that the deepest ρ_{xx} minima at $B \approx 0.19$ Tesla and $B \approx 0.105$ Tesla exhibit negative resistivity, similar to theoretical predictions.[22, 23, 25, 29] Theory states,[24] that the only time-independent state of a negative resistivity/conductivity includes a current which almost everywhere has a magnitude j_0 fixed by the condition that nonlinear dissipative resistivity equals zero. As a consequence, the ρ_{xx} curve of Fig. 1(b) turns into the magnetoresistance, R_{xx}, trace shown in Fig. 1(c), with zero-resistance over the B-domains that exhibited negative resistivity in Fig. 1(b).

3. Numerical simulation

Hall effect devices can be numerically simulated on a grid/mesh,[39, 40, 41, 42], by enforcing $\nabla.\overrightarrow{j} = 0$, where $\overrightarrow{j}$ is the 2D current density with components j_x and j_y, $\overrightarrow{j} = \sigma\overrightarrow{E}$, and σ is the conductivity tensor.[39] Enforcing $\nabla.\overrightarrow{j} = 0$ is equivalent to solving the Laplace equation $\nabla^2 V = 0$, which may be carried out in finite difference form using a relaxation method, subject to the boundary conditions that current injected via current contacts is confined to flow within the conductor. Simulations were carried out using a 101×21 point grid with 6 points wide current contacts at the ends. For the sake of simplicity, the negative current contact is set to ground potential, i.e., $V = 0$, while the positive current contact is set to $V = 1$.

Fig. 2(a) shows the potential profile at positive conductivity $\sigma_{xx} = +0.026\sigma_{xy}$. The salient feature here is that the equipotential contours are nearly parallel to the long axis of the Hall bar, see Fig. 2(b). Concurrently, Fig. 2(c) suggests a large Hall voltage between the bottom and top edges. Here the Hall voltage decreases from the bottom- to the top- edge.

Fig. 2(d) shows the potential profile at $\sigma_{xx} = -0.026\sigma_{xy}$, i.e., the negative conductivity case. The important feature here is the reflection of the potential profile with respect Fig. 2(a) about the line at $y = 10$ when the σ_{xx} shifts from a positive ($\sigma_{xx} = +0.026\sigma_{xy}$) to a negative ($\sigma_{xx} = -0.026\sigma_{xy}$) value. Fig. 2(e) shows, remarkably, that in the negative σ_{xx} condition, the potential still decreases from left to right, implying $V_{xx} > 0$ and $R_{xx} > 0$ even in this $\sigma_{xx} \leq 0$ condition. Fig. 2(f) shows that for $\sigma_{xx} = -0.026\sigma_{xy}$, the potential *increases* from the bottom edge to the top edge, in sharp contrast to Fig. 2(c). Thus, these simulations show that the Hall voltage undergoes sign reversal when $\sigma_{xx} \leq 0$, although the diagonal voltage (and resistance) exhibits positive values. Thus, a negative diagonal conductivity state is expected to exhibit a positive diagonal resistance along with a sign reversal in the Hall effect.

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