Magnetically Induced Electronic States in 2D Superconductors

Jongsoo Yoon
University of Virginia

Carlos Vicente
Yongho Seo
Yongguang Qin
Yize Li

Christine Lyon
Chester Rubbo
Brian Gross

National High Magnetic Field Laboratories (NHMFL)

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Magnetically Induced Electronic States in 2D Superconductors

Resistance ($\rho$) vs. Temperature ($T$)

- **Insulating phase**
  \[ \left( \frac{d\rho}{dT} < 0 \right) \]

- **Superconducting phase**
  \[ \rho = 0 \]

Increasing Magnetic fields ($B$)
How does the phase change occur?

Superconductor – Insulator Transition

Superconductor – Metal – Insulator Transition

Resistance ($\rho$) vs. Temperature ($T$)

- Insulating phase
- Superconducting phase
- Metallic phase
How does the phase change occur?

Superconductor – Insulator Transition

Superconductor – Metal – Insulator Transition

\(\text{InO} \ (\text{Bi, Be, MoSi, \ldots})\)

\(\text{MoGe}\)


Mason and Kapitulnik, PRL 81, 5342 (1999)
1. **What we are studying – material system**
   - Material selection (tantalum)
   - Growth
   - Characterization

2. **What we found – magnetic field induced metallic phase**
   - How to identify the phases – transport characteristics
   - Is the metallic phase real?
   - What is the origin?
   - The nature of the phase transitions?

3. **Future experiments and related issues**

4. **Summary**
1. What we are studying – material system
   Material selection (tantalum)

Amorphous vs. Granular Films

Amorphous Films
(Uniform, or homogenous films)

Granular Films
(Non-uniform, or inhomogeneous films)

$T_c$: decreases with decreasing thickness

$T_c$: independent of thickness

$\text{metal-metal interaction} < \text{metal-substrate interaction}$

$\implies$ “wetting”

$\text{metal-metal interaction} > \text{metal-substrate interaction}$

$\implies$ “non-wetting”

$\text{Ti : } T_c \text{ (bulk) } = 0.4 \text{ K}$

$\text{Ta : } T_c \text{ (bulk) } = 4.5 \text{ K}$
1. What we are studying – material system

Growth

Dc sputtering

Chamber cleaning
Baking 3-4 days at ~ 110 °C
Pre-sputtering for ~ 30 minutes

growth
~ 4 mtorr Ar pressure
0.01 nm/sec growth rate

Patterning
shadow mask patterning (Hall bar shape)
growth of 12 samples at one batch
Substrates: silicon, glass, quartz, …
1. What we are studying – material system

Characterization

![Graph showing material system characterization with various data points and curves, including X-ray intensity and thickness data.](image)
2. What we found – magnetic field induced metallic phase

How to identify the phases – non-linear transport characteristics

**M-I boundary**

**Insulating phase**

\[
\frac{d^2V}{dI^2} < 0
\]

**Metallic phase**

\[
\frac{d^2V}{dI^2} > 0
\]

**S-M boundary**

**Superconducting phase**

hysteretic \( I - V \)

(\( \rho = 0 \))

How to identify the phases – non-linear transport characteristics

- Insulating phase: \( \frac{d^2V}{dI^2} < 0 \)
- Metallic phase: \( \frac{d^2V}{dI^2} > 0 \)
- Superconducting phase: \( \rho = 0 \)
2. What we found – magnetic field induced metallic phase

Is the metallic phase real?

**Question:** Can it be due to electron heating?

Joule heating due to the measurements  
Inefficient electron-phonon coupling  
\[\Rightarrow \begin{align*}
\text{electron temperature} & > \\
\text{sample stage temperature}
\end{align*}\]

Superconducting phase  
Metallic phase \((\rho = \text{finite})\)  
Insulating phase

\[\text{direct S-I transition (no metallic phase)}\]

\[\begin{align*}
\text{hysteretic } I - V \\
\text{Thermal run-away}
\end{align*}\]

\[\frac{d^2V}{dI^2} > 0\]  
\[\frac{d^2V}{dI^2} < 0\]
2. What we found – magnetic field induced metallic phase

Is the metallic phase real?

Question: Can it be due to electron heating?

No, it cannot be. The metallic phase is real.

In the heating scenario, \( P_c \) should slowly decrease with increasing \( B \).

Strong increase of \( P_c \)

Smooth evolution across S-M boundary
2. What we found – magnetic field induced metallic phase

What is the origin?

\[ P_c = I_c V_c \] (\( I_c \), \( V_c \))

By tracing the S-M critical fields, we can map the phase diagram in B-T plane.
2. What we found – magnetic field induced metallic phase

What is the origin?

Phase diagram in B-T plane

Hysteresis in the S-phase is likely due to Pinning-depinning transition of vortices.
Vortex pinning – depinning transition

The transition arises from the competition between

\[
\begin{align*}
\text{Pinning force} & \text{ due to disorder potential} \\
\text{Lorentz driving force} & \text{ due to the bias current}
\end{align*}
\]

\[\implies \begin{cases} 
\text{Hysteresis with respect to the driving force} \\
\text{Slow relaxation} \quad \text{(logarithmic time dependence)}
\end{cases}\]

**Vortex system** Irreversible magnetic properties in type II superconductor (thermal activation of magnetic flux lines out of pinning site)

\[
\begin{align*}
\text{Hysteresis} : \\
\text{Slow relaxation} : \\
\end{align*}
\]


**Vortex motion** in the presence of disorder is analogous to the flow of sand grains in a sand pile.

**Sand pile**

Granular flow under the competition between jamming and driving force

\[
\begin{align*}
\text{Hysteresis} : \\
\text{Slow relaxation} :
\end{align*}
\]


Vortex pinning – depinning transition

Slow relaxation is observed in dynamic transport measurements

Logarithmic dependence

\[ V(t) = V_0 + V_1 \exp\left(-t/\tau\right) \]
Vortex pinning – depinning transition

Slow relaxation is observed in dynamic transport measurements
2. What we found – magnetic field induced metallic phase

What is the origin? Vortex dynamics in the presence of disorder

Phase diagram in B-T-disorder space
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3. Future experiments and related issues

4. Summary
2. **What we found – magnetic field induced metallic phase**

**The nature of the phase transitions?**

M-I transition at \( T = 0 \)

Phase change is caused by increasing bias current

⇒ MIT is percolation-like.

![Graph showing phase transitions and data points](image-url)
The nature of the phase transitions?

2. What we found – magnetic field induced metallic phase

percolation-like.

In this percolation-type picture, it is expected

dV/dI should be non-monotonic

• in the insulating phase
• in the limited range of magnetic fields
• with $I_s$ that increases with $B$

![Graphs showing the effect of magnetic field on current and resistance.](image-url)
3. Future experiments and related issues

- Measurements down to \(~ 100 \mu K\).
- High B insulating phase, up to \(~ 45 \text{T}\).
- Effect of parallel magnetic fields.
- Direct measurements of electron temperature.
- High temperature superconductivity.

LaSrCuO

Ando et. al. PRL (1995)

InO

InOLaSrCuO

Gantmakher et. al. LETP (2000)

Steiner et. al. PRL (2005)
3. Future experiments and related issues

- Measurements down to ~ 100 µK.
- High B insulating phase, up to ~ 45 T.
- Effect of parallel magnetic fields.
- Direct measurements of electron temperature.
- High temperature superconductivity.
- Quantum Hall Effect
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