Radiation Induced “Zero-Resistance State” and Photon-Assisted Transport

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Outline

• Introduction
• Experiment
• A toy model to understand the phenomena
• Generalized Kubo-Greenwood formula
• Implications of negative conductivity
• New phase formation
• Conclusions
Two-dimensional electron (hole) system (2DEG) forms at the interfaces.
Transports in 2DEG

Oscillatory Density of States

\[ \Delta \left( \frac{\mu}{\hbar \omega_c} \right) = 2\pi \]

Shubnikov-de Hass Effect

\[ \omega_c = \frac{eB}{mc} \]

\[ R_H = \frac{h}{ie^2} \]
New Experiments: Microwave Radiation


A typical (quantum) driven system!
New Discovery: Giant Magneto-Resistance Oscillations and “Zero-Resistance State”

• Resistance minima:
  \[ \frac{\omega}{\omega_c} = n + 1/4 \]

• Oscillation amplitude increases with the microwave power.

• “zero resistance state” is observed under strong microwave radiation.

• “Fixed points” at:
  \[ \frac{\omega}{\omega_c} = n \text{ or } n + 1/2 \]
Speculations

• exciton superconductors
• various strong correlation excitations: skyrmion …
• charge density wave
• plasma
• relativity effect
• …
**Simple Theory**

Driven systems (by microwave radiation)

Negative conductivity

Dynamic instability

New phase: non-equilibrium, self-organization
Absolute negative resistance found in the calculation

Durst, Sachdev, Read, Girvin, cond-mat/0301569

What is the origin of these negative resistance states?
Our Study

Junren Shi and X.C. Xie, cond-mat/0302393.

• the transport anomaly (negative resistance) is the result of photon assisted transport and the non-trivial electron density of states of the system.

• The transport anomaly is NOT a special property of 2DEG. Similar anomaly could also be observed in other systems, provided the necessary conditions are met.

• When the conductivity becomes negative, the system will be driven to a far-from-equilibrium regime where nonlinear and self-organization effects dominate.
A Toy Model to Elucidate the Mechanism

• The simplest photon-assisted transport system:

\[ V_{ac} = \Delta \cos \omega t \]

- The density of states for each lead is assumed to be of 2DEG under a weak magnetic field.
Conductance Formula

\[ I = eD \int d\varepsilon \sum_n J_n^2 \left( \frac{\Delta}{\hbar \omega} \right) \left[ f(\varepsilon) - f(\varepsilon + n\hbar \omega + eV) \right] \rho_L(\varepsilon) \rho_R(\varepsilon + n\hbar \omega + eV) \]

Photon assisted tunneling: \( \varepsilon \rightarrow \varepsilon + n\hbar \omega + eV \)

\[ \sigma = \frac{dI}{dV}|_{V=0} = e^2 D \int d\varepsilon \sum_n J_n^2 \left( \frac{\Delta}{\hbar \omega} \right) \left[ -f'(\varepsilon) \rho(\varepsilon) \rho(\varepsilon + n\hbar \omega) \right. \\
\left. + \left[ f(\varepsilon) - f(\varepsilon + n\hbar \omega) \right] \rho(\varepsilon) \rho'(\varepsilon + n\hbar \omega) \right]. \]

Negative conductance results from the negative derivative of the density of states and the photon-assisted tunneling.
Comparison with Experiments and Numerical Calculations

Numerical

Experimental

Toy model

\[ \rho_{xx} \approx \rho_{xy}^2 \sigma_{xx} \]
Qualitative Features

• The positions of the conductance minima are determined by:

\[ \tan x = -\frac{x}{2}, \quad x = 2\pi \frac{\omega}{\omega_c} \]
\[ \omega/\omega_c = 1.29, 2.27, 3.27, 4.26... \]

\[ \omega/\omega_c = n + 1/4 \]

\[ \sigma (\omega = n\omega_c) = \sigma \]

• Deviation induced by high power of radiation
Uniform Systems: Generalized Kubo-Greenwood Formula

Generalized Kubo-Greenwood formula for photon-assisted transport:

\[
\sigma_{dc} = \frac{\partial}{\partial \epsilon_0} \sum_n \int d\epsilon D_n(\epsilon, \epsilon + n\hbar \omega) \\
\times \left[ f(\epsilon) - f(\epsilon + \epsilon_0 + n\hbar \omega) \right] \rho(\epsilon) \rho(\epsilon + \epsilon_0 + n\hbar \omega)
\]

\[
D_n(\epsilon, \epsilon + n\hbar \omega) = 2\pi \hbar J_n^2(\Delta_{\alpha\beta}/\hbar \omega) \left| \hat{J}_{\alpha\beta} \right|^2.
\]

Photon assisted transport probability

The same formula as that for the tunneling junction!
Derivation of the Formula

Hamiltonian: \( H = H_0 + H_{ac}(\omega) + H_{dc} \)

un-perturbed system

Effect of MW:

\[ |\alpha(t)\rangle \longrightarrow e^{-i\hat{E}_\alpha t/\hbar} \sum_{n=-\infty}^{\infty} e^{-in\omega t} |\alpha, n\rangle \]

Floquet theorem (Bloch theorem in time domain)

\[
\hat{j}(t) = e^{i\hat{H}_0 t/\hbar} \left[ \sum_{n=-\infty}^{\infty} \hat{j}_n e^{-in\omega t} \right] e^{-i\hat{H}_0 t/\hbar}
\]

\[
\hat{j}_n = \sum_m |\alpha\rangle \langle \alpha, m | \hat{j} |\beta, m+n\rangle \langle \beta|,
\]

Kubo Formula:

\[
\sigma_{dc} = \frac{2\pi}{V} \frac{\partial}{\partial \omega_0} \sum_{f,i} \sum_n (P_i - P_f) |\langle f | \hat{j}_n | i \rangle|^2 \\
\times \delta (\hbar \omega_0 + n\hbar \omega - \tilde{E}_f + \tilde{E}_i),
\]

\[
P_i(f) = e^{-\beta E_{i(f)}} / Z
\]
How Effective of Photon-Assisted Process in a Uniform System?

\[ D_n(\epsilon, \epsilon + n\hbar\omega) = \frac{2\pi\hbar J_n^2(\Delta_{\alpha\beta}/\hbar\omega)}{|\mathbf{j}_{\alpha\beta}|^2}. \]

\[ \Delta_{\alpha\beta} \approx e|\mathbf{r}_\alpha - \mathbf{r}_\beta| \cdot |\mathbf{E}_\omega| \]

\[ \Delta_{\text{eff}} \sim E_\omega l \]

Typical electron length scale

\[ E_\omega \sim 10 \text{ V/m} \]
\[ l \sim 10^{-4} \text{ m} \]

mean free path

\[ \Delta_{\text{eff}} \sim 1 \text{ meV} \]

\[ \hbar\omega \sim 0.4 \text{ meV} \]

\[ \Delta_{\text{eff}} > \hbar\omega \]
Search in Other Systems

The phenomena could be observed in other uniform systems, provided:

• An effective way to couple the radiation field and the electron motion

• Non-trivial density of states

• Strong enough radiation: \( \Delta_{\text{eff}} > \hbar \omega \)
• negative conductance implicates the instability of the system. The system will re-organize to a new phase.

• The resulting new phase sensitively depends on the detailed setup of the system.
Uniform System: Far-From-Equilibrium and Self-Organization

Heat Transfer

\[ Q = \kappa(T_2 - T_1) \]

Convection current & Benard Cells

Near-Equilibrium

Far-From-Equilibrium
Why Self-Organization?

Self-organization originates from the competition between subsystems for the finite resource.

In negative conductivity regime, subsystems have to compete the energy flow provided by the microwave radiation.
A Phenomenological Theory

A.V. Andreev, I.L. Aleiner, and A.J. Millis, cond-mat/0302063

P.W. Anderson and W.F. Brinkman, cond-mat/0302129

• A homogeneous time independent with a current magnitude less than $j_0$ is unstable in the negative conductivity regime.

• Only possible time-independent state is one in which the current $j$ has magnitude $j_0$ everywhere except at isolated singular points (vortex) or lines (domain wall) convection current.
Conclusions

• Microwave radiation will induce negative conductivity, which results from the non-trivial density of states of the system and photon-assisted transport.

• Negative conductivity implicates the instability of the system. The system will be driven to a far-from-equilibrium phase: self-organization; pattern formation; convection current…

Remaining Issues:

• The microscopic path from the dynamic instability to the far-from-equilibrium new phase?

• Quantum effect in such far-from-equilibrium dissipative systems?