# Radiation Induced "Zero-Resistance State" and Photon-Assisted Transport

**Junren Shi**

*Oak Ridge National Laboratory*

**X.C. Xie**

*Oklahoma State University*

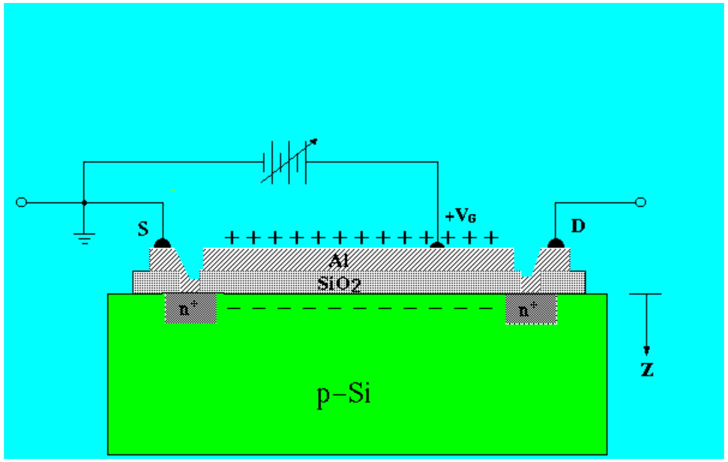
Thanks to: Zhenyu Zhang, Biao Wu, Fuchun Zhang (Cincinnati), R.R. Du(Utah), R.G. Mani(Harvard), N. Read (Yale), A.F. Volkov(Germany)

# Outline

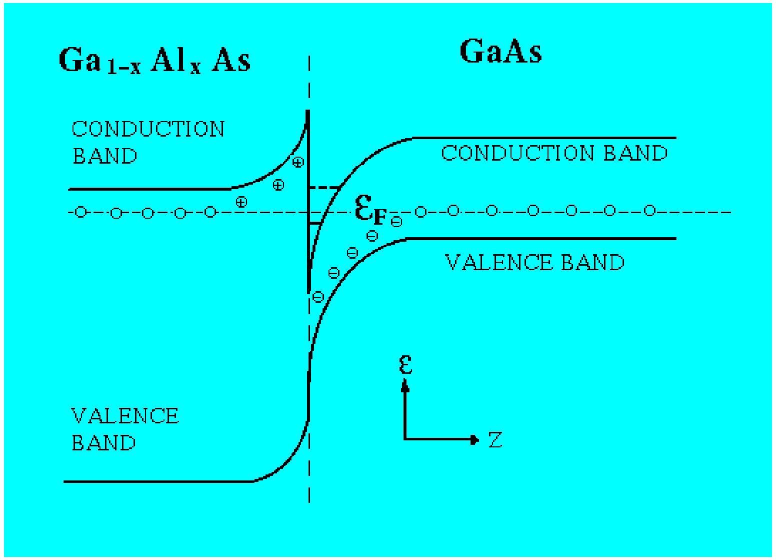
- Introduction
- Experiment
- A toy model to understand the phenomena
- Generalized Kubo-Greenwood formula
- Implications of negative conductivity
- New phase formation
- Conclusions

# Two-Dimensional Electron Systems

Si MOSFET



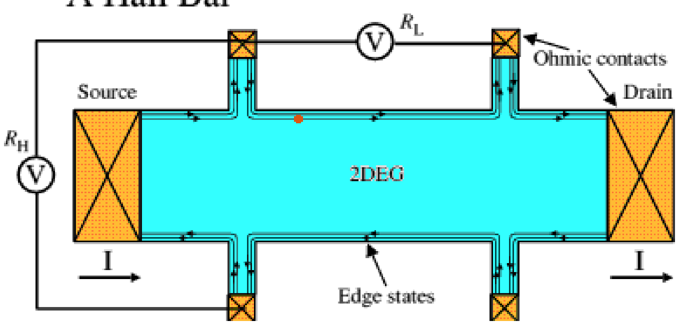

GaAs/GaAlAs Heterostructure



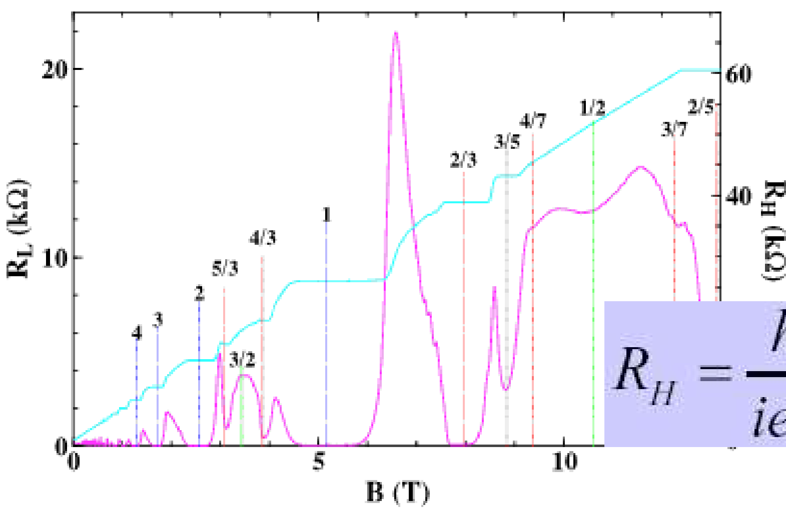

Two-dimensional electron (hole) system (2DEG) forms at the interfaces.

# Transports in 2DEG

A Hall Bar

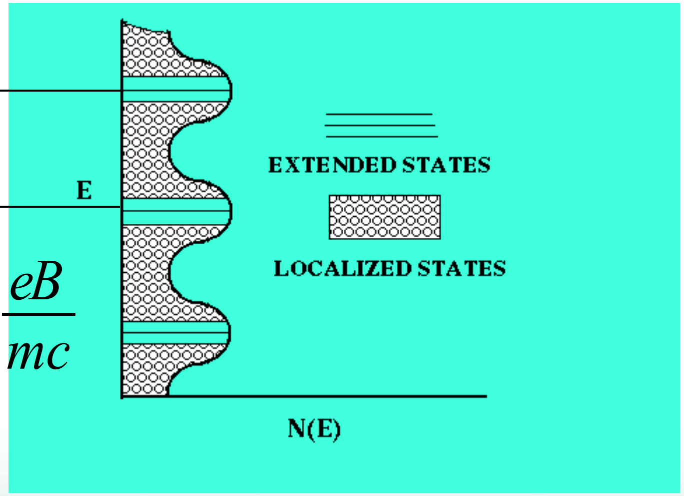



Integer and Fractional Quantum Hall Effects




$$R_H = \frac{h}{ie^2}$$

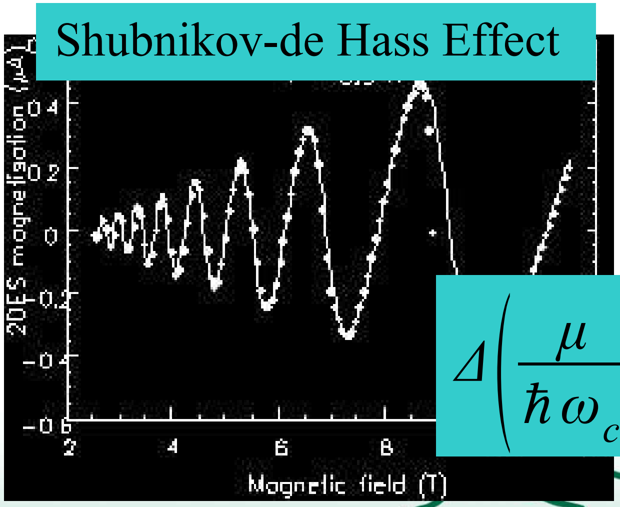
Oscillatory Density of States




$\hbar\omega_c$

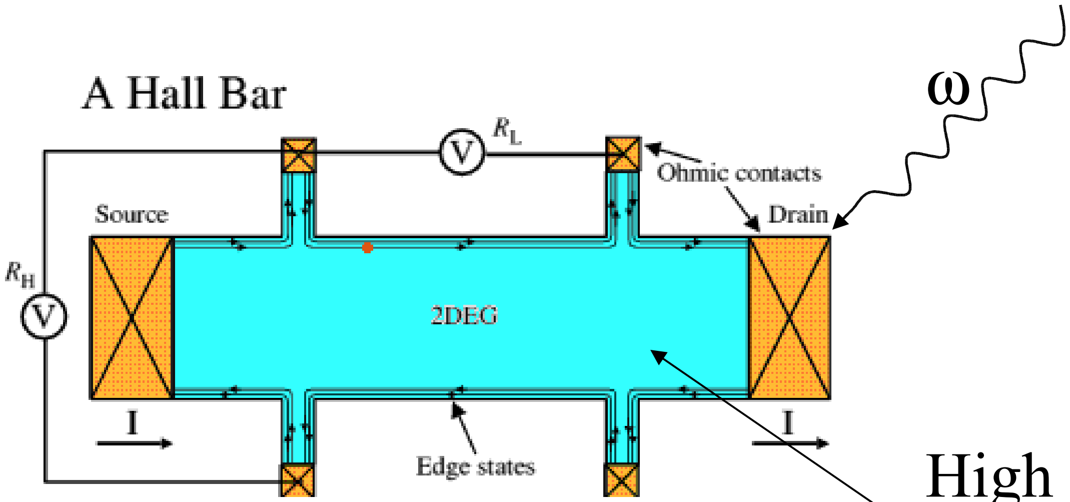
$$\omega_c = \frac{eB}{mc}$$

Shubnikov-de Hass Effect




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

# New Experiments: Microwave Radiation




High Mobility
GaAs/AlGaAs

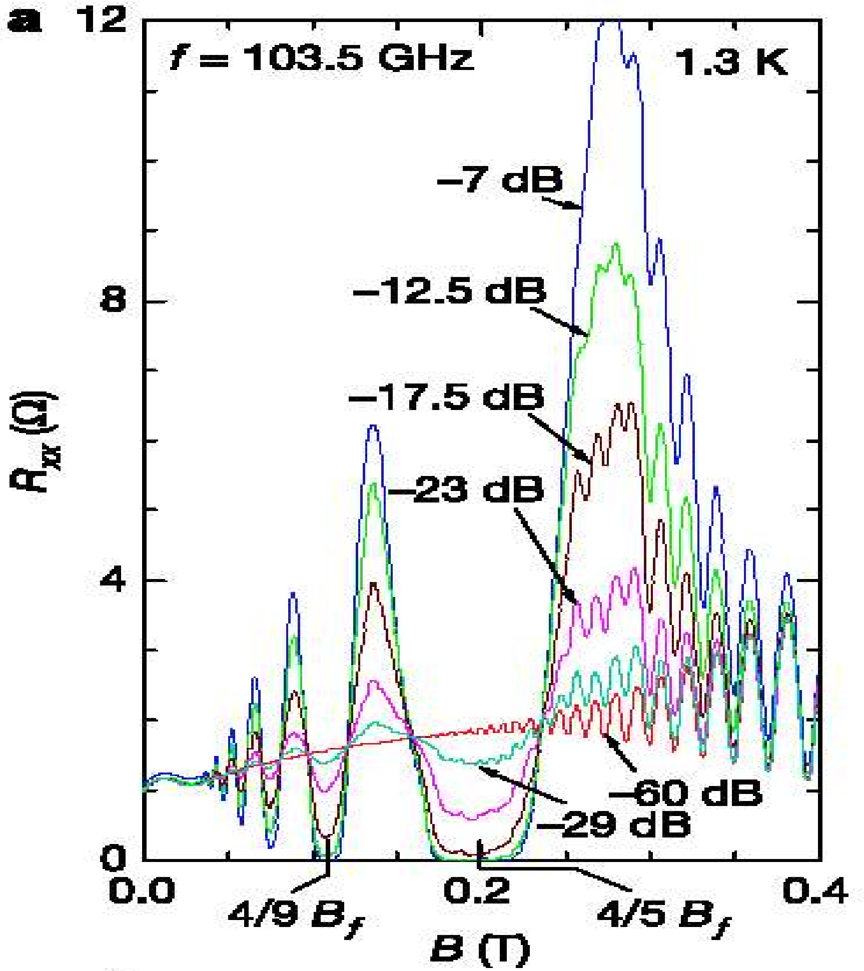
Mani et al., Nature, 420, 646 (2002).

Zudov et al., Phys. Rev. Lett. 90, 046807 (2003).

Zudov et al., Phys. Rev. B 64, R201133 (2001).

A typical (quantum) driven system!

# New Discovery: Giant Magneto-Resistance Oscillations and “Zero-Resistance State”




- Resistance minima:

$$\omega/\omega_c = n + 1/4$$

- Oscillation amplitude increases with the microwave power.
- “zero resistance state” is observed under strong microwave radiation.
- “Fixed points” at:

$$\omega/\omega_c = n \text{ or } n + 1/2$$

# Speculations

- exciton superconductors
- various strong correlation excitations: skyrmion …
- charge density wave
- plasma
- relativity effect
- …

# Simple Theory

Driven systems (by microwave radiation)

↓

Negative conductivity

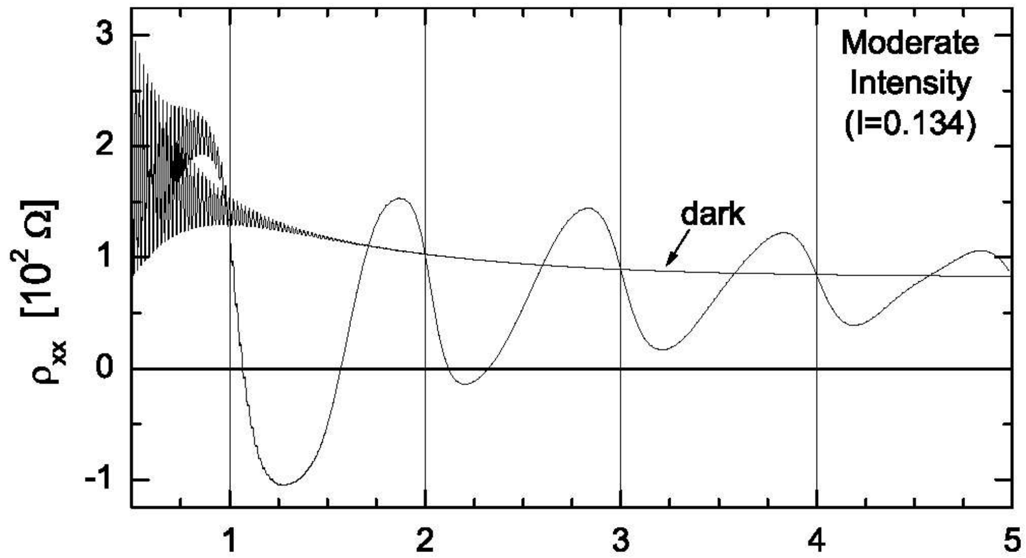
↓

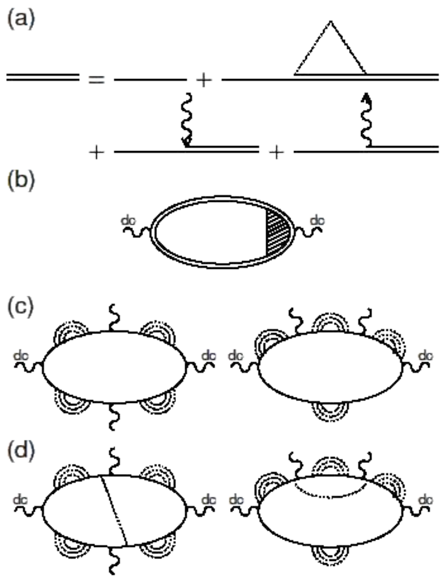
Dynamic instability

↓

New phase: non-equilibrium, self-organization

# Numerical Result




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.

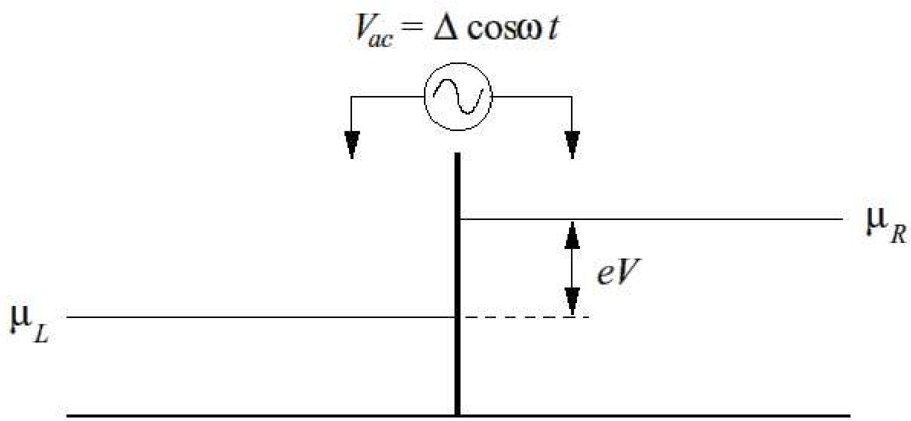
• the transport anomaly (negative resistance) is the result of photon assisted transport and the non-trivial electron density of states of the system.

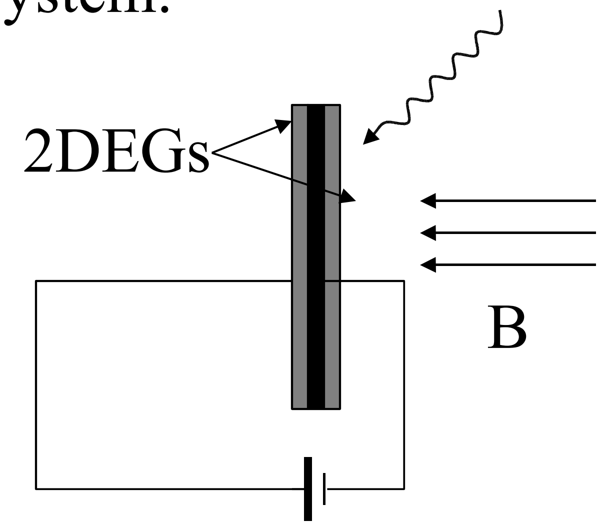
• The transport anomaly is NOT a special property of 2DEG. Similar anomaly could also be observed in other systems, provided the necessary conditions are met.

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

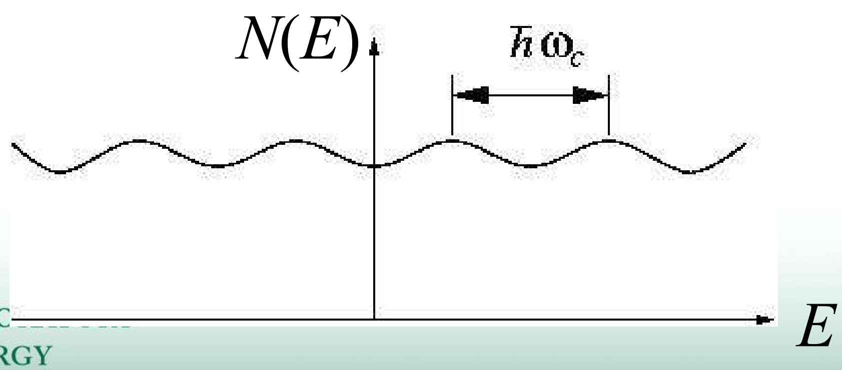
# A Toy Model to Elucidate the Mechanism

• The simplest photon-assisted transport system:




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



# Conductance Formula

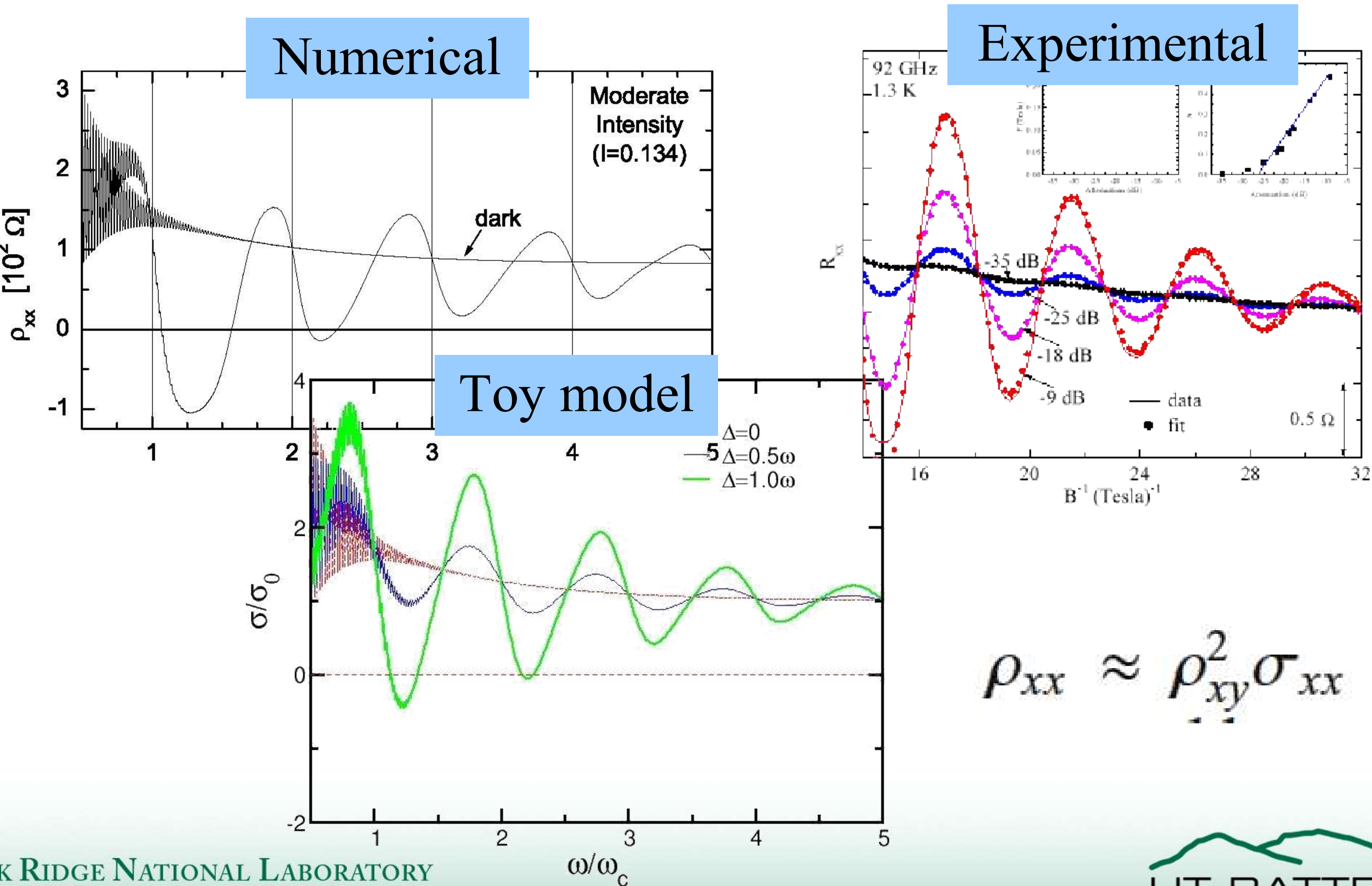
$$I = eD \int d\epsilon \sum_n J_n^2\left(\frac{\Delta}{\hbar\omega}\right)[f(\epsilon) - f(\epsilon + n\hbar\omega + eV)]\,\rho_L(\epsilon)\rho_R(\epsilon + n\hbar\omega + eV)$$

Photon assisted tunneling: $\epsilon \longrightarrow \epsilon + n\hbar\omega + eV$

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

Negative conductance results from the negative derivative of the density of states and the photon-assisted tunneling.

# Comparison with Experiments and Numerical Calculations




$$\rho_{xx} \approx \rho_{xy}^2 \sigma_{xx}$$

# Qualitative Features

- The positions of the conductance minima are determined by:

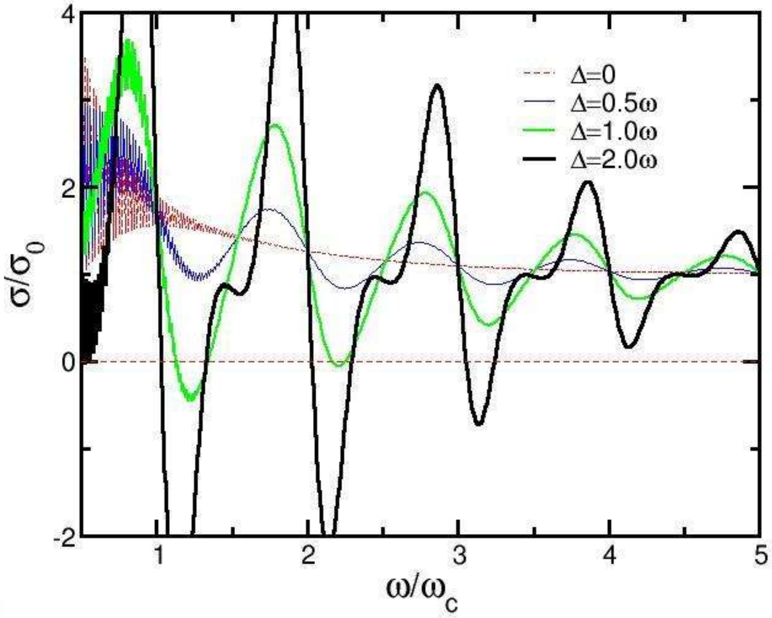
$$\tan x = -x/2, \quad x = 2\pi\omega/\omega_c$$
$$\omega/\omega_c = 1.29,\ 2.27,\ 3.27,\ 4.26\ldots$$

↔

$$\omega/\omega_c = n + 1/4$$

- $\sigma(\omega = n\omega_c) = \sigma$

- Deviation induced by high power of radiation



# Uniform Systems: Generalized Kubo-Greenwood Formula

Generalized Kubo-Greenwood formula for photon-assisted transport:

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

$$D_n(\epsilon, \epsilon + n\hbar\omega) = 2\pi\hbar \overline{J_n^2(\Delta_{\alpha\beta}/\hbar\omega) \left|\hat{\mathbf{j}}_{\alpha\beta}\right|^2}$$

Photon assisted transport probability

The same formula as that for the tunneling junction!

# Derivation of the Formula

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

$\underbrace{H_0 + H_{ac}(\omega)}$ un-perturbed system

Effect of MW: $|\alpha(t)\rangle \longrightarrow e^{-i\tilde{E}_\alpha t/\hbar} \sum_{n=-\infty}^{\infty} e^{-in\omega t} |\alpha, n\rangle$

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

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

Floquet theorem (Bloch theorem in time domain)

Kubo Formula:

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

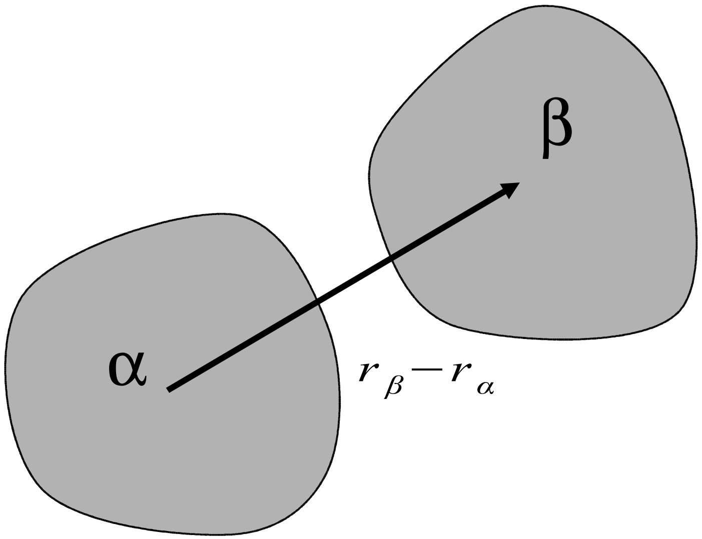
$$P_{i(f)} = e^{-\beta E_{i(f)}}/Z$$

# How Effective of Photon-Assisted Process in a Uniform System?

$$D_n(\epsilon, \epsilon + n\hbar\omega) = 2\pi\hbar \overline{J_n^2(\Delta_{\alpha\beta}/\hbar\omega)\left|\hat{\mathbf{j}}_{\alpha\beta}\right|^2}$$

$$\Delta_{\alpha\beta} \approx e\left|(\mathbf{r}_\alpha - \mathbf{r}_\beta)\cdot \mathbf{E}_\omega\right|$$

$\Delta_{\mathrm{eff}} \sim E_\omega l$ ← Typical electron length scale




$E_\omega \sim 10\,\mathrm{V/m}$

$l \sim 10^{-4}\,\mathrm{m}$ mean free path

$\Delta_{\mathrm{eff}} \sim 1\,\mathrm{meV}$

$\hbar\omega \sim 0.4\,\mathrm{meV}$ ⇒ $\Delta_{\mathrm{eff}} > \hbar\omega$

# Search in Other Systems

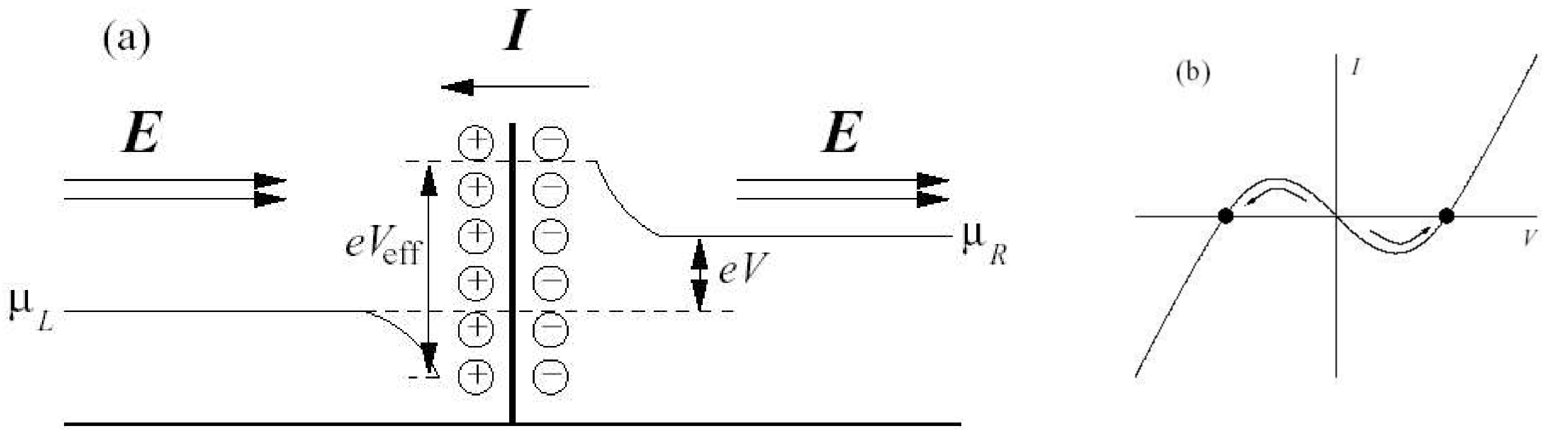
The phenomena could be observed in other uniform systems, provided:

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

• Non-trivial density of states

• Strong enough radiation: $\Delta_{\mathrm{eff}} > \hbar\omega$

# Implication of Negative Conductance: Toy Model

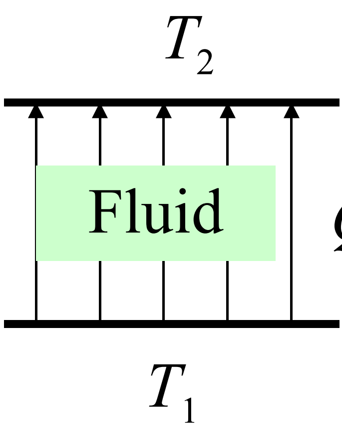



• negative conductance implicates the instability of the system. The system will re-organize to a new phase.

• The resulting new phase sensitively depends on the detailed setup of the system.

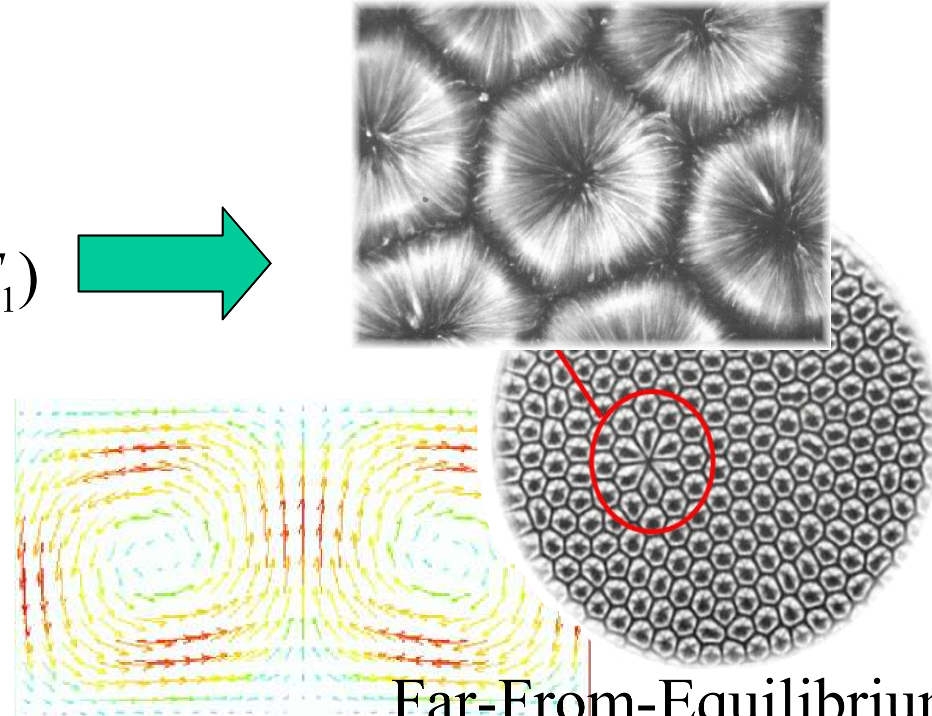
# Uniform System: Far-From-Equilibrium and Self-Organization

Heat Transfer




$Q=\kappa(T_2-T_1)$

Convection current & Benard Cells



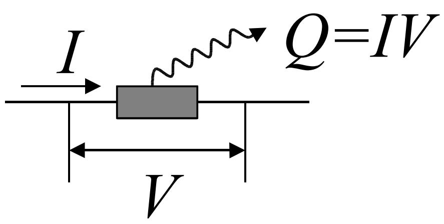
Near-Equilibrium

Far-From-Equilibrium

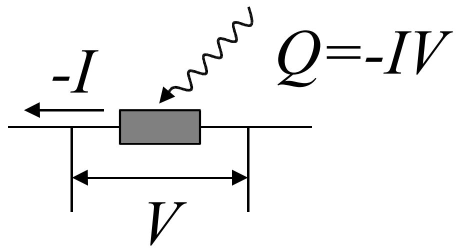
# Why Self-Organization?

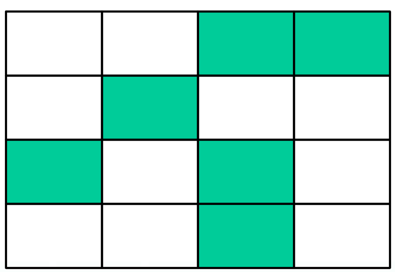
Self-organization originates from the competition between subsystems for the finite resource.

Positive Conductivity




Negative Conductivity



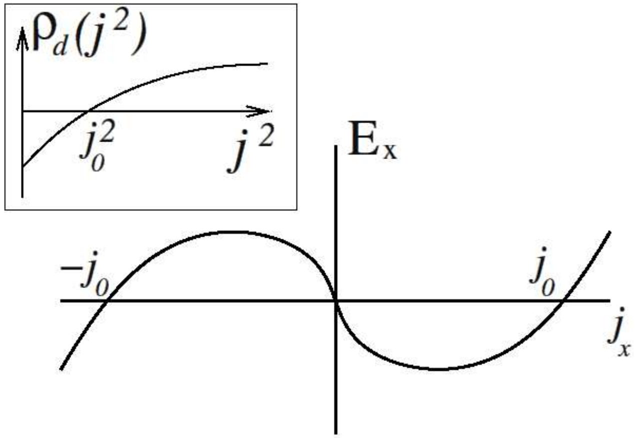



In negative conductivity regime, subsystems have to compete the energy flow provided by the microwave radiation.

# 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




Nonlinear *I-V* curve

$$\boldsymbol{E} = \boldsymbol{j}\rho_d\left(\boldsymbol{j}^2\right)$$

- 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?