NOVEL PHENOMENA IN DILUTE 2D ELECTRON SYSTEMS

Background and Some Recent Developments

Myriam P. Sarachik

City College of New York, CUNY

With: Sergey A. Vitkalov, Yeekin Tsui, Kurt James, Teun M. Klapwijk

Islam Hoxha, Hairong Zheng, Dima Simonian, Kevin Mertes, Sergey Kravchenko, V. M. Pudalov

Research Supported by DOE and NSF
OUTLINE

I - Brief History

II - The temperature dependence: - an apparent metal-insulator transition in 2D

Partial list of theoretical suggestions

Important question:

Mundane? e. g. oxide traps
Profound? e. g. new ground state

III - The effect of magnetic field applied parallel to the plane

IV - Scaling of the magnetoconductance -

Evidence for a divergence in the susceptibility
\[ \chi \rightarrow \infty , \; g^* m^* \rightarrow \infty , \; m^* \rightarrow \infty \]
Quantum phase transition; to what new ground state??
No metallic state is possible in *non-interacting* 2D electron systems

Abrahams, Anderson, Licciardello and Ramakishnana, 1979

Weak disorder: $\sigma = ne^2\tau/m^* + A(e^2/h) \ln (T/T_0)$

Strong disorder: $\sigma \sim \exp \left[ -(T/T_0)^{1/p} \right] \quad p=1,2,3$

No metallic state is possible in *weakly interacting* 2D electron systems

stronger localization

Altshuler, Aronov, Lee 1980
Dolan and Osheroff, PRL 43, 721 (1979)

Bishop, Tsui and Dynes, PRL 44, 1153 (1980)
WEAKLY

INTERACTING ELECTRONS (HOLES) ARE

ALWAYS

LOCALIZED in 2D

in the limit $T \to 0$


OUTLINE

I - Brief History

II - The temperature dependence: an apparent metal-insulator transition in 2D
Kravchenko, Mason, Bowker, Furneaux, Pudalov, D’Iorio
PRB 52, 7038 (1995)
Kravchenko, Mason, Bowker, Furneaux, Pudalov, D’Iorio
PRB 52, 7038 (1995)
Temperature scaling

Kravchenko, Mason, Bowker, Furneaux, Pudalov, D’Iorio
PRB 51, 7038 (1995)
Electric field scaling

Kravchenko, Simonian, Sarachik, Mason, Furneaux, PRL 77, 4938 (1996)
(Z+1)ν = 2.7

Zν = 1.2

z = 0.8 ν = 1.5

Kravchenko, Simonian, Sarachik, Mason, Furneaux, PRL 77, 4938 (1996)
QUESTION:

Why had this transition not been seen in Earlier experiments in silicon MOSFET’s?

Why had this not been seen in 2D systems in other materials?
Hanein, Meirav, Shahar, Li, Tsui, Shtrikman, PRL 80, 1288 (1998)
In silicon MOSFET’s

Fermi energy:

\[ E_F = n_s \pi \hbar^2 / 2m = 0.63 \text{ meV} \]

Electron-electron interaction energy:

\[ E_{ee} \sim e^2 / \epsilon a \sim e^2 (\pi n_s)^{1/2} / \epsilon \sim 10 \text{ meV} \]

\[ \frac{E_{ee}}{E_F} > 1 \]

\[ \frac{E_{ee}}{E_F} \sim n^{-1/2} \]
Change to metallic behavior occurs at:

1. Low densities -
   interaction energy $\gg$ Fermi energy
   role of interaction $\ ?$

2. Critical resistivity $\approx \hbar/e^2$
   role of disorder $\ ?$
No metallic state is possible in non-interacting 2D electron systems

Abrahams, Anderson, Licciardello and Ramakishnana, 1979

Weak disorder: $\sigma = ne^2\tau/m^* + A(e^2/h) \ln (T/T_0)$

Strong disorder: $\sigma \sim \exp \left[-(T/T_0)^{1/p}\right]$  $p=1, 2, 3$

No metallic state is possible in weakly interacting 2D electron systems

stronger localization

Altshuler, Aronov, Lee 1980

Can strong electron-electron interactions cause delocalization?

Finkelstein, 1983
Castellani, DiCastro, Lee and Ma, 1984
Efros and Pikus, 1995
I - Brief History

II - The temperature dependence: an apparent metal-insulator transition in 2D

Partial list of theoretical suggestions

Important question:

Mundane? e.g. oxide traps
Profound? e.g. new ground state
THEORY

“Finkelshtein” metallic phase
   Si and Varma; Castellani, DiCastro, and Lee; Shamon, Ludvig and Nayak

Perfect metal (R → 0 as T → 0)
   Dobrosavljevic, Abrahams, Miranda, and Chakravarty
   Chakravarty, Yin and Abrahams

Superconductivity
   Phillips, Wan, Martin, Knysh, and Dalidovich
   Belitz and Kirkpatrick; Zhang and Rice; Mathew Fisher

Spin-orbit effects, spin-split bands
   Pudalov; Lyander-Geller; Skvorcsov; Papadakis, de Poortere, Manohara
   and Shayegan; Yaish, Prus, Buchstab, Yoseph, Sivan and Stern

Wigner crystal, Wigner glass
   Chakravarty, Kilvelson, Nayak, and Voelker; Efros

Between Wigner crystal and Fermi glass
   Benenti, Baintal and Pichard

Interaction-driven localization
   Shepelyansky

Percolation
   electron (hole) vapor-liquid phases- He and Xie
   Yigal Meir

Ferromagnetism in 2D
   Chamon, Mucciolo and Castro Neto
**Important Question**

**New physics?**

Do these effects signal the existence of a new state of matter?

- a strongly paramagnetic low-density conducting phase (Finkelshtein)
- a perfect metal
- a non-Fermi liquid
- superconductivity
- Wigner crystal or glass
- ferromagnetism

**Known physics?**

Can they be explained by applying or extending old physics?

- a vapor/gas separation in the electron system
- filling and emptying of charge traps
- temperature-dependent screening
- crossover from Boltzmann to Fermi statistics
- interband scattering
- thermal screening of a percolation threshold
OUTLINE

I - Brief History

II - The temperature dependence: an apparent metal-insulator transition in 2D

III - The effect of magnetic field applied parallel to the plane
Simonian, Kravchenko, Sarachik, Pudalov, PRL 79, 2304 (1997)
Simonian, Kravchenko, Sarachik, Pudalov, PRL 79, 2304 (1997)
Pudalov, Brunthaler, Prinz, Bauer, JETP Lett. 65, 932 (1997)
Yoon, Li, Shahar, Tsui, Shayegan, PRL 84, 4421 (2000)
Shubnikov-de Haas measurement
(a) $H = 18T < H_{\text{sat}}$
spins partially polarized

$n_s = 9.28 \times 10^{11} \text{ cm}^{-2}$

(b) Fourier amplitude ($\hbar/e^2$)

S. A. Vitkalov et al., PRB (2001)
The image contains two graphs labeled (a) and (b) with the following annotations:

(a) 
- Resistivity $\rho$ in units of $10^{-2} \text{h/e}^2$ as a function of the filling factor $\nu$.
-标注: $H = 18 \text{T} \geq H_{\text{sat}}$ spins completely polarized.
- $n_s = 3.72 \times 10^{11} \text{cm}^{-2}$

(b) 
- Fourier amplitude in units of $\hbar/e^2$ as a function of frequency $v^{-1}$.

Graph (b) includes an inset showing the energy levels with $E_F$ and $\Delta Z$ indicated.

Reference: S. A. Vitkalov et al., PRB (2001)
SCALING OF THE
MAGNETOCONDUCTANCE
Vitkalov, Zheng, Mertes, Sarachik, Klapwijk, PRL 87, 086401 (2001)
SCALING:

\[
\frac{\sigma(0) - \sigma(H)}{\sigma(0) - \sigma(\infty)} = \phi \left( \frac{H}{H_0} \right)
\]
\[
\frac{\sigma(0)-\sigma(H)}{\sigma(0)-\sigma(\text{inf})}
\]

\[n = 1.2 \times 10^{11} \text{ cm}^{-2}\]
\[ H_\sigma(T) = A(\Delta^2 + T^2)^{1/2} \]
\[ H_\sigma = A(\Delta^2 + T^2)^{0.5} \]

\[ \Delta \to 0 \text{ at } n_s \approx n_c, \quad H \propto T \]

\[ \Phi(H/H_\sigma) \to \Phi(H/T) \]

\[ \Delta (K) \]

Electron density \((10^{11} \text{ cm}^{-2})\)
\[ g^* \mu_B H_\sigma = 2E_F = \left( n_s h / \pi g_v g_s \right) (m^*)^{-1} \]

\[ (\chi^*)^{-1} \propto (g^* m^*)^{-1} \]
SCALING OF THE MAGNETOCO nductance

Spin susceptibility diverges at finite density

\[ g^* m^* \to \infty \quad \text{at} \quad n_0 \sim n_c \]

Quantum phase transition to a new ground state?
Pudalov, Gershenson, Kojima, Butch, Dizhur, Brunthaler, Prinz, Bauer, PRL 88, 196404 (2002)

Vitkalov, Sarachik, Klapwijk, PRB 65, 201106 (2002)
SUMMARY

II - The temperature dependence: - an apparent metal-insulator transition in 2D

III - The effect of magnetic field applied parallel to the plane

IV - Scaling of the magnetoconductance -

Evidence for a divergence in the susceptibility
\[
\chi \to \infty \ , \ g^*m^* \to \infty \ , \ m^* \to \infty
\]

Important question:

Mundane? e. g. oxide traps
Profound? e. g. new ground state
\( n = 1.08 \times 10^{11} \text{ cm}^{-2}; \ S#2 \)
Vitkalov, Sarachik, Klapwijk, PRB 65, 201106 (2002)
$H = 0T$ \hspace{1cm} $\mu gH_{\sigma} = 2E_F^0$ \hspace{1cm} $\mu gH_{\rho} = 2E_F^0 + \delta$

$E_F^0$ \hspace{1cm} $2E_F^0$ \hspace{1cm} $2E_F^0 + \delta$

$\delta$ \hspace{1cm} $\delta/2$ \hspace{1cm} $\delta/2$
$H_\rho$ versus $H_\sigma$

$H_\sigma$ reflects behavior of high-mobility states.

$H_\rho > H_\sigma$ required to align ALL states, including tails

$H_\rho \neq H_\sigma$ in the presence of disorder

$H_\rho \approx H_\sigma$ at high densities $n$

Difference $(H_\rho - H_\sigma)$ grows as $n_c$ is approached, and as the fraction of tail states grows.

Scaled magnetoconductance identifies an energy scale that tends to zero at or near $n_c$ in response to application of in-plane magnetic field.
\[ \tau = \mu m^* c/e \]
Bogdanovich and Popovic, PRL 88, 236401 (2001)

Noise power $\mu 1/f^\alpha$
Kravchenko and Klapwijk, PRL 84, 2909 (2000)
Sample #1

\[
\frac{(\sigma(0) - \sigma(\infty))}{(\sigma(0) - \sigma(\infty))} = \frac{\sigma(H)}{\sigma(0)}
\]

T (K)
- 0.27
- 0.45
- 1.0
- 1.63
- 0.60

0.82 \times 10^{11} \text{ cm}^{-2}

H/T \quad (T/K)
\[ n_s = 7.5 \times 10^{10} \text{ cm}^{-2} \]

\[ B_{\parallel} = 1 \text{ Tesla} \]

\[ B = 0 \]
Does \( m^*g^* \) diverge in silicon inversion layers?

Transport experiments - Yes

Shubnikov-de Haas - No
RECAP

1. Brief history.

2. An apparent MIT in two dimensions: the temperature dependence.

3. The effect of magnetic field applied parallel to the 2D plane.

4. An important question: mundane (e.g. oxide traps)? profound (e.g. a new state of matter)?

6. Recent experimental results:

MAGNETIC PHASE in 2D?
Does $m^*g^*$ diverge at finite density?
Electron glass?

Bogdanovich and Popovic, PRL 88, 236401 (2002)
Jaroszynski, Popovic and Klapwijk, cond-mat/0205226