Magnetically Induced Electronic States in 2D Superconductors

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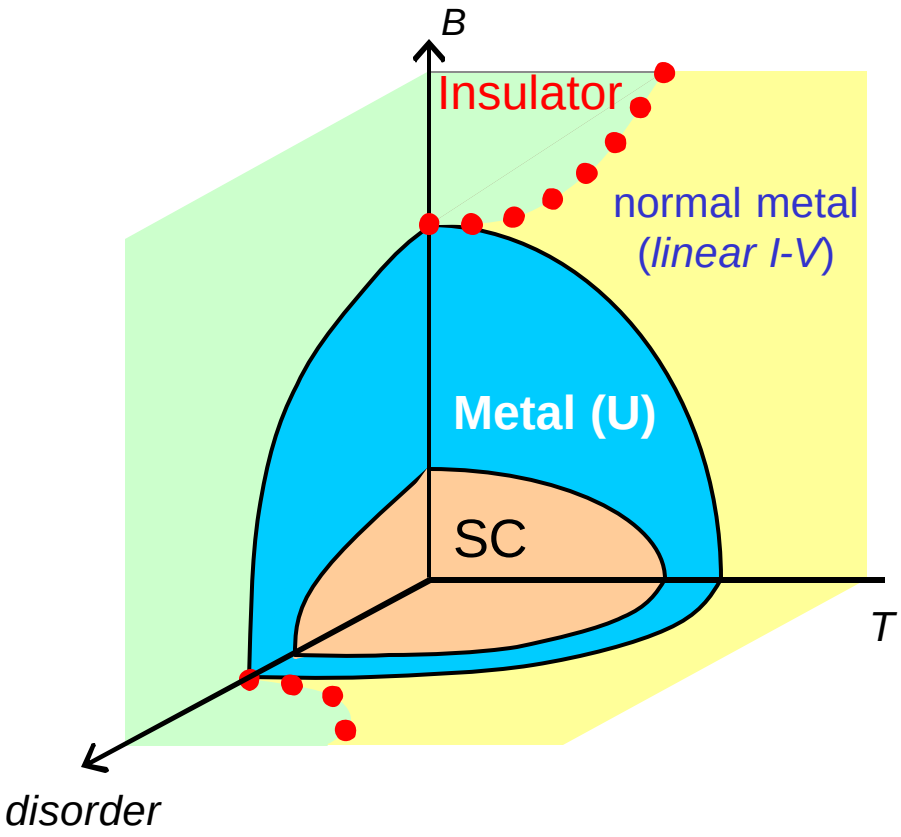

National High Magnetic Field Laboratories (NHMFL)

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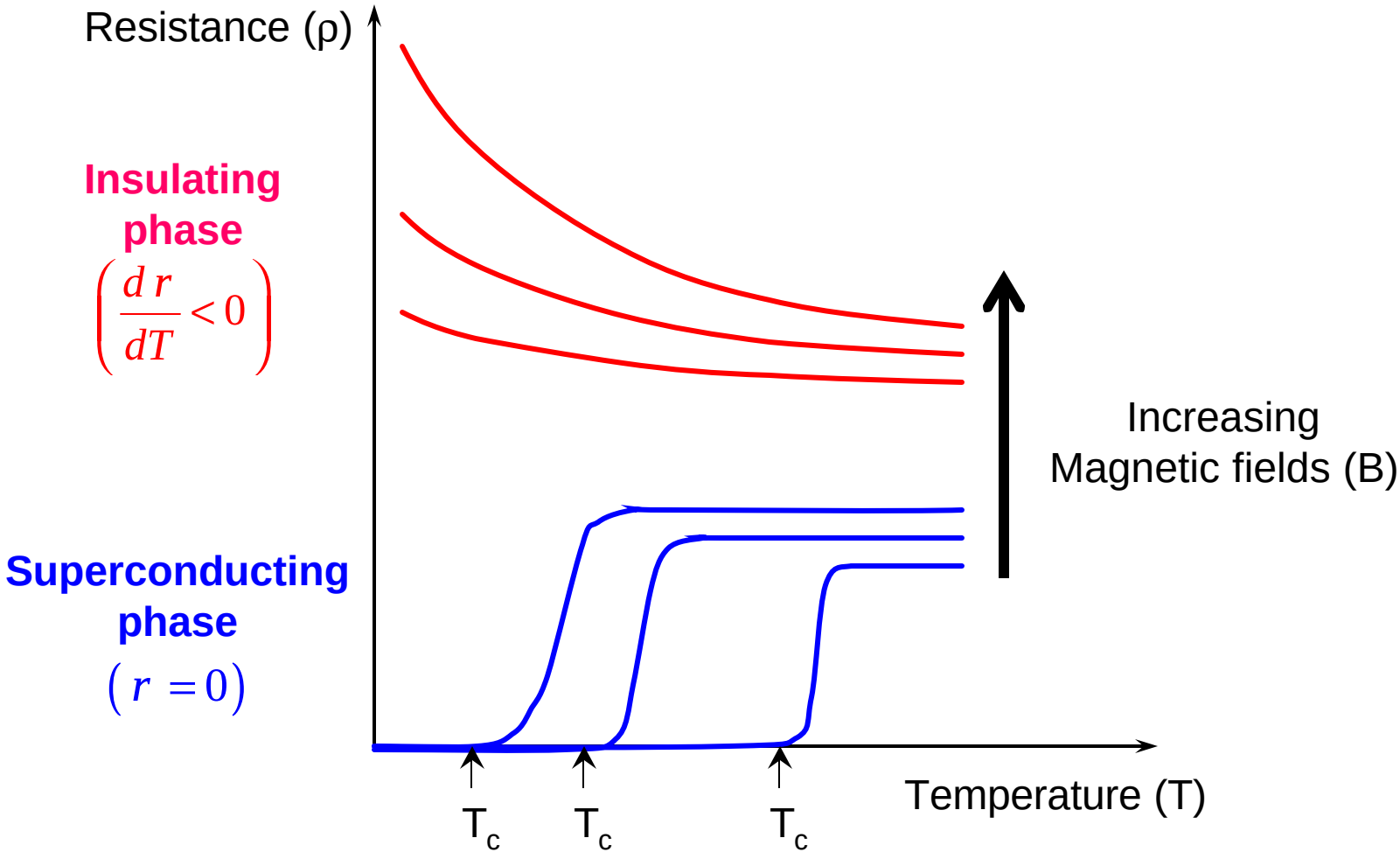
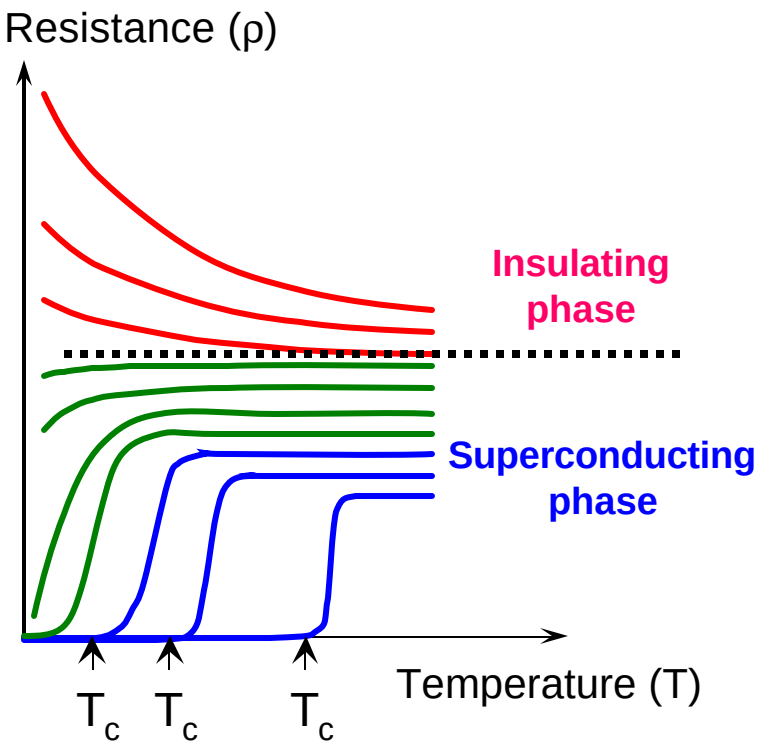
Magnetically Induced Electronic States in 2D Superconductors

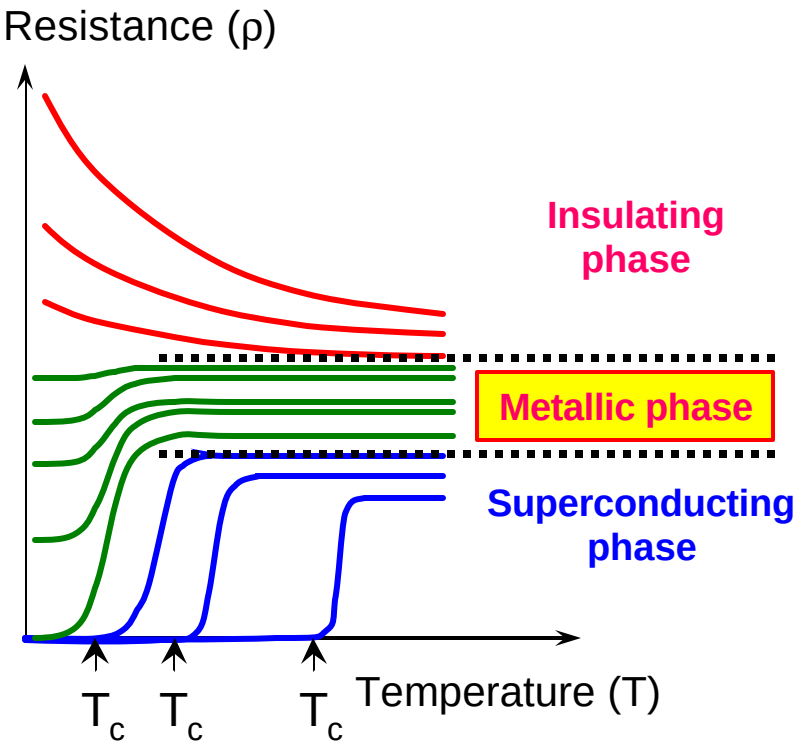


How does the phase change occur?

Superconductor – Insulator Transition



Superconductor – Metal – Insulator Transition

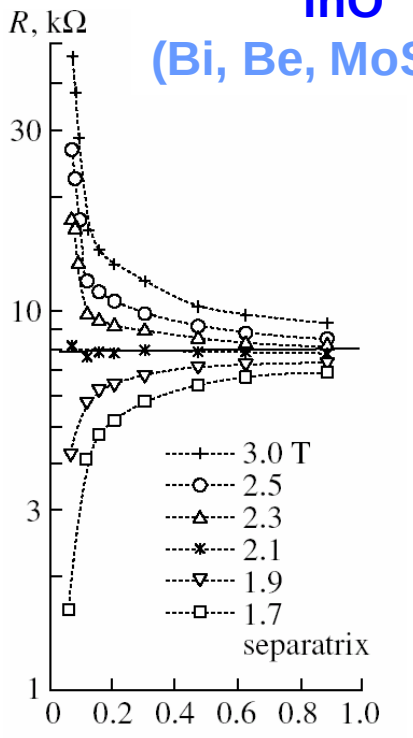


How does the phase change occur?

Superconductor – Insulator Transition

InO

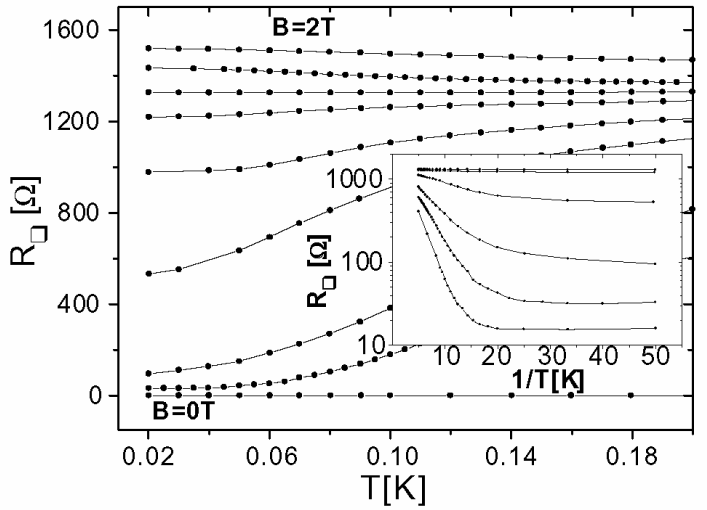
(Bi, Be, MoSi, …)



V. F. Gantmakher et al, LETP **71**, 160 (2000)

Superconductor – Metal – Insulator Transition

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

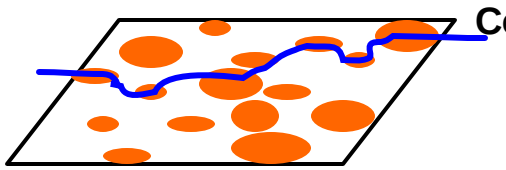
Amorphous Films
(Uniform, or homogenous films)

T_c : decreases with decreasing thickness

[metal-metal interaction] < [metal-substrate interaction]

Þ **"wetting"**

Granular Films
(Non-uniform, or inhomogeneous films)



T_c : independent of thickness

[metal-metal interaction] > [metal-substrate interaction]

Þ **"non-wetting"**

Ti : T_c (bulk) = 0.4 K

Ta : T_c (bulk) = 4.5 K

1. What we are studying – material system

Growth

Dc sputtering

Chamber cleaning

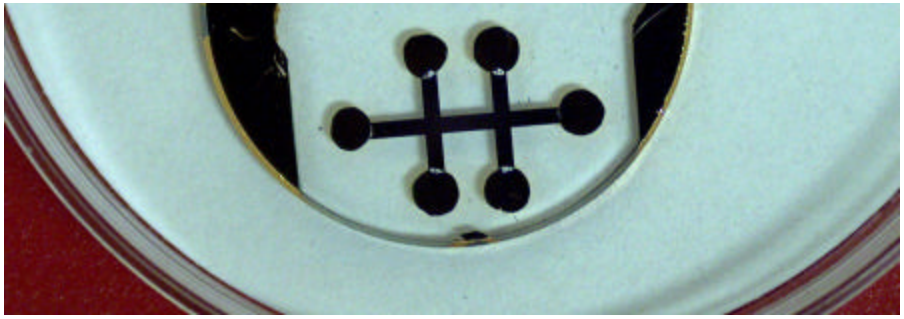
Baking 3-4 days at ~ 110 °C
Pre-sputtering for ~ 30 minutes

growth

~ 4 mtorr Ar pressure
0.01 nm/sec growth rate

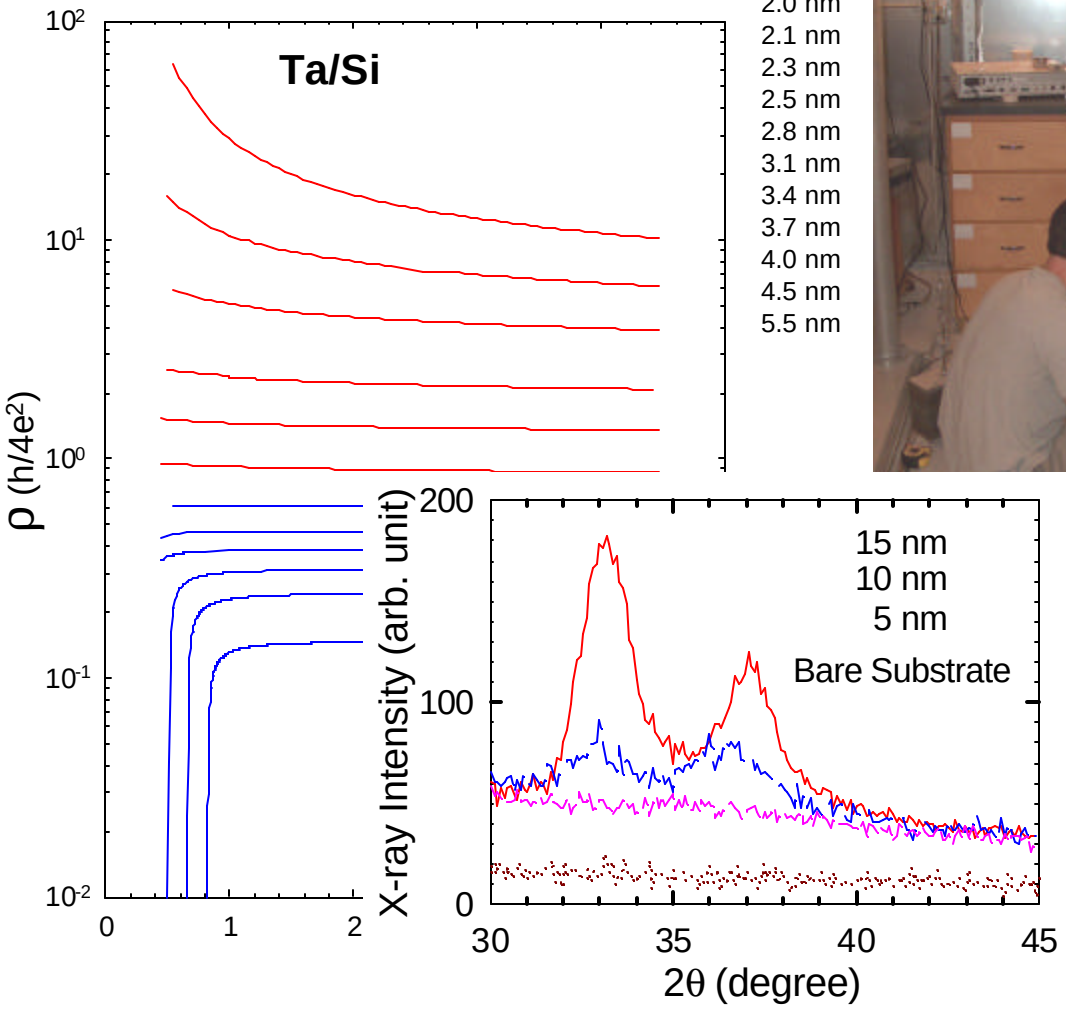
Pattering

shadow mask patterning (Hall bar shape)
growth of 12 samples at one batch
Substrates: silicon, glass, quartz, …



1. What we are studying – material system

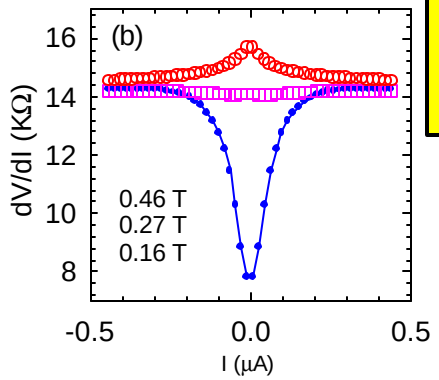
Characterization



2. What we found – magnetic field induced metallic phase

How to identify the phases – non-linear transport characteristics

M-I boundary

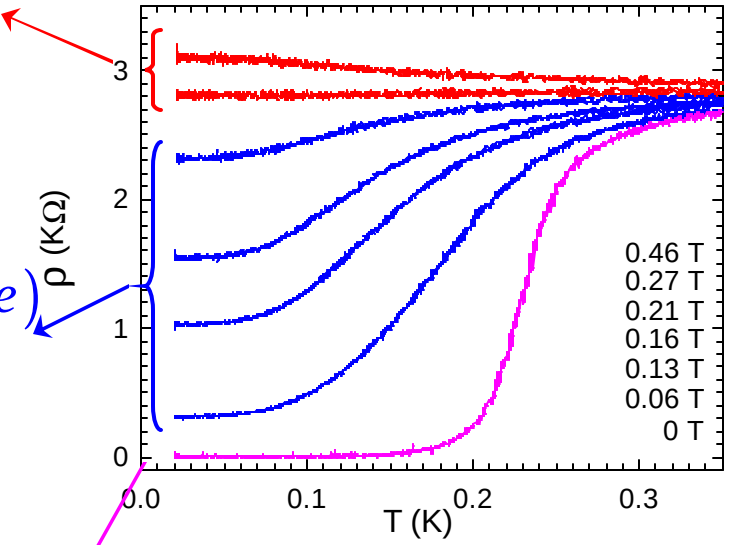


Insulating phase $\left(\frac{dr}{dT} < 0\right)$

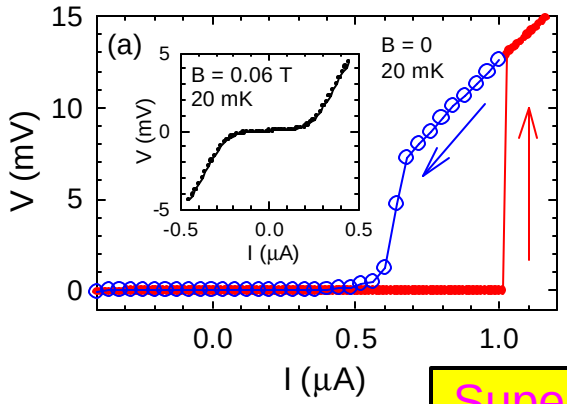
$$\frac{d^2V}{dI^2} < 0$$

Metallic phase $(r = finite)$

$$\frac{d^2V}{dI^2} > 0$$



S-M boundary



Superconducting phase $(r = 0)$

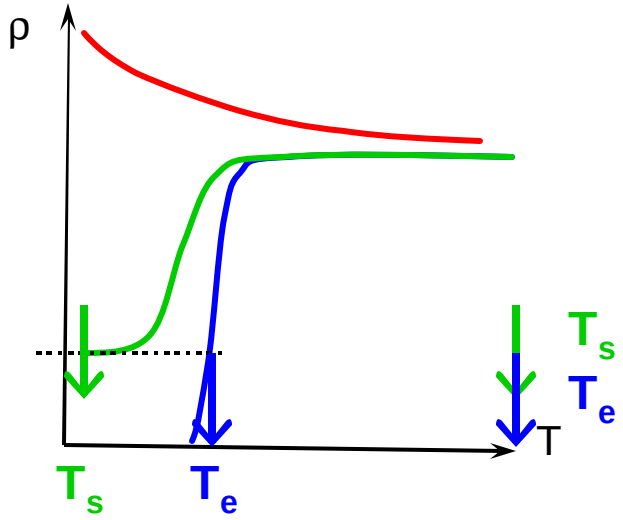
hysteretic $I - V$

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
$\Rightarrow$ [electron temperature] > [sample stage temperature]



direct S-I transition (no metallic phase)

Superconducting phase

$hysteretic\ \ I-V$

Thermal run-away

Metallic phase

$(r = finite)$

$\frac{d^2V}{dI^2} > 0$

Insulating phase

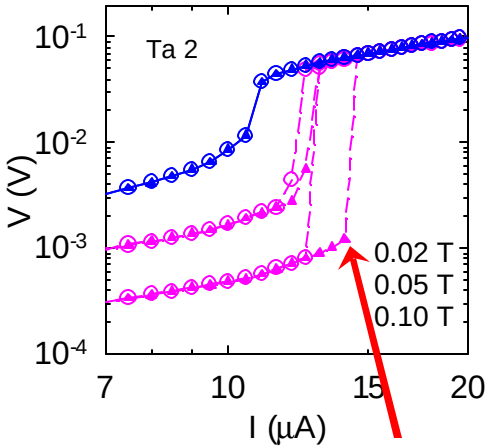
$\frac{d^2V}{dI^2} < 0$

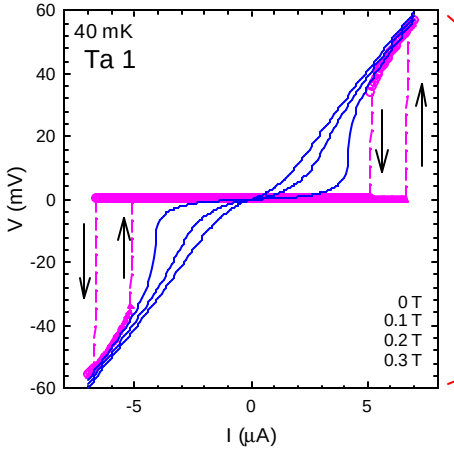
2. What we found – magnetic field induced metallic phase

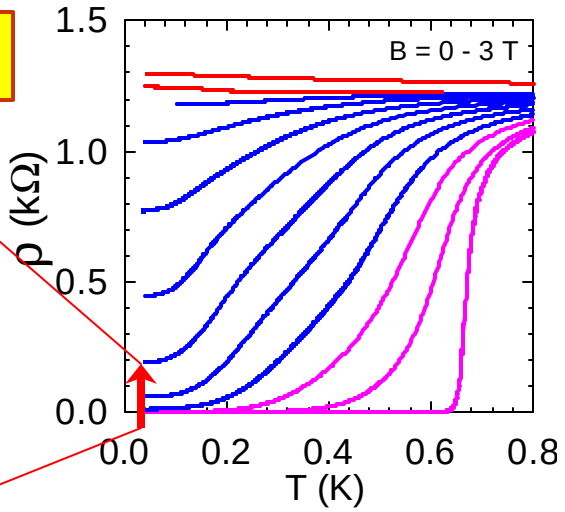
Is the metallic phase real?

Question: Can it be due to electron heating ?

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

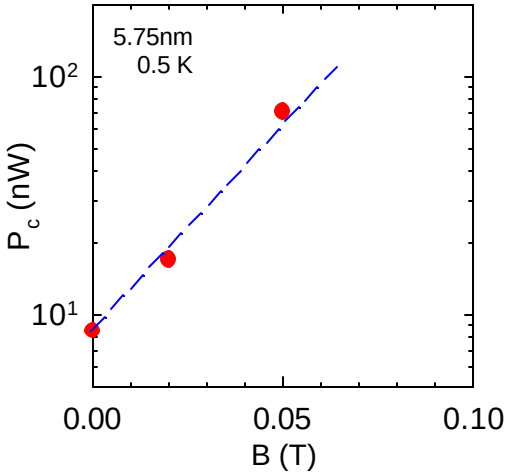


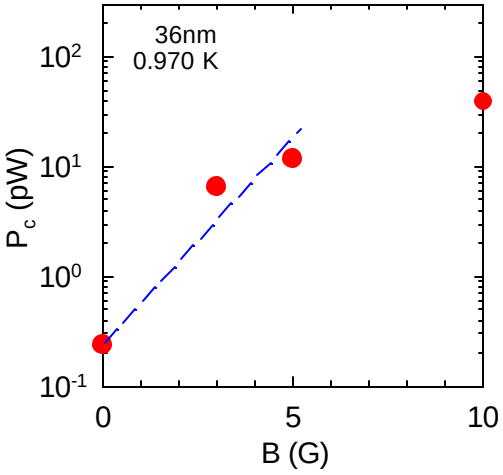




$P_c = I_c V_c \ (I_c, V_c)$

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

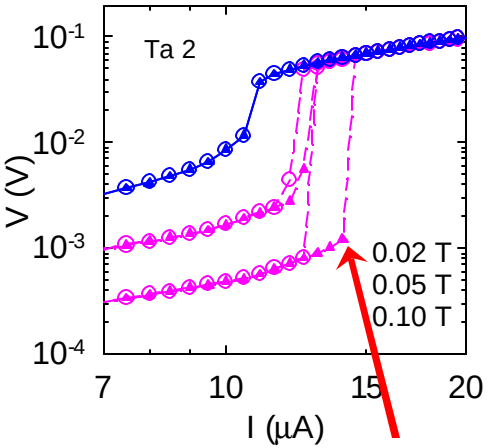


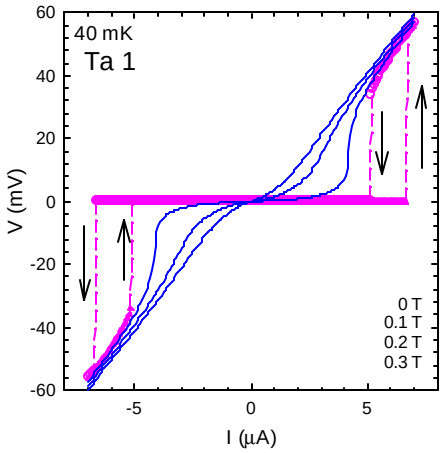


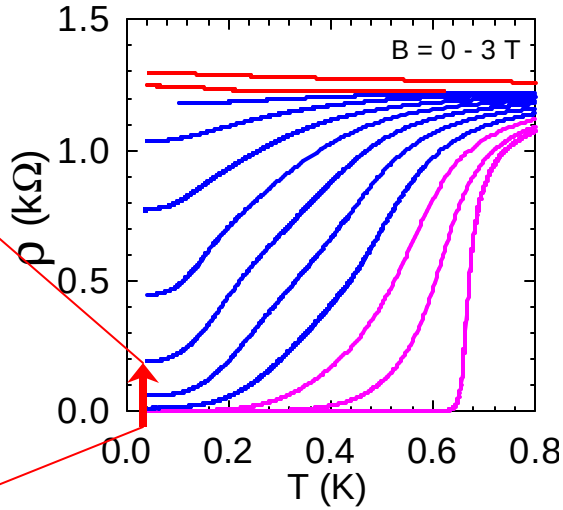
Strong increase of P_c
Smooth evolution across S-M boundary

2. What we found – magnetic field induced metallic phase

What is the origin?





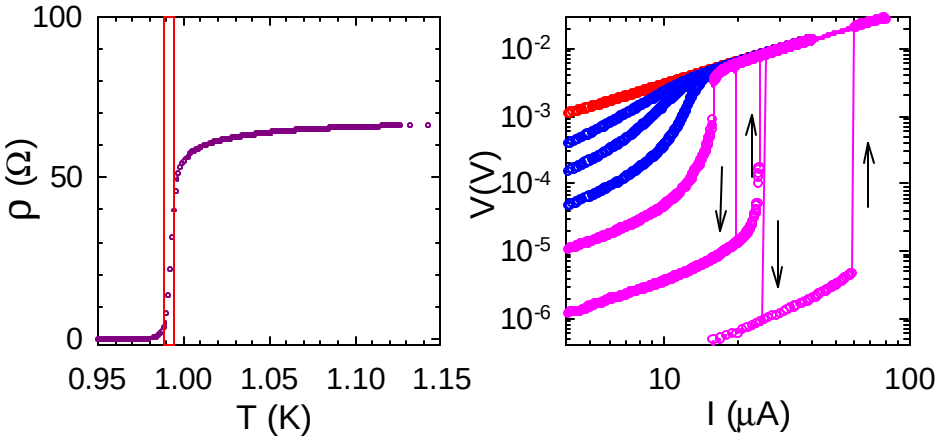


$P_c = I_c V_c$ (I_c, V_c)

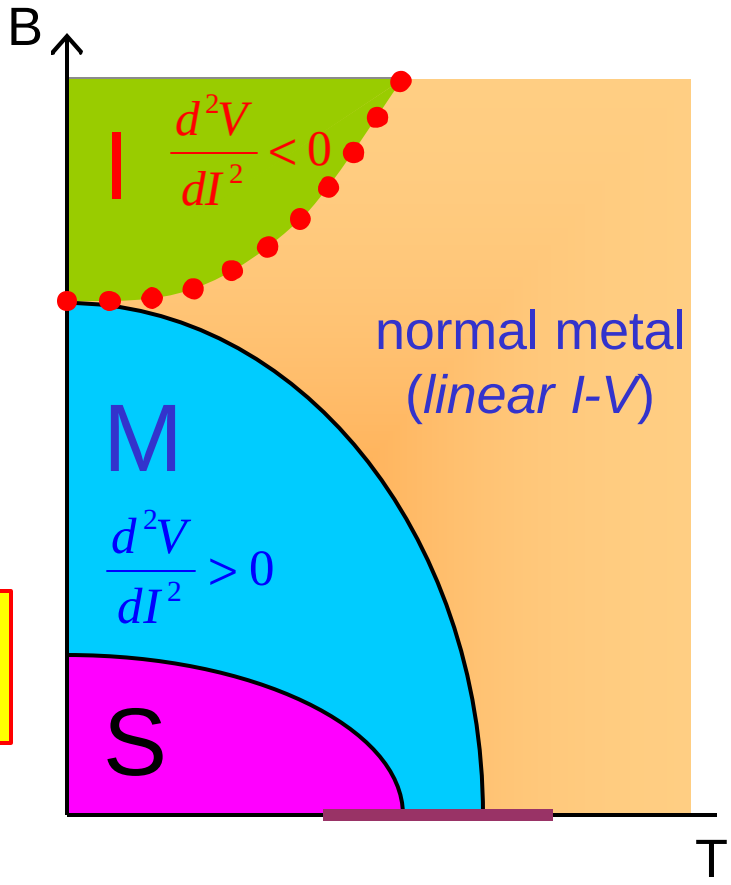
By tracing the S-M critical fields,
we can map the phase diagram in B-T plane.

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

{ Pinning force due to disorder potential
{ Lorentz driving force due to the bias current

$\Longrightarrow$ { Hysteresis with respect to the driving force
{ Slow relaxation (logarithmic time dependence)

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

Hysteresis :
Slow relaxation : } Y. Yashurun et. Al. Rev. Mod. Phys. **68**, 911 (1996)

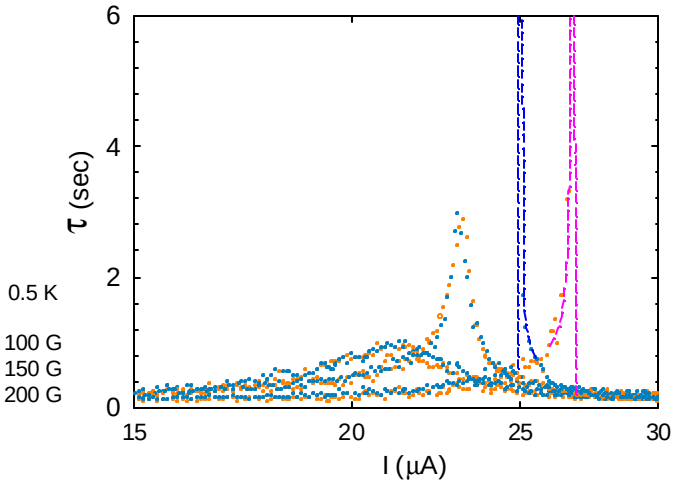
Vortex motion in the presence of disorder is analogous to the flow of sand grains in a **sand pile**.

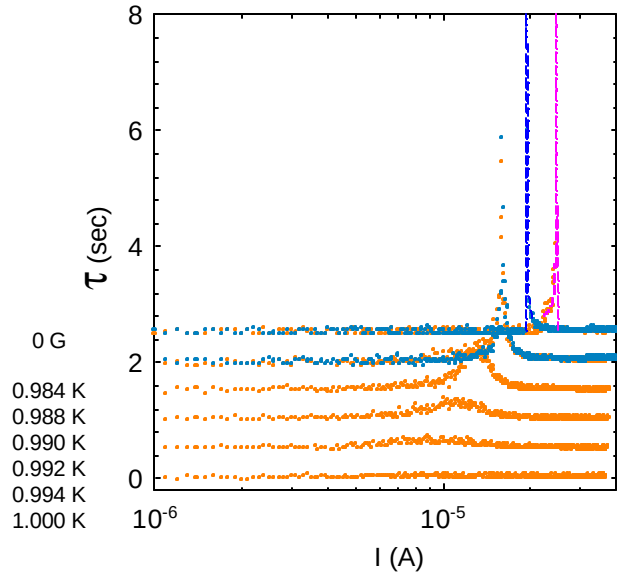
Sand pile granular flow under the competition between jamming and driving force

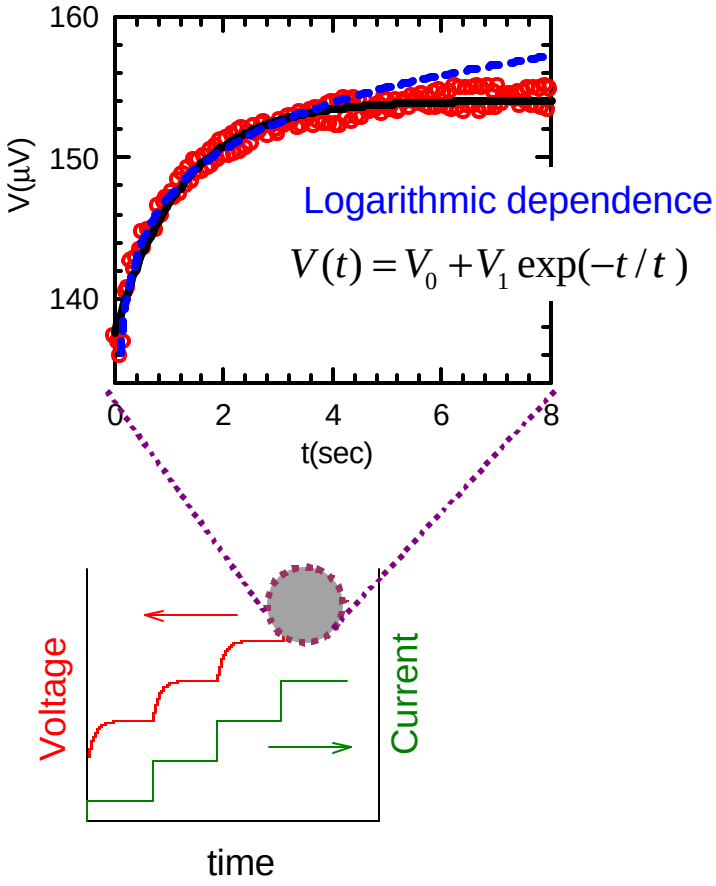
Hysteresis : S. G. K. Tennakoon et al. Europhys. Lett. **45**, 470 (1999)
Slow relaxation : H. M. Jaeger et al. Phys. Rev. Lett. **62**, 40 (1989)

Vortex pinning – depinning transition

Slow relaxation is observed in dynamic transport measurements

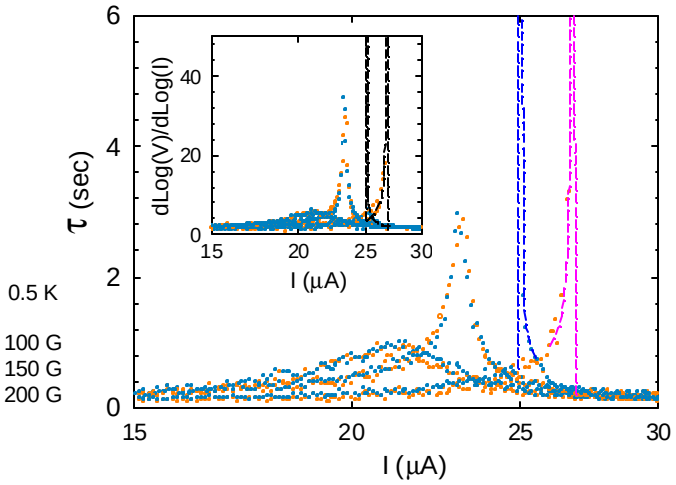


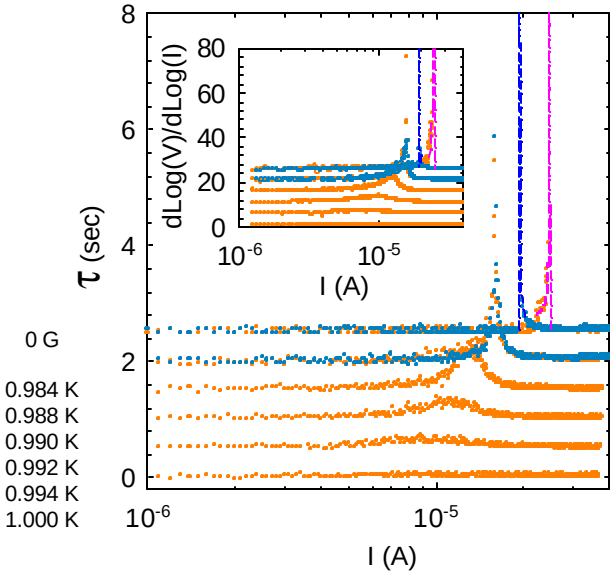


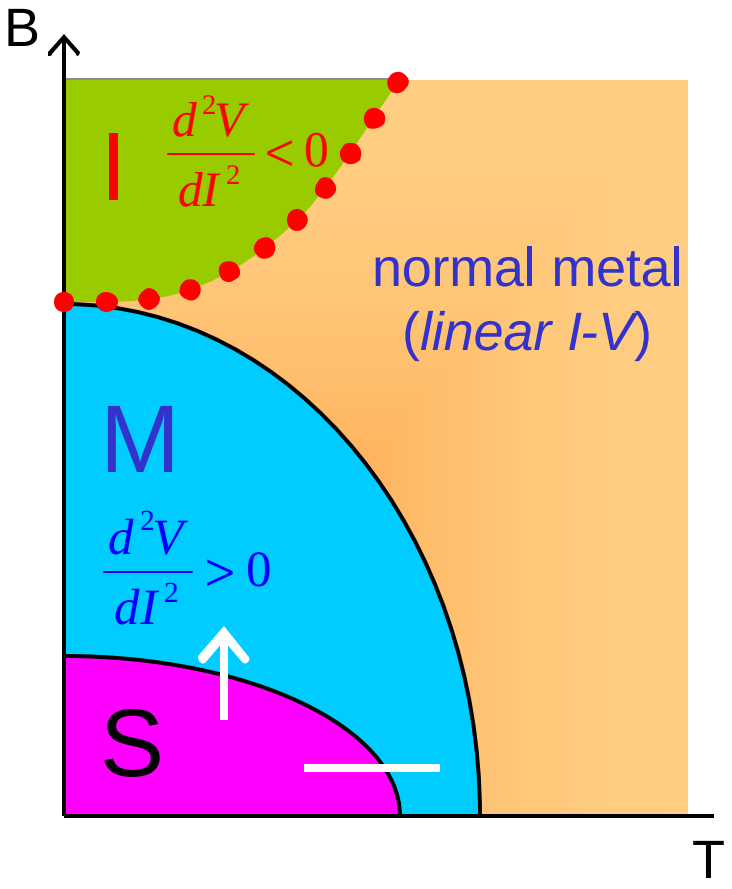


Vortex pinning – depinning transition

Slow relaxation is observed in dynamic transport measurements





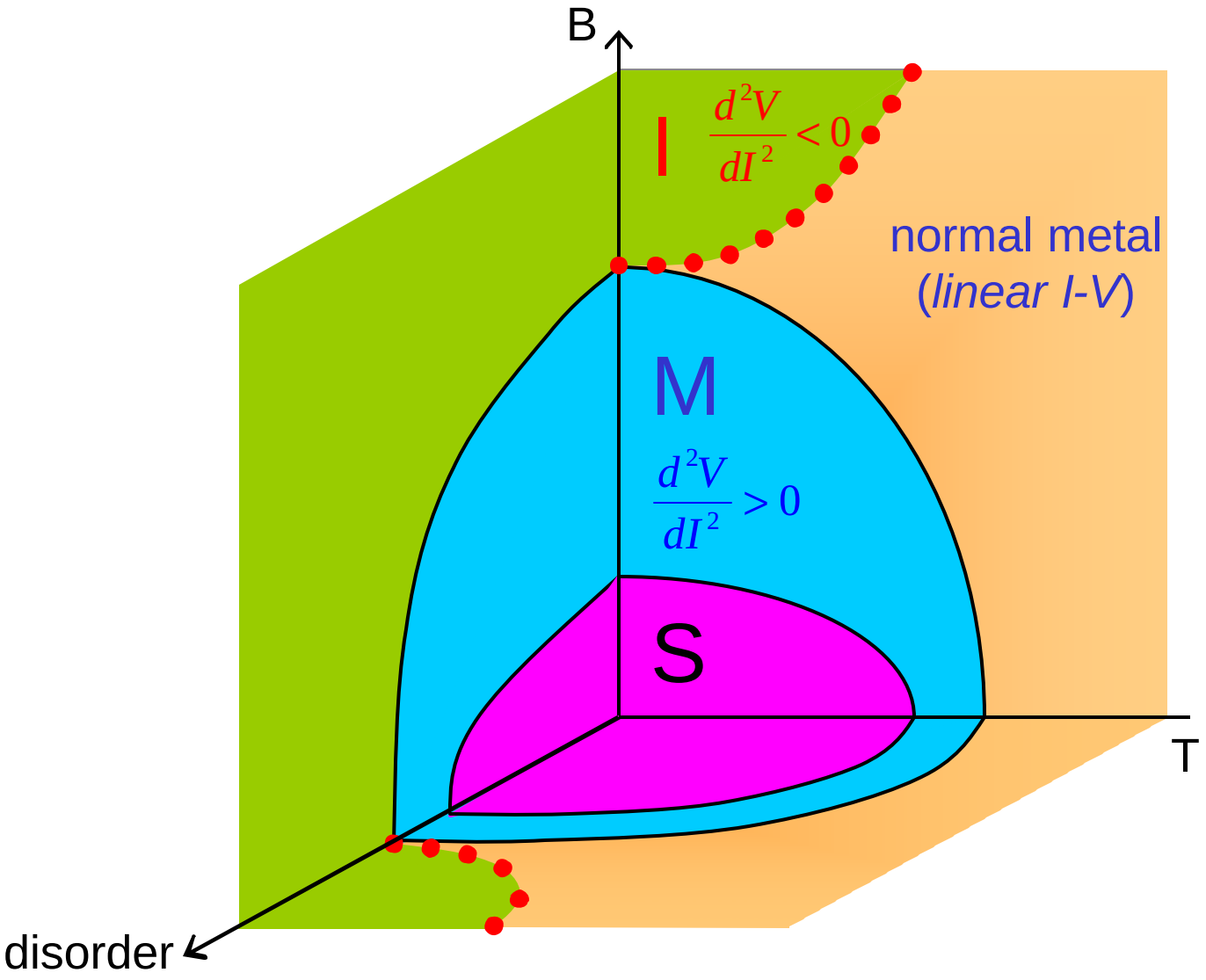


2. What we found – magnetic field induced metallic phase

What is the origin?

Vortex dynamics in the presence of disorder

Phase diagram in B-T-disorder space



1. **What we are studying – material system**

   Material selection (tantalum)

   Growth

   Characterization

   } Homogeneous (amorphous) superconducting films

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

   How to identify the phases – transport characteristics — Nonlinear transport

   Is the metallic phase real? — It is real !

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

   The nature of the phase transitions ?

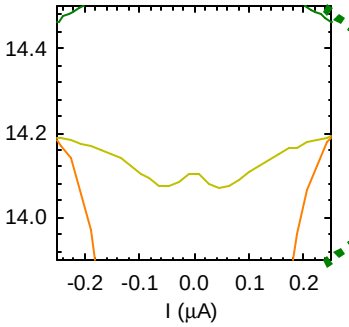
3. **Future experiments and related issues**

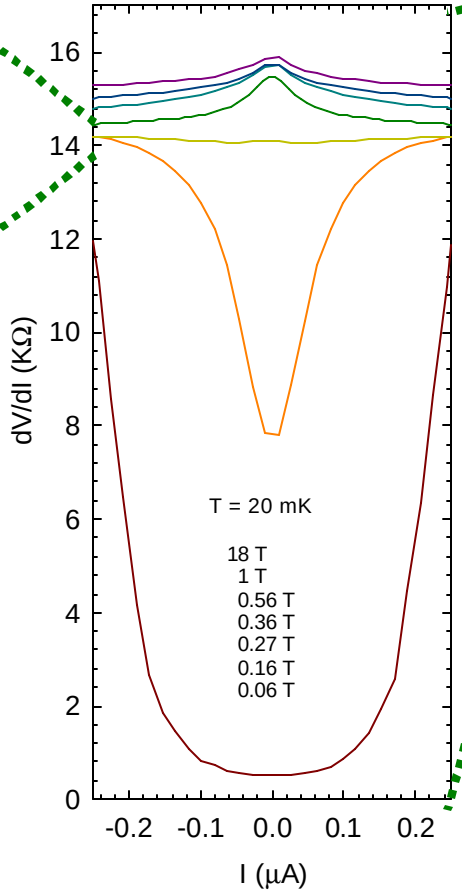
4. **Summary**

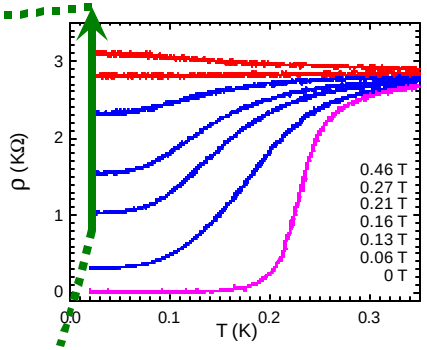
2. What we found – magnetic field induced metallic phase

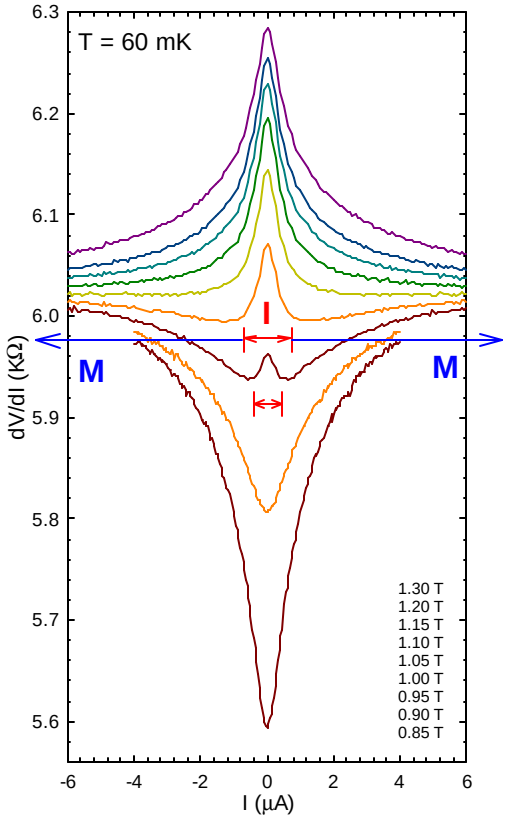
The nature of the phase transitions ?

M-I transition at T? 0









Phase change is caused by increasing bias current

⇒

MIT is percolation-like.

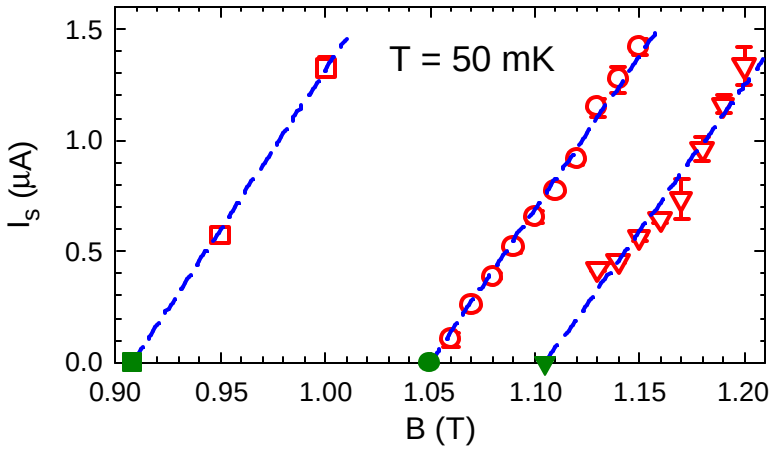
2. What we found – magnetic field induced metallic phase

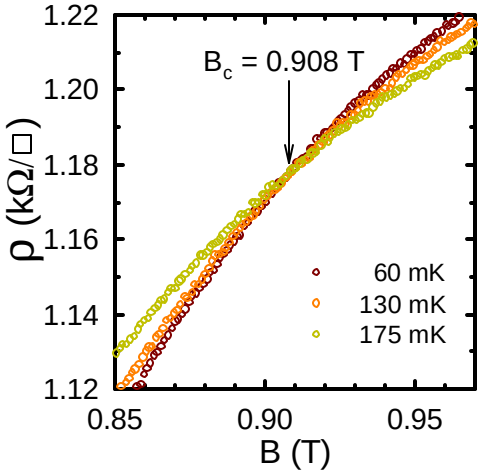
The nature of the phase transitions ? **percolation-like.**

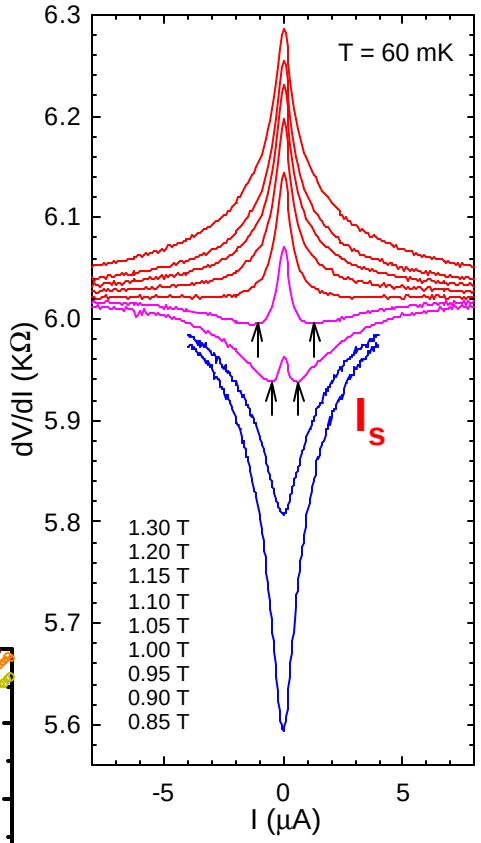
In this percolation-type picture, it is expected

dV/dI should be non-monotonic

- **in the insulating phase**
- **in the limited range of magnetic fields**
- **with I_s that increases with B**



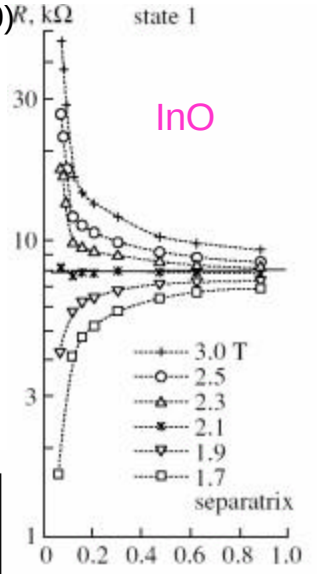


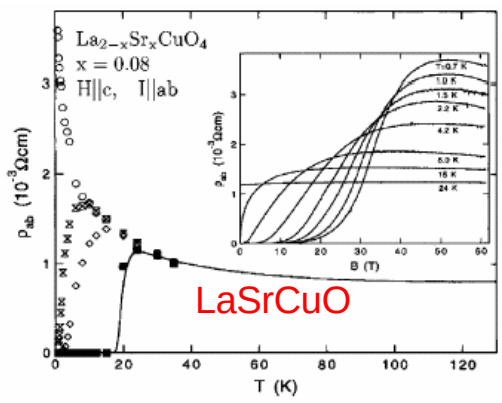


3. Future experiments and related issues

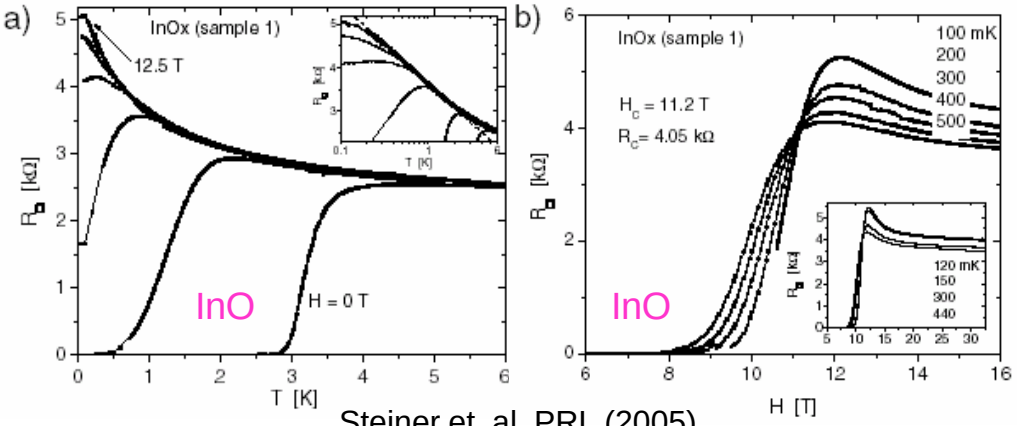
- Measurements down to ~ 100 μK.
- High B insulating phase, up to ~ 45 T.
- Effect of parallel magnetic fields.
- Direct measurements of electron temperature.
- High temperature superconductivity.

Gantmakher et. al. LETP (2000)

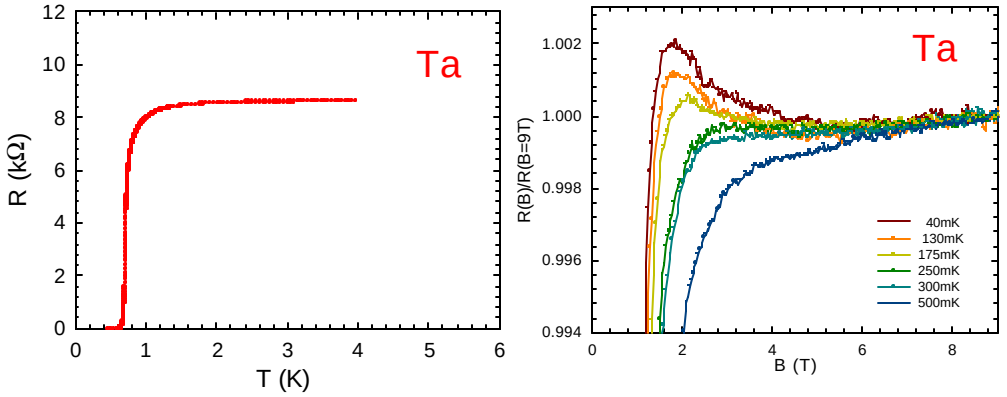




Ando et. al. PRL (1995)



Steiner et. al. PRL (2005)

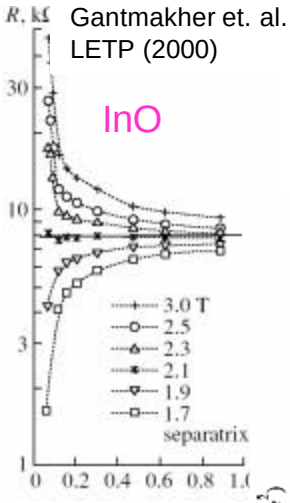


3. Future experiments and related issues

- 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

Gantmakher et. al.
LETP (2000)

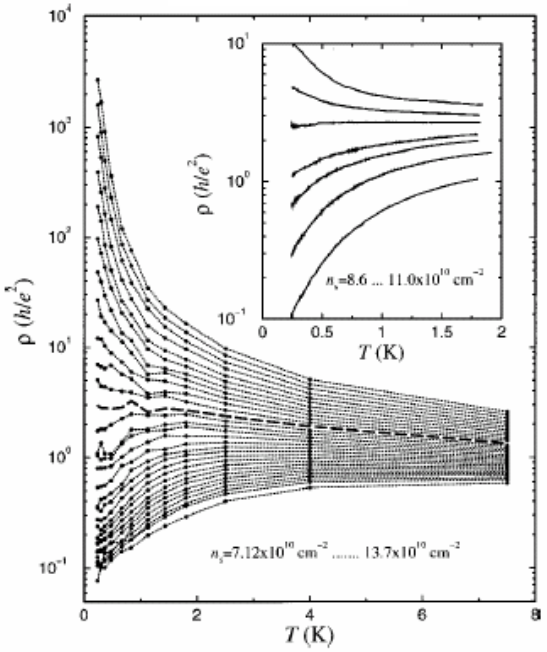
InO



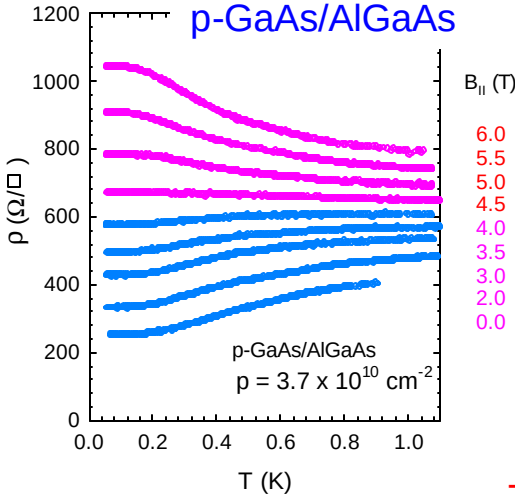
Kravchenko et. al. (1995)

Sarachik and Kravchenko (1999)

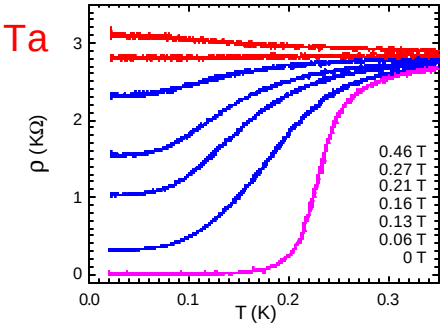
Si-MOSFET



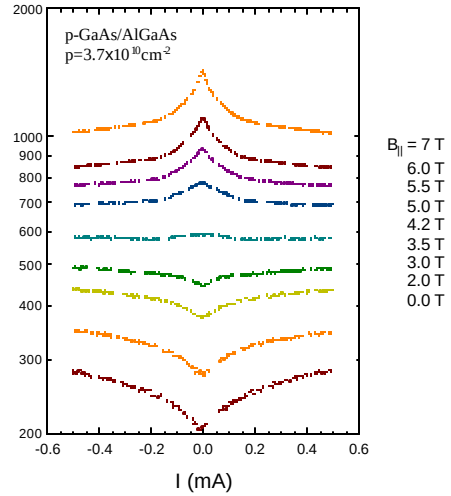
p-GaAs/AlGaAs



Ta



p-GaAs/AlGaAs



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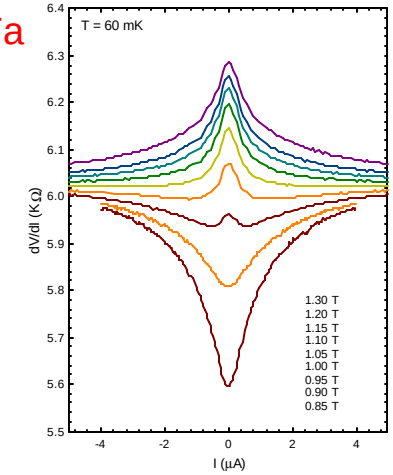

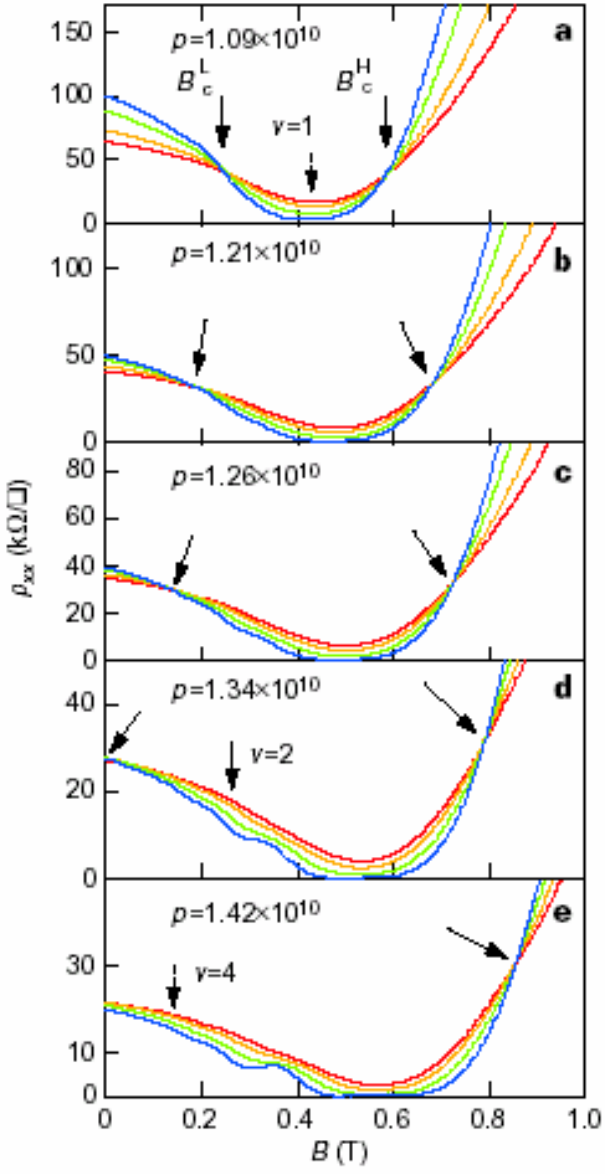
p=1.09×10^10
B_c^L
B_c^H
ν=1
a
p=1.21×10^10
b
p=1.26×10^10
c
p=1.34×10^10
ν=2
d
p=1.42×10^10
ν=4
e
ρ_xx (kΩ/□)
B (T)
0
0.2
0.4
0.6
0.8
1.0

1. **What we are studying – material system**

   Material selection (tantalum)
   Growth
   Characterization

   } Homogeneous (amorphous) superconducting films

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

   How to identify the phases – transport characteristics — Nonlinear transport

   Is the metallic phase real? — It is real !

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

   The nature of the phase transitions ? — Percolation-like

3. **Future experiments and related issues**

4. **Summary**