Out-of Equilibrium Behavior of One and Two Dimensional Systems of Disordered Metals

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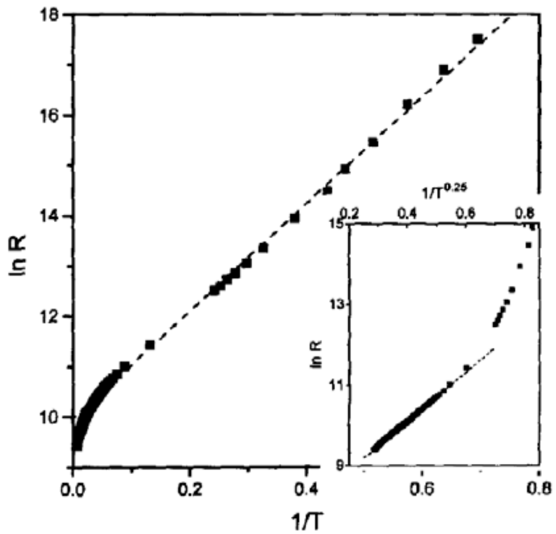
KITP Conference: Out of Equilibrium Quantum Systems

Outline

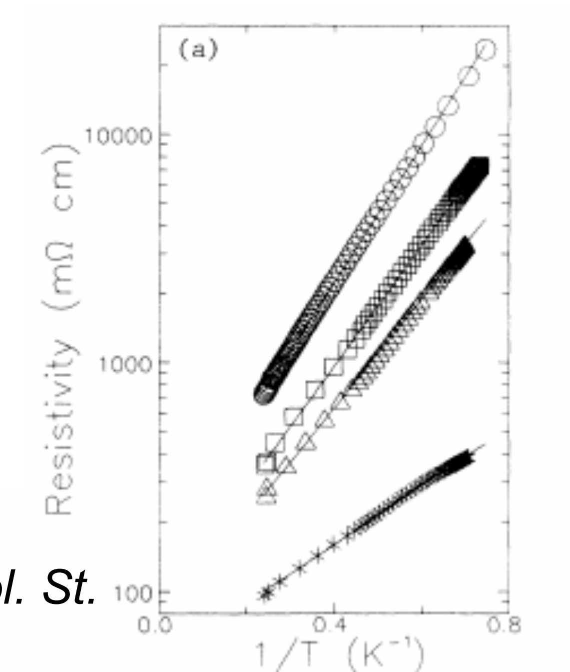
Hard Gap in Insulators near the Superconductor-Insulator Transition.
(Yen-Hsiang Lin with data from H. M. Jaeger, C. Christiansen, and K. Parendo)

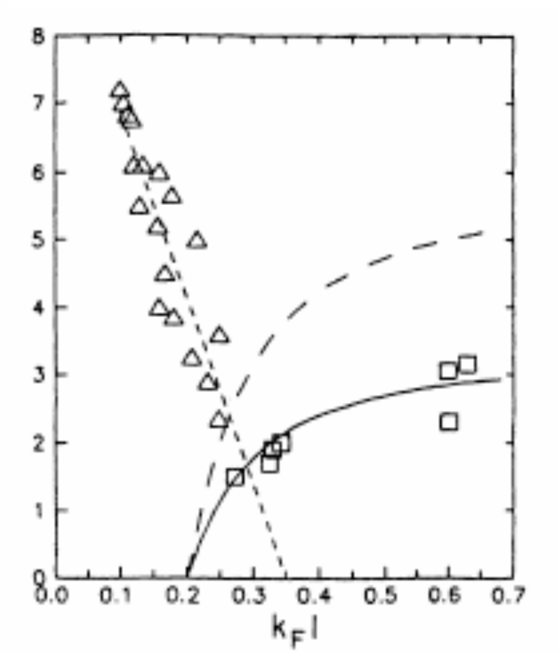
Magnetic-Field -Tuned Nonequilibrium Transport in Zn Nanowires
(Yu Chen and Stephen Snyder)

Hard Gap:- Simple Activated Transport near the SI Transition in InO_x



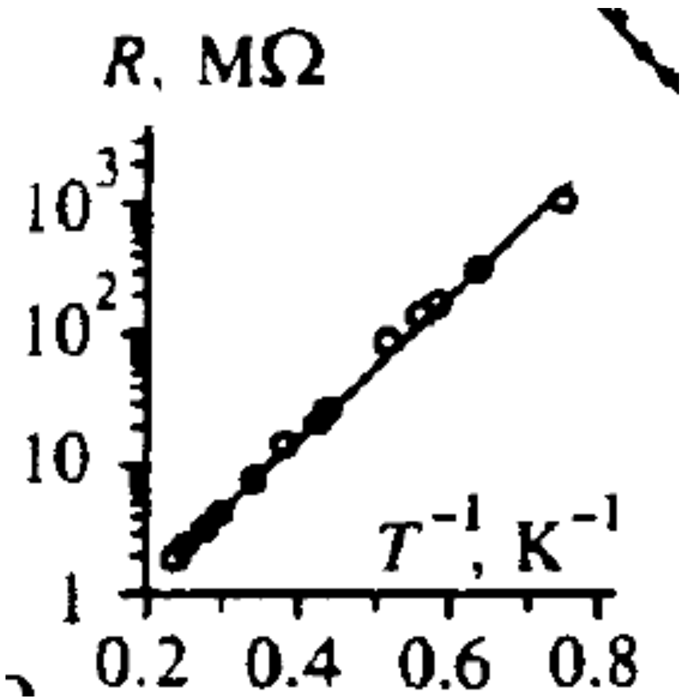
D. Kowal and Z. Ovadyahu, Sol. St. Comm. ***90, 783 (1994).***





D. Shahar, Z. Ovadyahu, PRB ***46, 10971 (1992).***

A second example involving insulating InO_x



$$R = R_0 \exp\left[\Delta / T\right]$$

V. F. Gantmakher, M. V. Golubkov, J. Lok, A. K. Geim, Sov. Phys. JETP, ***82, 951 (1996).***

The First Thickness Dependence of Resistance Measurements

Phil Mag 28 467 (1914)

LII. *The Electrical Resistance of Thin Metallic Films, and a Theory of the Mechanism of Conduction in such Films.* *By* W. F. G. Swann, *D.Sc., A.R.C.S.**

THE theory which attributes electrical conduction to the presence of free electrons requires, in order that the variation of the resistance of a metal with the temperature θ shall be explained, that the mean free path of an electron shall vary as θ^{-2} †.

The original object of the present work was to test this fact by direct experiment. Patterson ‡ has shown that the specific resistance of a very thin film is abnormally high, and moreover, that it increases enormously rapidly as the thickness diminishes below a certain critical value. Sir J. J. Thomson has shown that a rapid increase of this kind can be explained as due to the fact that when the dimensions of the film get comparable with the mean free path of an electron, those electrons which at any instant are moving in a direction inclined to the plane of the film do not get a chance of travelling for their complete mean free path, so that the electric field does not produce in them the full velocity which it would produce if the true mean free paths were described. Sir J. J. Thomson shows that if t, the thickness of the film, is greater than 2λ, where λ is the mean free path in a large mass of the metal, λ' the mean free path in the film is given by

$$\lambda' = \lambda\left(1 - \frac{\lambda}{4t}\right), \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and if $t < \lambda$

$$\lambda' = t\left\{\frac{3}{4} + \frac{1}{2}\log\frac{\lambda}{t}\right\}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

from which it follows that λ' does not begin to diminish rapidly as t decreases, until t becomes less than λ. The thickness at which λ', and consequently the conductivity, starts to diminish rapidly gives, on this theory, an approximate measure of the mean free path. Now if λ varies as

* Communicated by the Author. Experiments performed at the University of Sheffield. Paper read at the Meeting of the British Association, 1913.

† Formerly it was supposed that the mean free path should vary as θ^{-1} (see Sir J. J. Thomson, 'Corpuscular Theory of Matter,' p. 80), but O. W. Richardson (Phil. Mag. [6] xxiii. p. 275) points out that in the theory of the Thomson effect (which plays an important part in the subject) a term has been omitted by all previous workers. The inclusion of this term leads to θ^{-2} as above.

‡ Patterson, Phil. Mag. [6] iv. 1902.

Fig. 1.

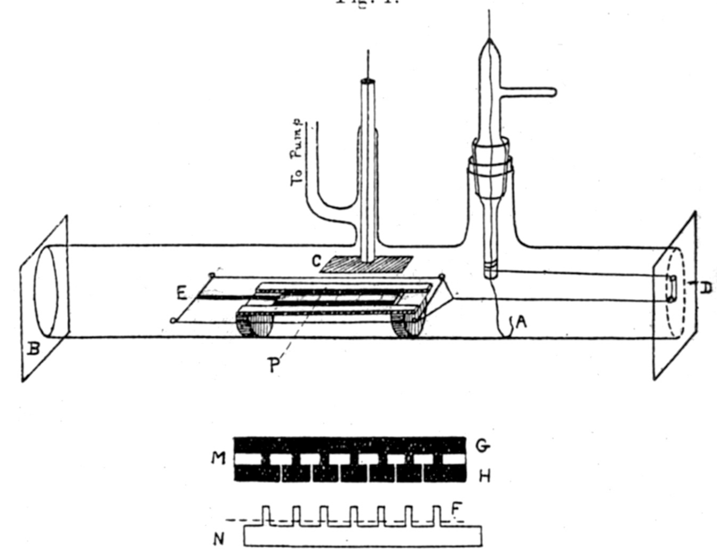
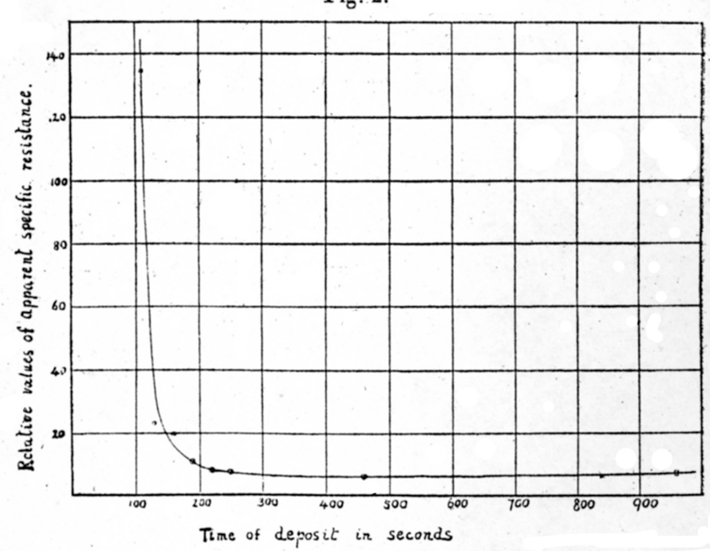
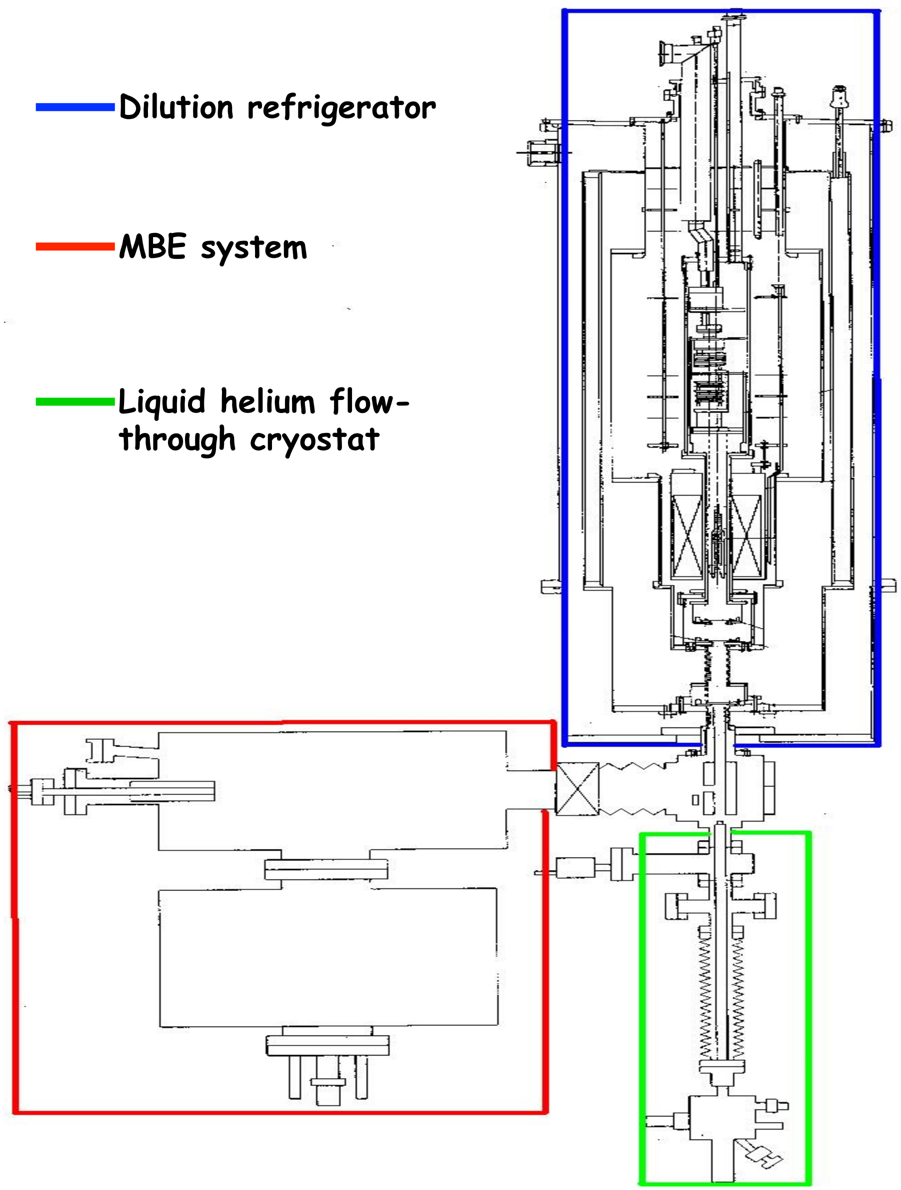
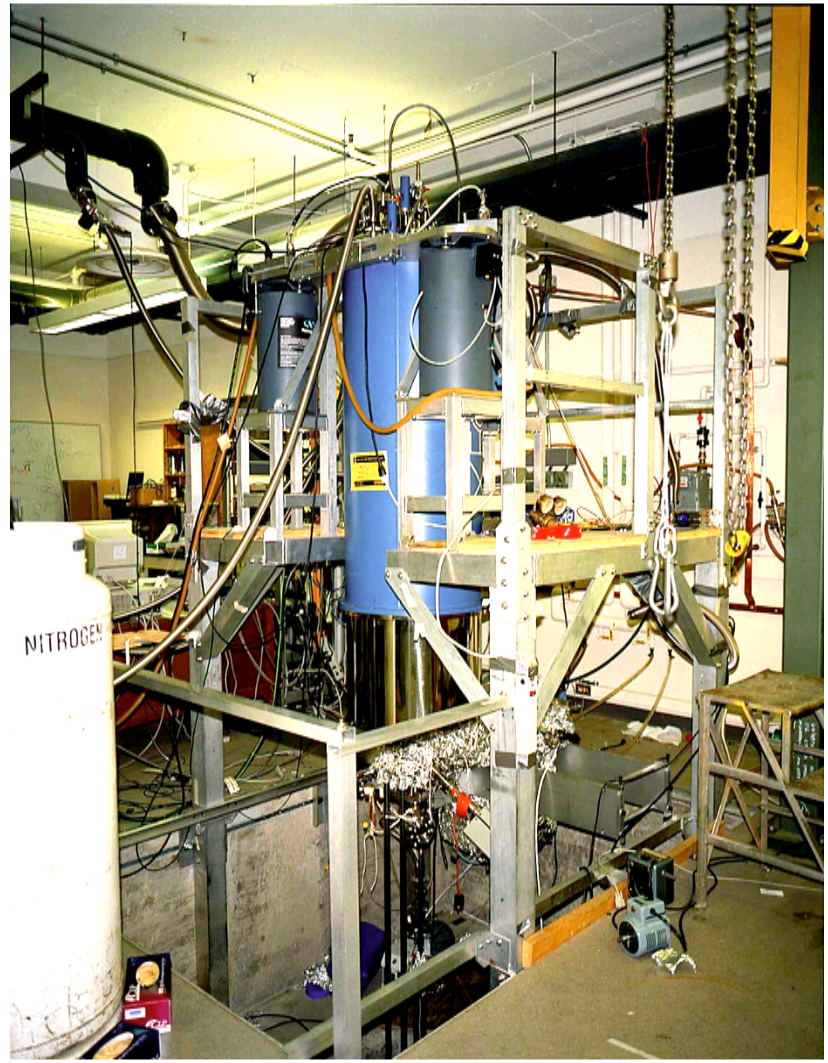


Fig. 2.



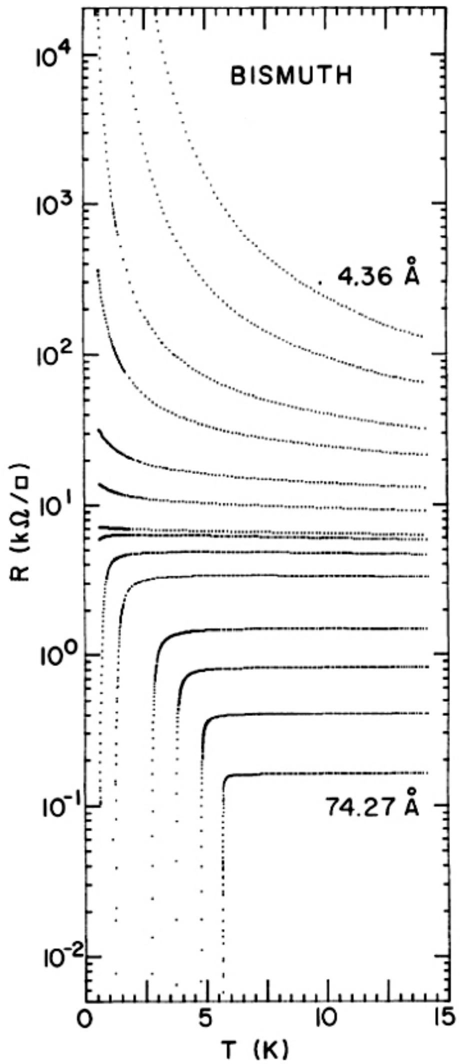
Modern Approach to Measuring the Thickness Dependence of Film Properties

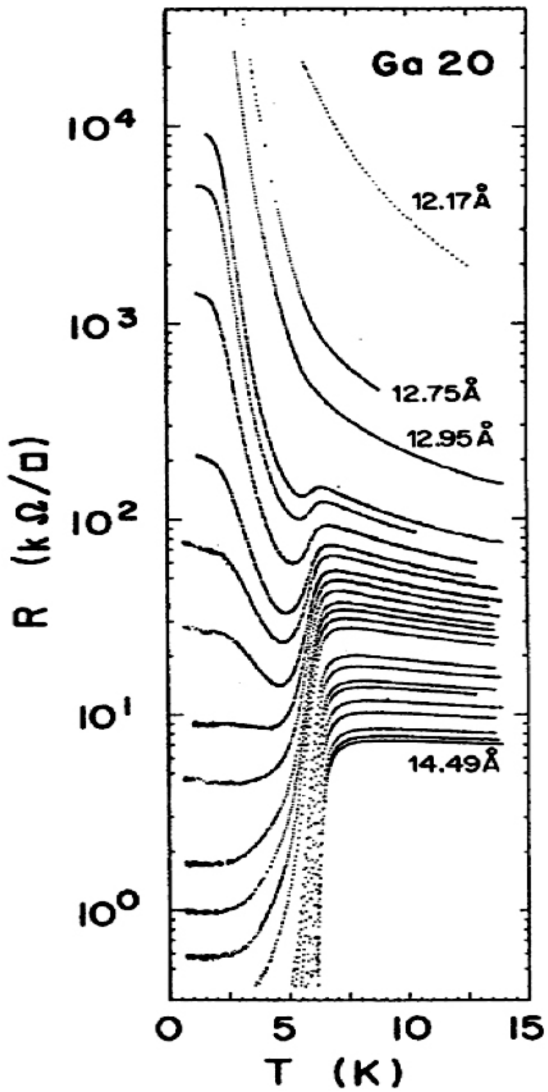




L.M. Hernandez and A.M. Goldman, Rev. Sci. Instrum. 73, 162 (2002)

Comparison of “Uniform” and “Granular” Films





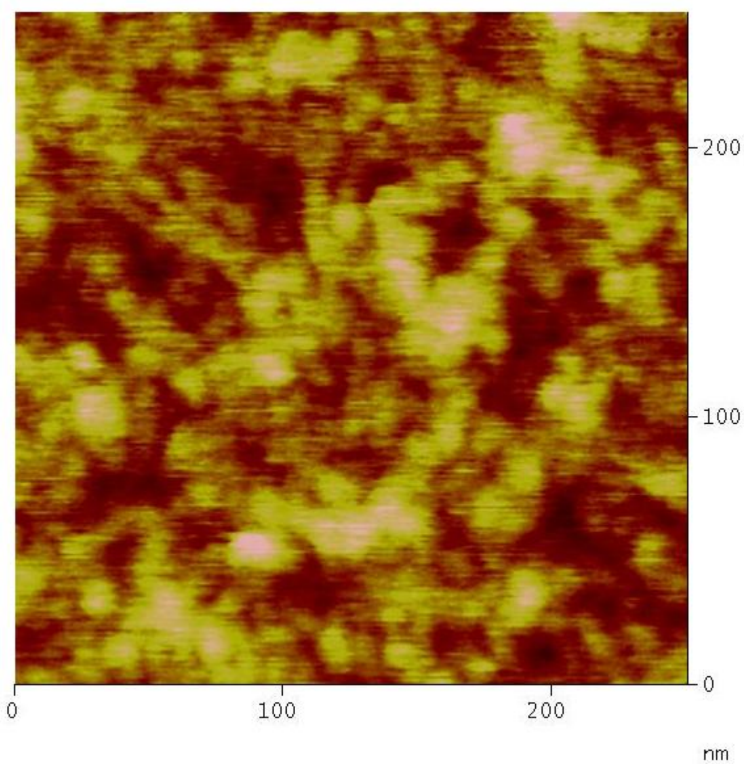
Left graph:

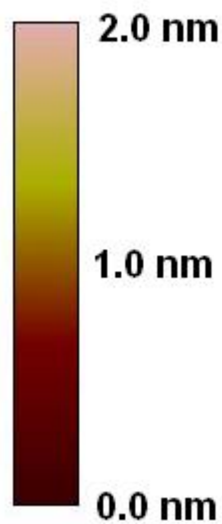
Bi film grown onto amorphous Ge underlayer on a glazed Al_2O_3 Substrate. Data suggests a QCP [Haviland, *et al*., 1989]

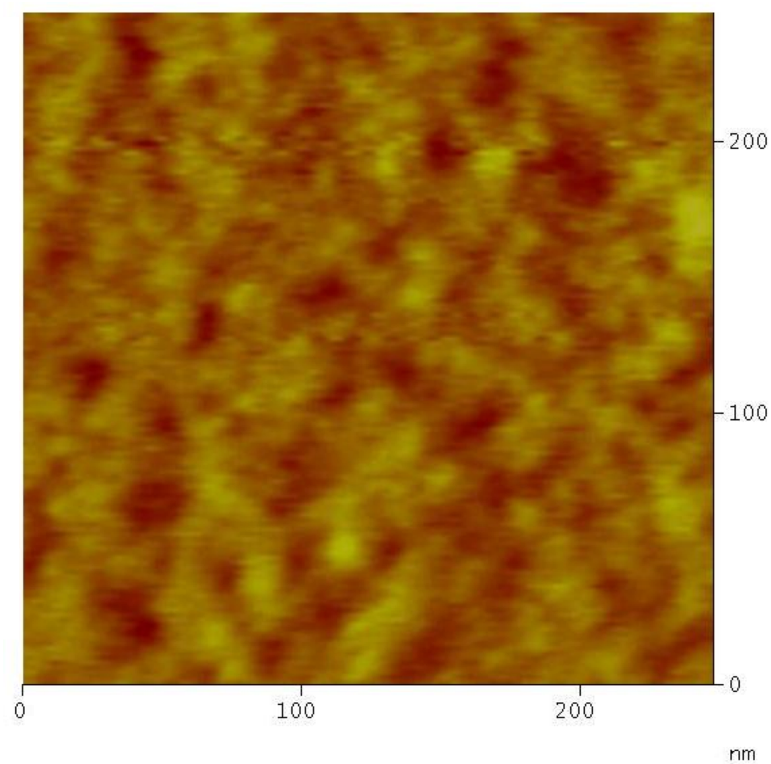
Right graph:

Ga film deposited directly onto a glazed Al_2O_3 substrate. [Jaeger, *et al*., 1989]

AFM of Granular and Homogenous *a*-Bi







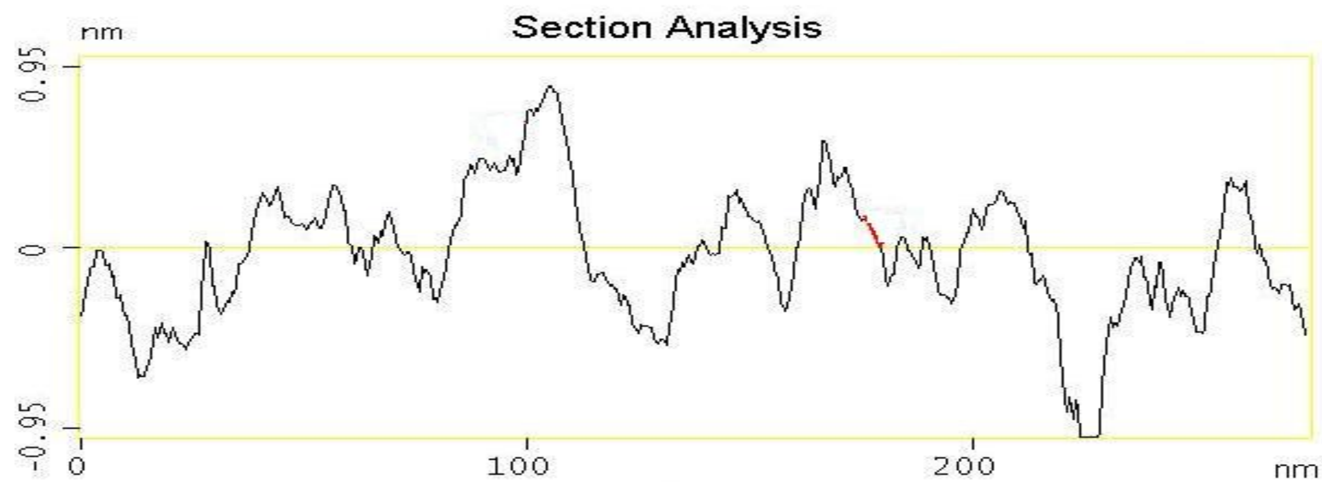
granular *a*-Bi films

homogeneous *a*-Bi films

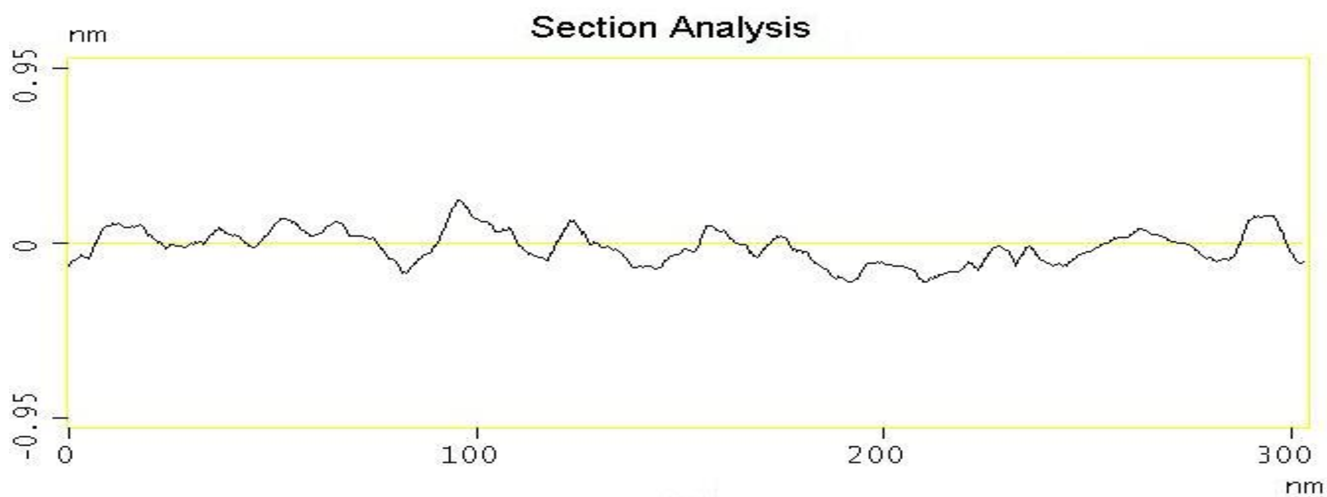
AFM *ex situ* with 10Å Sb capping layer

AFM of Granular and Homogenous *a*-Bi Films

"granular" *a*-Bi films: average grain size ~ 20nm



homogeneous *a*-Bi films



Film Roughness Can Lead to a Shortening of the Localization Length

PHYSICAL REVIEW B VOLUME 30, NUMBER 6 15 SEPTEMBER 1984

Localization of electrons in thin films with rough surfaces

Arthur R. McGurn
Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008

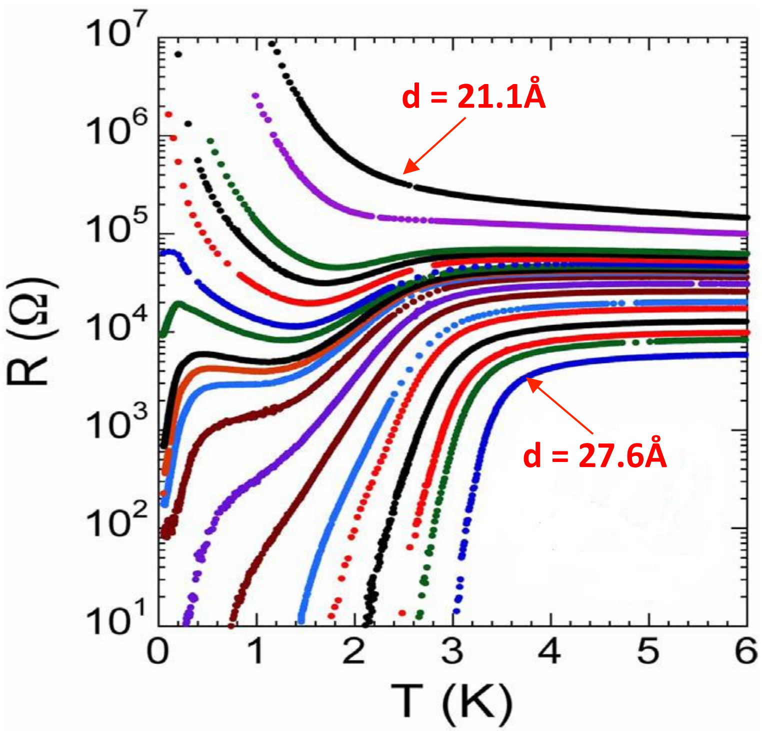
Alexei A. Maradudin
Department of Physics, University of California, Irvine, California 92717
(Received 8 March 1984)

A system of noninteracting electrons in a thin metal film which experience arbitrarily weak scattering from a randomly rough surface is shown to be always in localized states. The frequency- and wave-vector-dependent density response function, the frequency-dependent conductivity, and the localization length are calculated at $T=0$ in the $\omega\rightarrow 0$, $\vec{q}\rightarrow\vec{0}$ limits. We find that the localization length r_0 depends on the film thickness d as $r_0 \propto \exp(d^3/l^3)$, where l^3 is a constant depending on the Fermi energy and surface roughness.

Phys. Rev. B **30, 3136 (1984)**

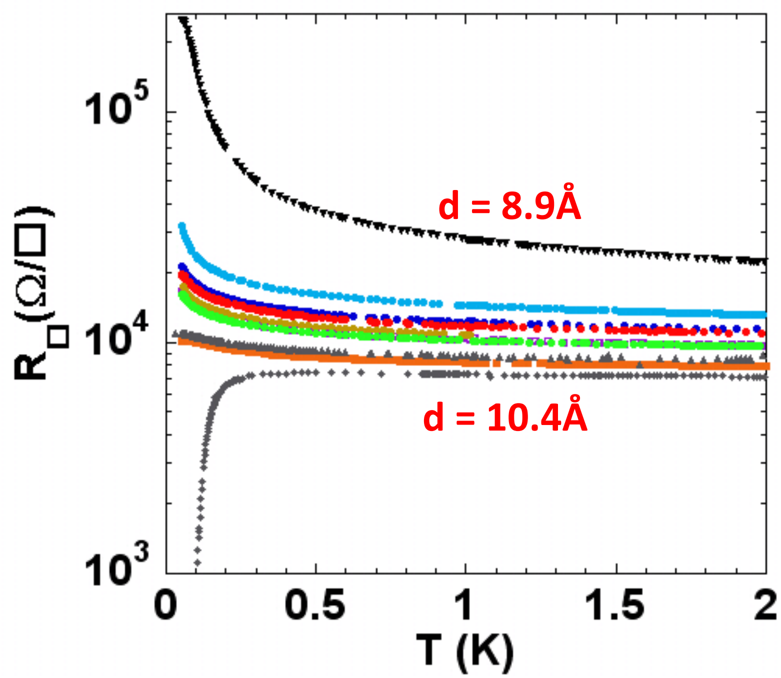
Disorder-Tuned Amorphous "Granular" and "Homogeneous" Bi Film

thickness tuning of granular *a*-Bi films – without Sb underlayer

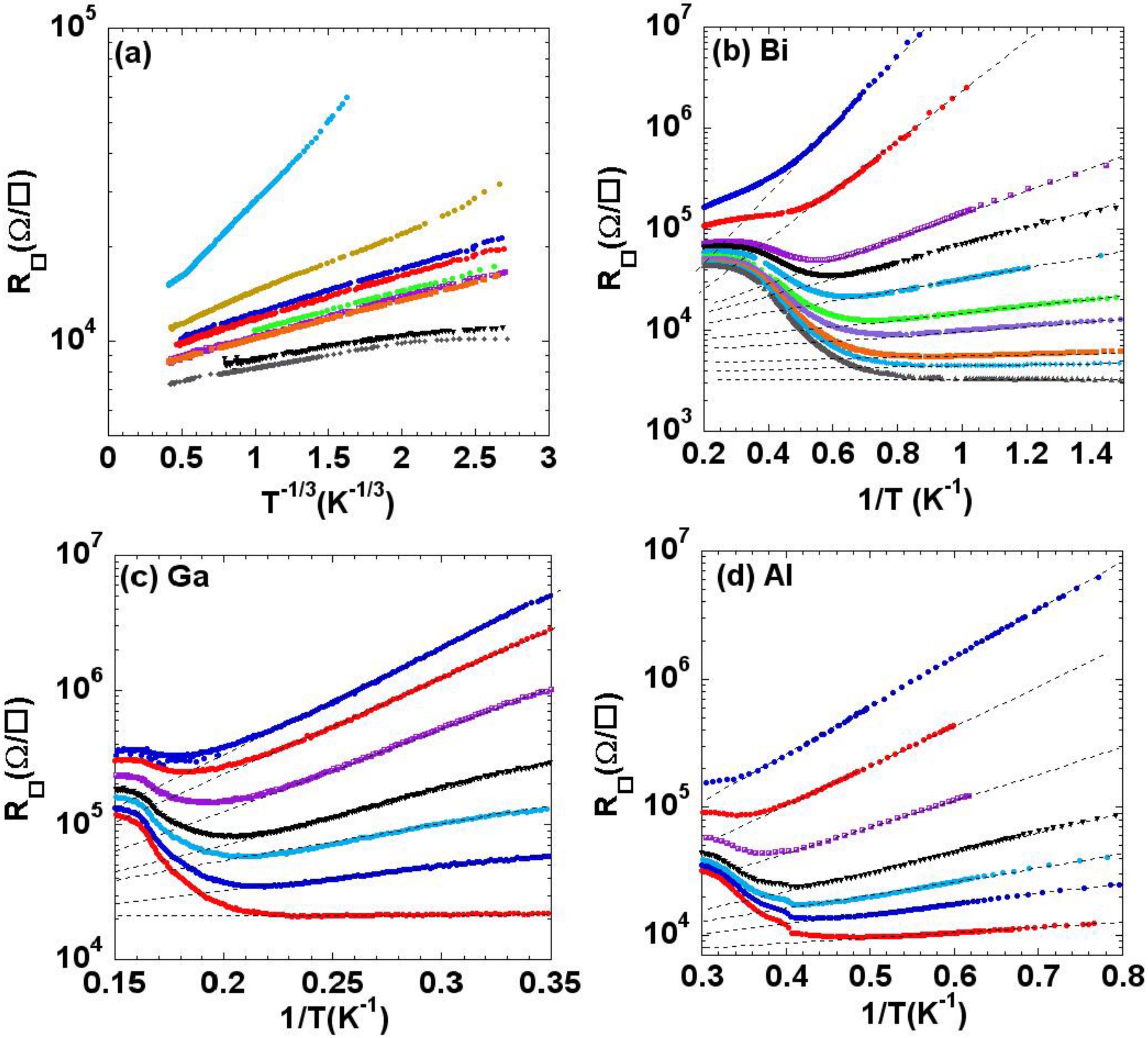


Parendo, *et al.*, PRB 69,100508(R)(2007)

thickness tuning of homogenous *a*-Bi films – with 10Å Sb underlayer



Arrhenius Conduction in Nominally "Granular" Films



What is the origin of this simple activated form?

- Gap in the density of states?
- Variable range hopping?
- Nearest neighbor hopping?
- Random Josephson coupled array?

Purely electronic transport and localization in the Bose glass

M.Muller, Ann. Phys. (Berlin) **18**, No. 12, 849 – 855 (2009)

Analyzed the spectral properties of interacting bosons in the absence of phonons

Argues that the resultant Bose glass phase admits three distinct regimes.

> For the strongest disorder the boson system is a fully localized, perfect insulator at any temperature.
>
> At smaller disorder, only the low temperature phase exhibits perfect insulation while delocalization takes place above a finite temperature.
>
> A third phase must intervene between these perfect insulators and the superconductor.

It is characterized by a mobility edge in the many body spectrum, located at finite energy above the ground state.

Purely electronically activated transport occurs, with a conductivity following an Arrhenius law at asymptotically low temperatures.

Super-activation is predicted at higher *T*.

Inhomogeneous Pairing in *s*-Wave Superconductors

Ghosal, Randeria, and Trivedi, PRL **81**, 3940 (1998).
Ghosal, Randeria, and Trivedi, PRB **65**, 014501 (2001).

Hubbard Model with on-site disorder:

$$H = -t \sum_{i,j,\sigma} (c^{*}_{i\sigma} c_{j\sigma} + h.c.) - |U| \sum_{i} n_{i\uparrow} n_{i\downarrow} + \sum_{i,\sigma} (V_i - \mu) n_{i\sigma}$$

Obtain a wide distribution of pairing amplitudes.

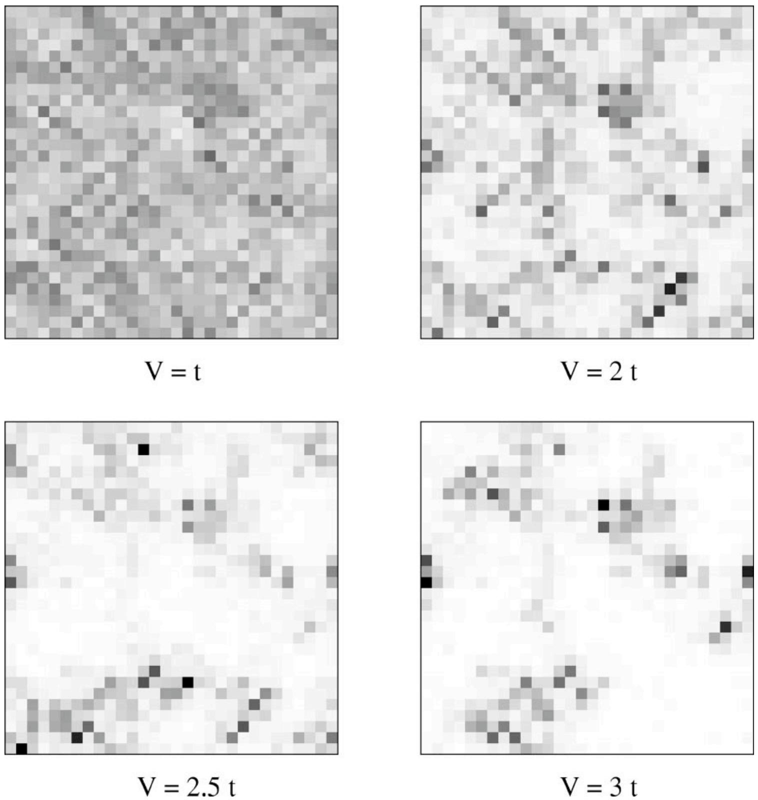
Spectral gap in one-particle DOS persists even at high disorder – have formation of locally superconducting “islands” separated by a nonsuperconducting sea.

Combination of the pairing interaction and strong disorder leads to formation of inhomogenous structures like in granular systems.

STM measurements will show a small gap with the tip on a SC island and a pseudogap elsewhere.

Spectral gap persists in the disordered insulator and increases with increasing disorder.

Nonmontonic *R(T)* is due to the formation of islands which don't percolate



Gray-scale plot for the spatial variation of the local pairing amplitude $\Delta(\mathbf{r})$ for a particular realization of the random Potential (same in all the panels) but with increasing disorder strength. Note that at large *V* the system generates ''SC islands'' (dark regions) with large pairing amplitude separated by an insulating ''sea'' (white regions) with negligible pairing amplitude.

Amit Ghosal, Mohit Randeria, and Nandini Trivedi
Phys. Rev. B **65**, 014501 (2001).

For large disorder can solve the gap equation.

The gap in the insulating regime is given by:

$$E_{gap} = \frac{|U|/2}{\zeta_{loc}^2}$$

where the localization length is that for states at the chemical potential.

The gap increases with decreasing localization length.

Local Superconductivity together with the Fractal Character of the Wavefunctions

M.V. Feigel'man, L. B. Ioffe, V. E. Kravtsov, and E. A. Yuzbashyan
*PRL **98,** 027001 (2007) and arXiv: 1002.0859v1*

Generalization of the idea that **Superconducting grains** exhibit a parity gap, calculated by Matveev and Larkin (K. A. Matveev and A. I. Larkin, PRL **78**, 3749 (1997)

$\Delta_P \sim T_I \sim \delta/\ln(\delta/\Delta)$ where $\delta = 1/(\nu_0 L^3)$ is the mean level spacing within grains

$\delta >> \Delta$ where Δ is the superconducting energy gap

For bulk Anderson insulators L is replaced by L_{loc} such that $\delta_L = 1/(\nu_0 L_{loc}^3)$

Δ is replaced by Δ_{crit} which is the superconducting gap at the Anderson transition

The near critical wave functions are fractal in nature.

$\ln(\delta/\Delta)$ is replaced by $\left(\delta_L/\Delta_{crit}\right)^{1-D_2/3} >> 1$, where D_2 is the fractal dimension, $D_2 < 3$

In more disordered materials with $\delta_L >> \Delta_{crit}$ the Cooper instability and long-range order disappear. The attraction between electrons persists as long as $\delta_L < \hbar\omega_D$.

This is the regime of a ***hard-gap*** **insulator**.

Have local pairing of electrons with opposite spins occupying the same localized state.

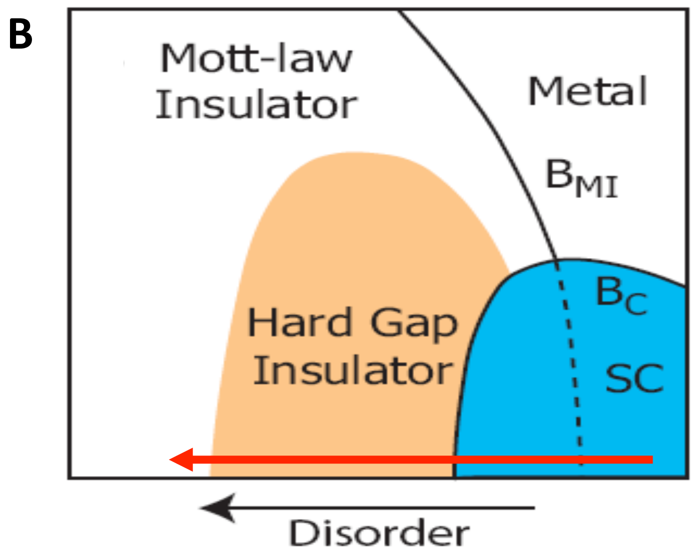
The physical properties of the electron system are controlled by electrons near the Fermi level so that a very important ingredient is the statistics of matrix elements between eigenstates in the vicinity of the Anderson mobility edge. ***These are fractal.***

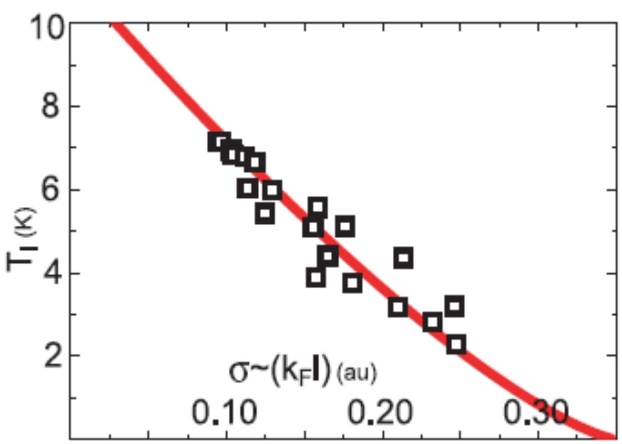
In the insulating regime the activation energy is ---

$$T_I = A(1 - \sigma/\sigma_c)^{\nu D_2}$$

The spectral gap is associated with the activation energy T_I assuming that hard gap conductivity behavior is due to single-electron hopping.

Model Describing Magnetoresistance Peak and the Hard Gap





Data of D. Shahar,and Z. Ovadyahu, PRB 46,10917 (1992)

- A hard-gap insulator is formed when $\delta > \Delta_{crit}$

δ: energy level spacing in localized superconducting grains.

Δ_{crit}: the superconducting gap at Anderson transition.

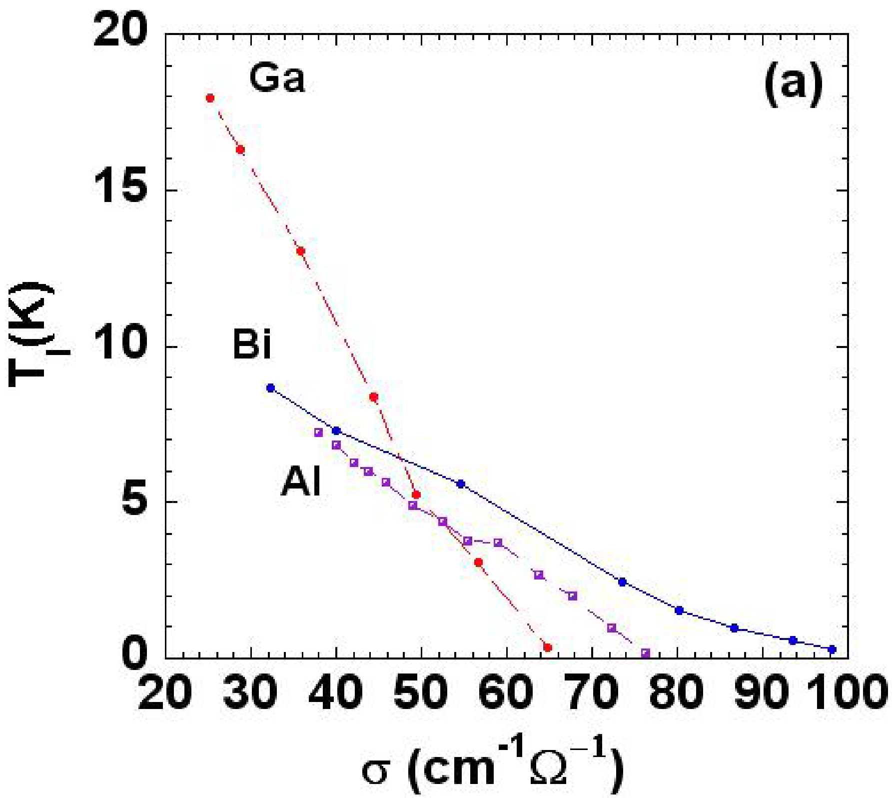
- A parity gap is formed due to the preformed Cooper pairs

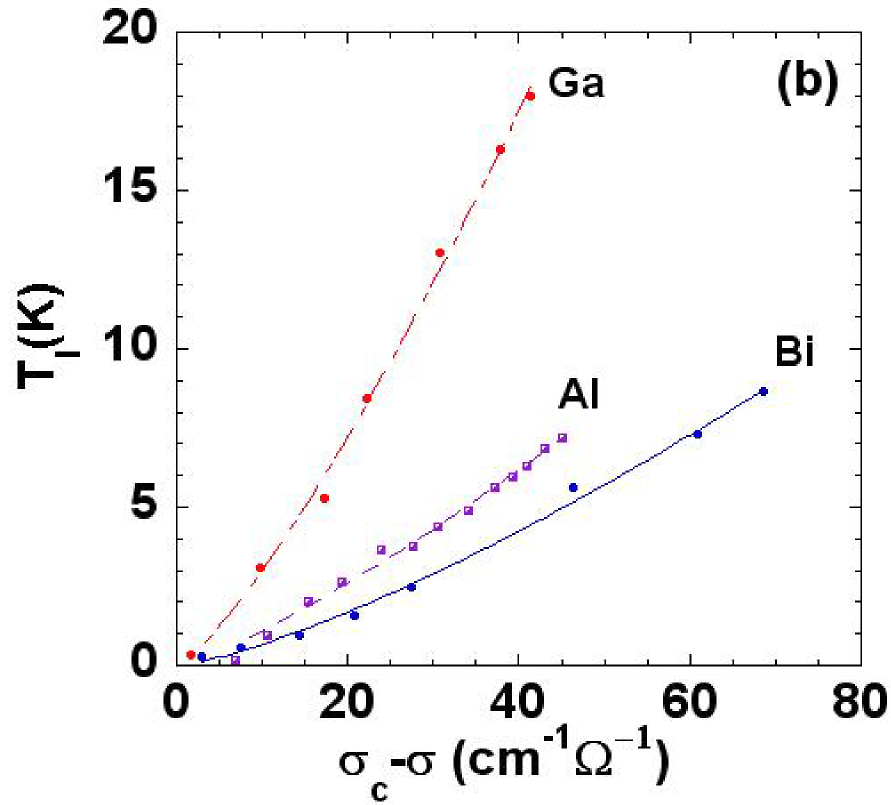
- νD_2=1.3 in In_xO_y for disorder tuned SI transition

$$T_I \propto (\sigma_c - \sigma)^{\nu D_2}$$

M. V. Feigel'man, *et al.*, PRL 98,027001 (2007)

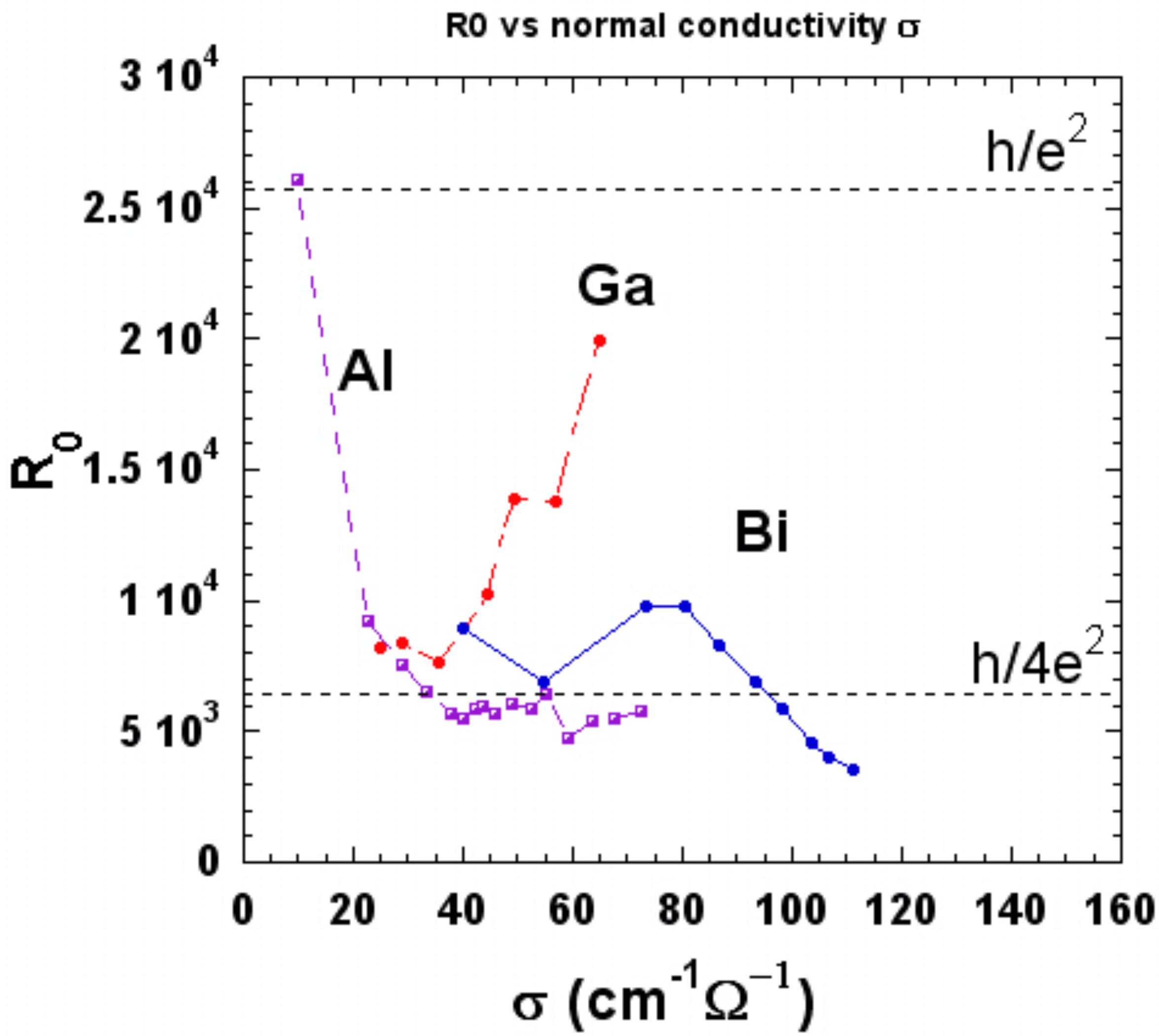
Activation Energy vs. Conductivity at High Temperatures





Activation energies T_I vary with conductivity as a power law with exponents:
Bi = 1.36 ± 0.06, Ga = 1.29±0.06 and Al=1.32±0.04

Prefactor of Activated Behavior



Some Issues

The success of $T_I = A(1-\sigma/\sigma_c)^{\nu D_2}$ in describing the data would suggest that the approach of Feigel'man *et al*. to describe the data is useful.

The value of the prefactor is suggestive of a non-phononic driver.

There is no regime of Mott hopping associated with the insulating state.

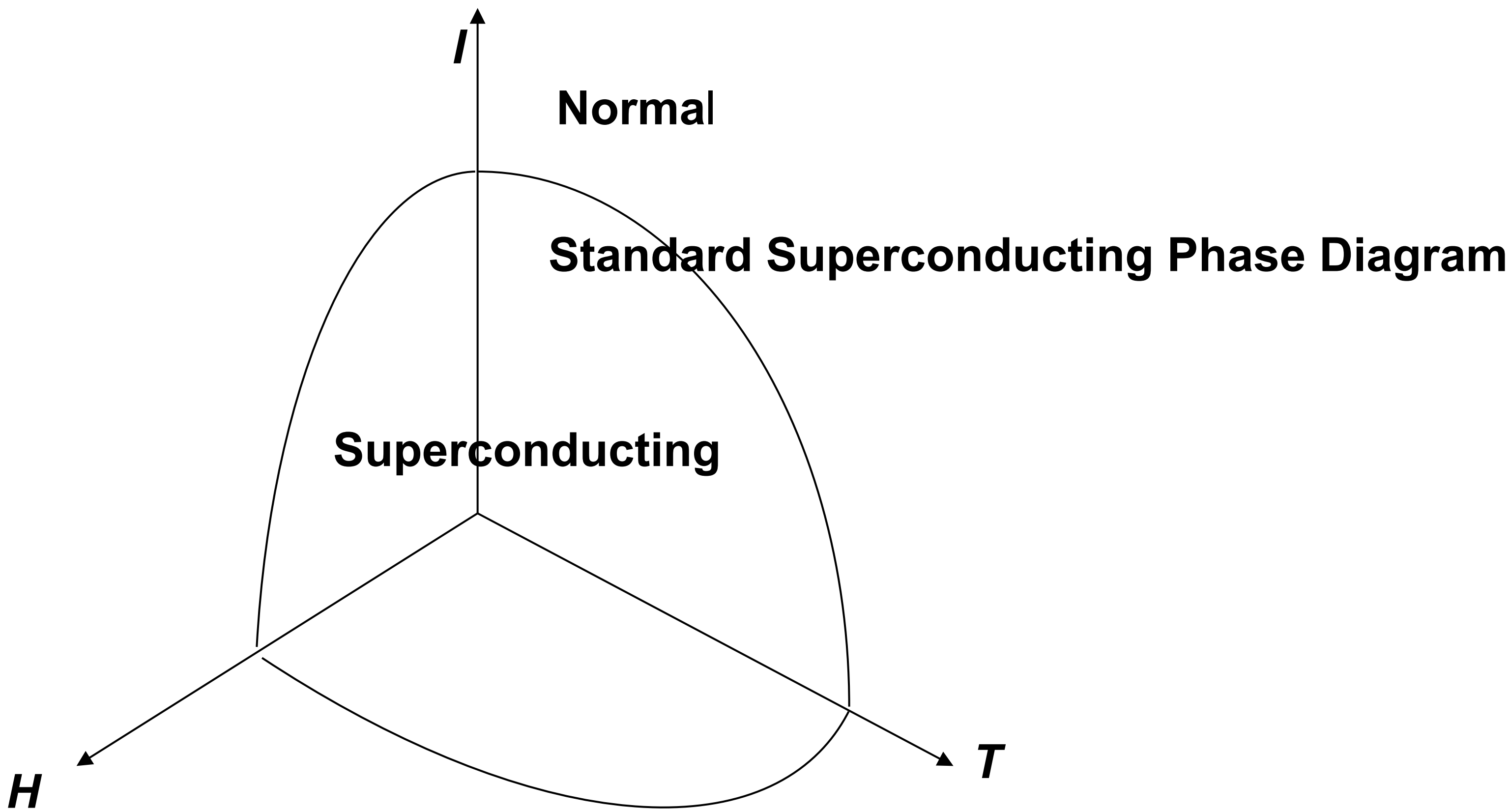
Nominally homogeneous films obey 2D Mott VRH

The overall behavior of the various films varies quite a bit, implying that the detailed microstructure may vary quite a bit, however the Arrhenius regime appears to behave in an almost universal manner.

Issue of actual dimensionality, 2D or 3D?

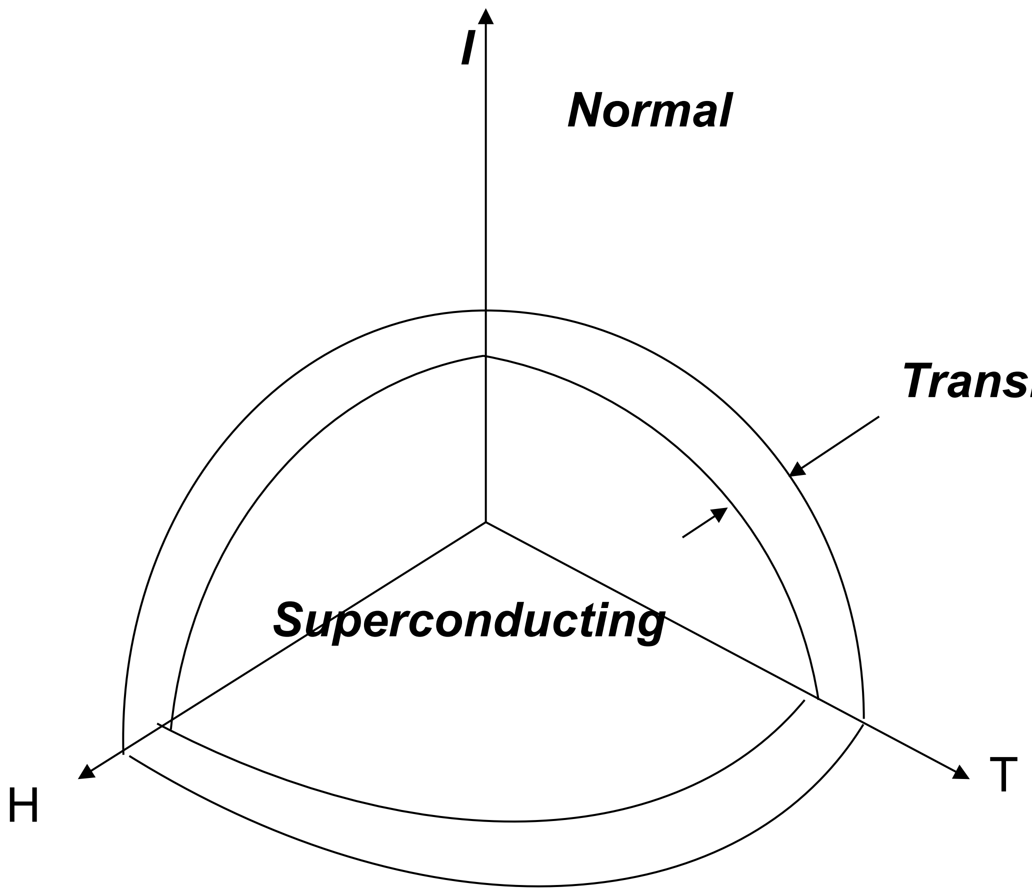
Need magnetoresistance data for further test of these ideas.

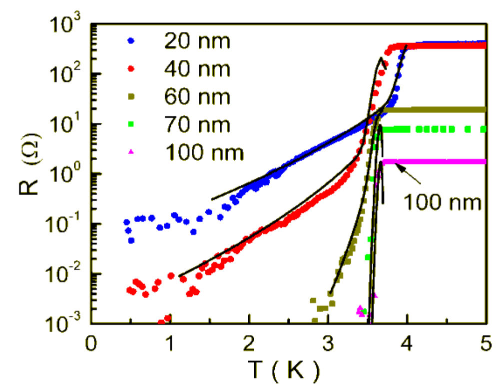
Magnetic-Field -Tuned Nonequilibrium Transport in Zn Nanowires



Sharp normal metal-superconductor transition tuned by temperature, current and magnetic field.

For a spatially confined superconducting nanowire:



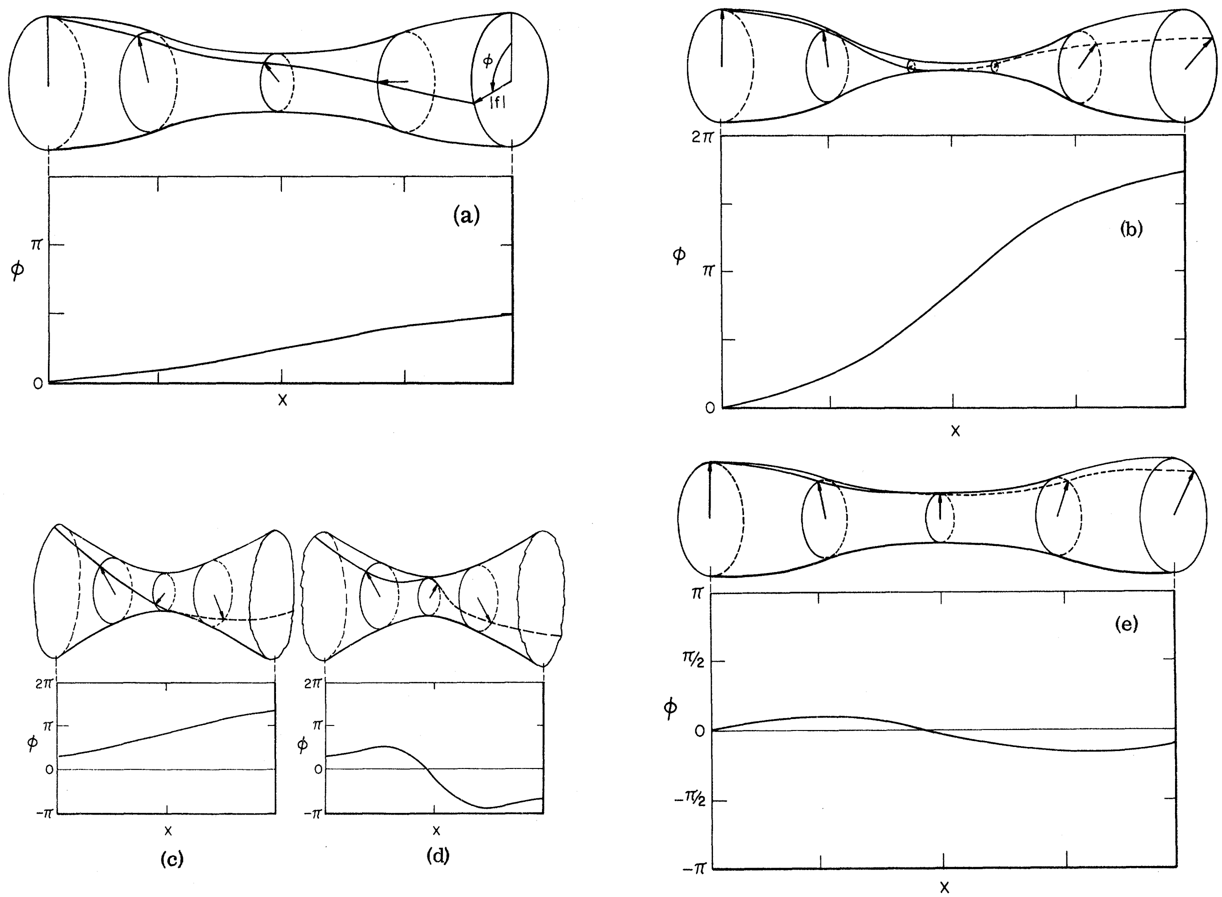


M. L. Tian *et. al*. PRB 71 104521 (2005)

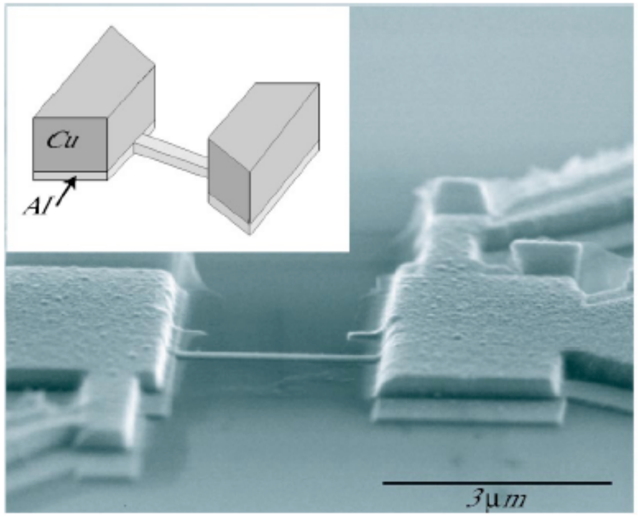
Broadened normal metal-superconductor transition due to phase slip processes.

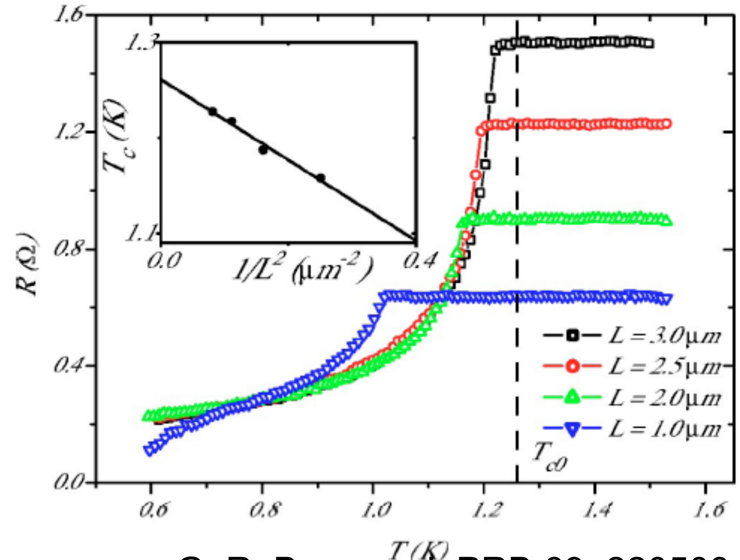
Works only for isolated wires (no boundaries).

Temporal Variation of the Phase Slip Process



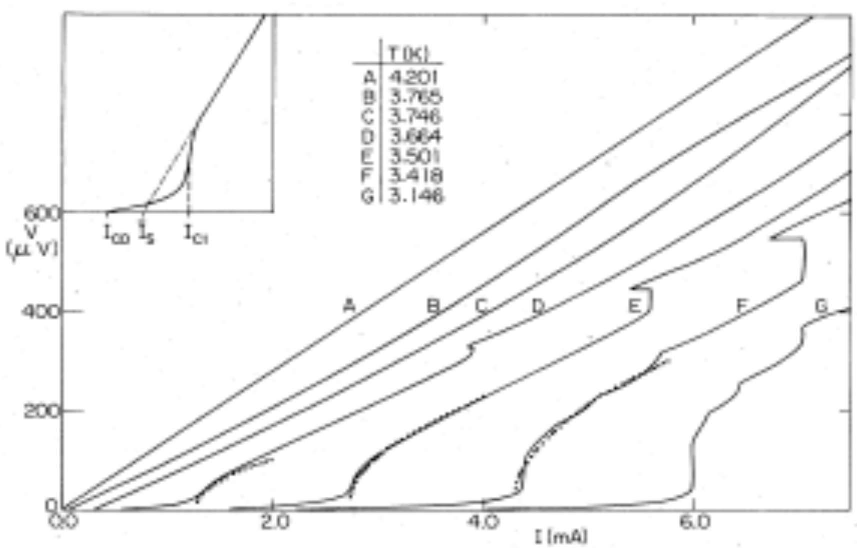
Normal boundary electrodes: suppressed superconductivity





G. R. Boogaard, PRB 69, 220503

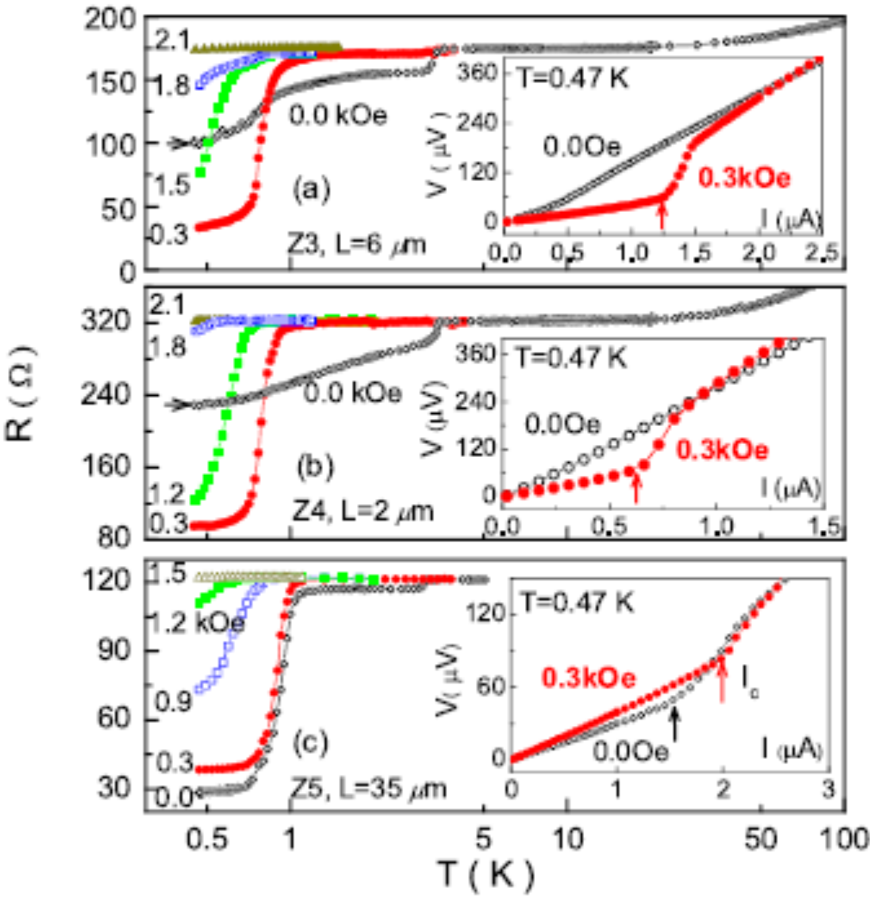
Superconducting electrodes: enhanced superconductivity

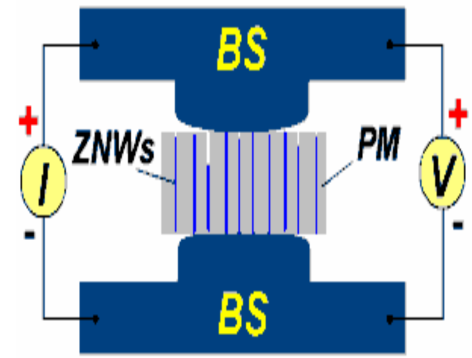


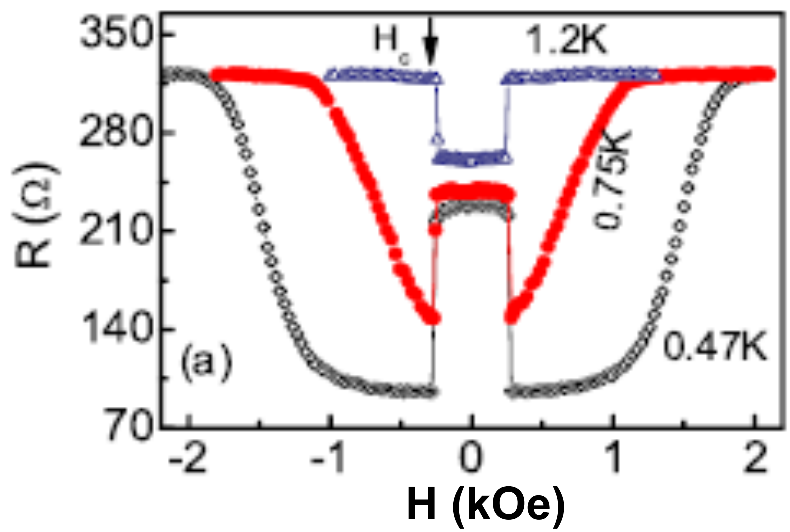
Enhanced critical currents in Sn superconducting microbridges.

M. Octavio et. al., PRB 17, 159

Something unexpected: anti-proximity effect







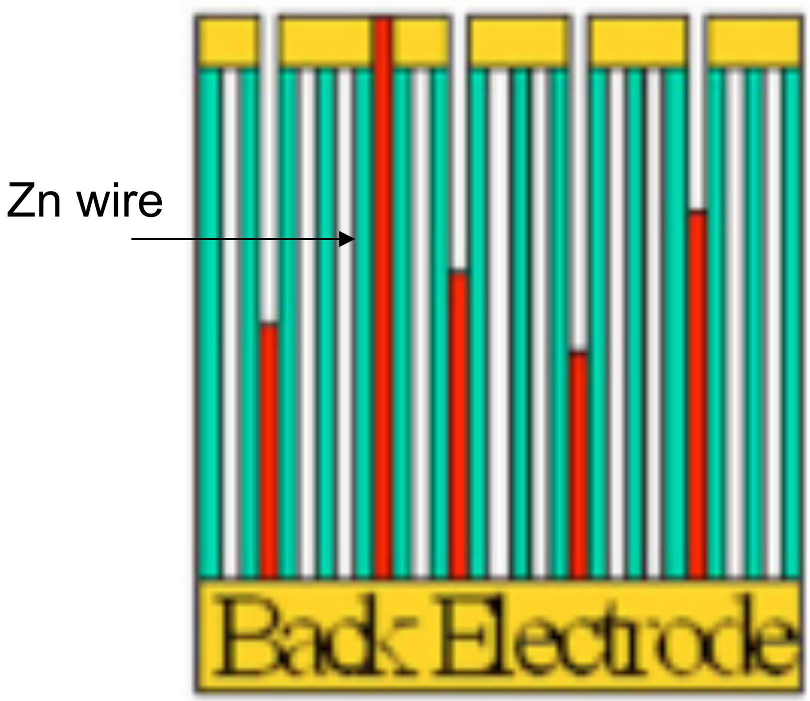
Superconducting electrodes: Zn wires is normal

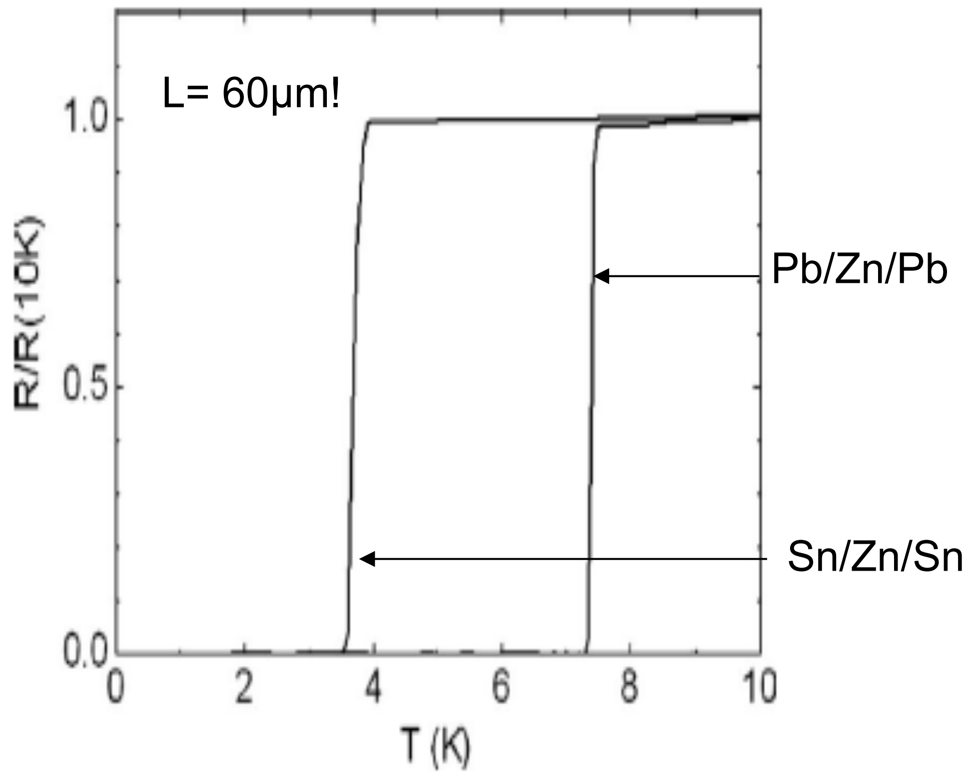
Normal electrodes: Zn wires is superconducting

M. L. Tian et. al. PRL 95 076802 (2005)

Different result from Wenhao Wu.

Sn or Pb film electrodes



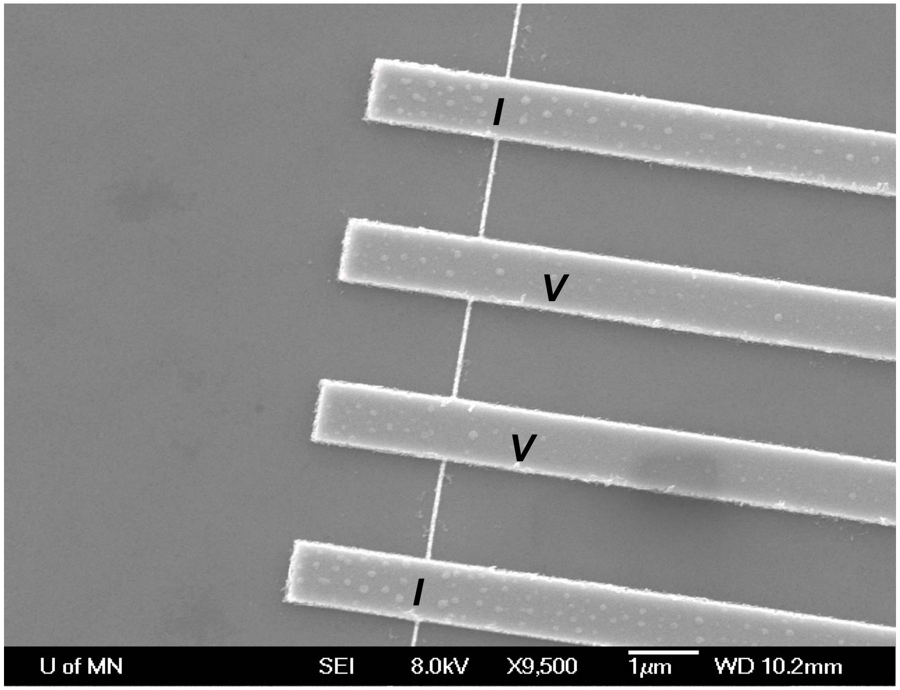


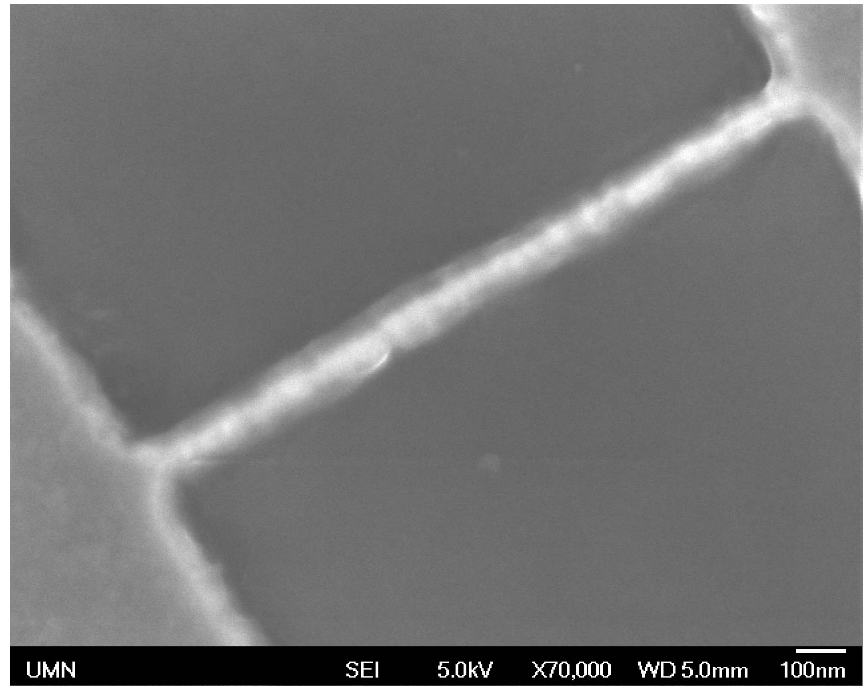
No anti-proximity effects

Proximity effect here is still enormous

Haidong Liu *et. al.*, JAP 105, 07E305(2009)

Zn wire + Zn electrodes formed in one deposition step





•Fabrication: Electron-beam lithography followed by a quenched deposition of Zn at 77K.

•Sample: **Wire:** $\xi(T=0) \approx 200nm > w \approx 100nm$

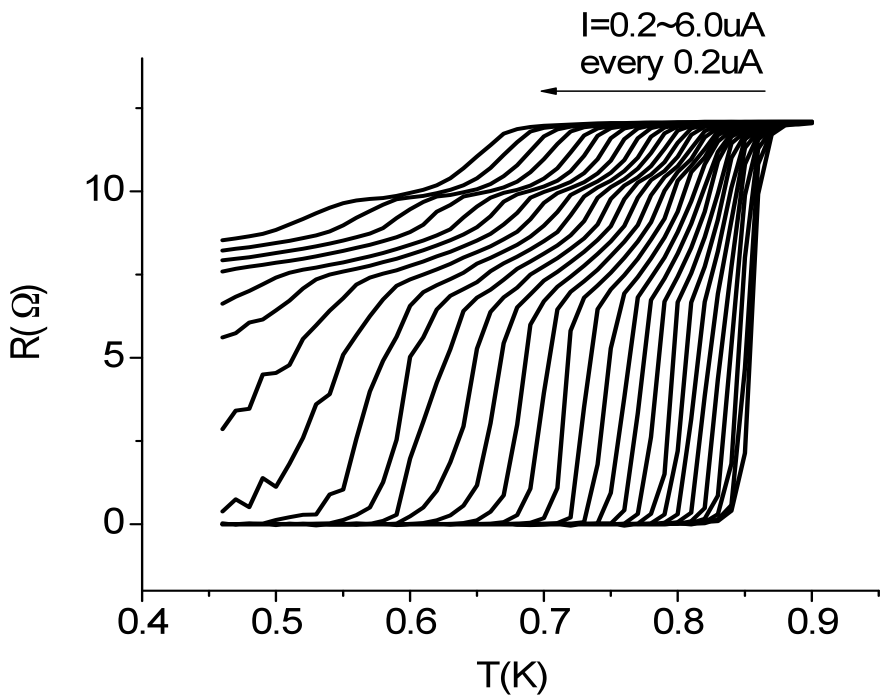
$t \approx 100nm$

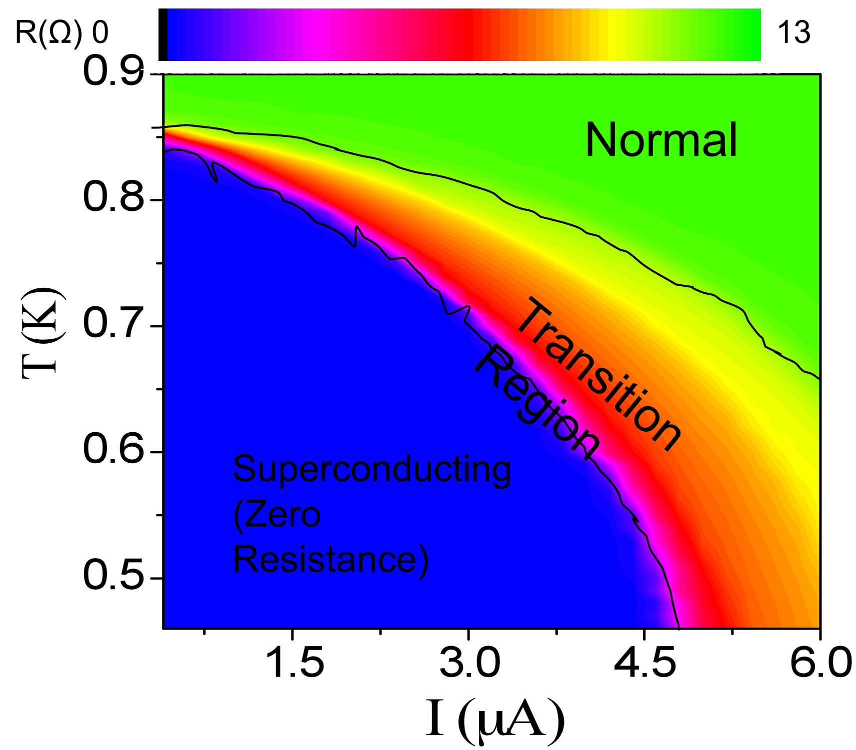
Electrodes: 1μm wide, 10um long

•Unique features: Four terminal measurement (R=V/I)

Transparent interface between the electrodes and the wire

Zero field measurement

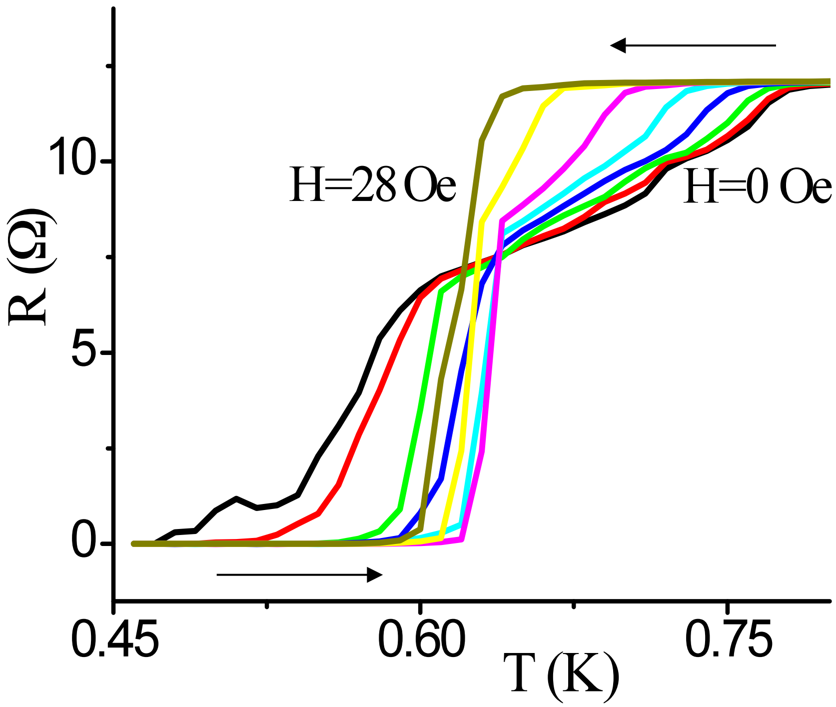


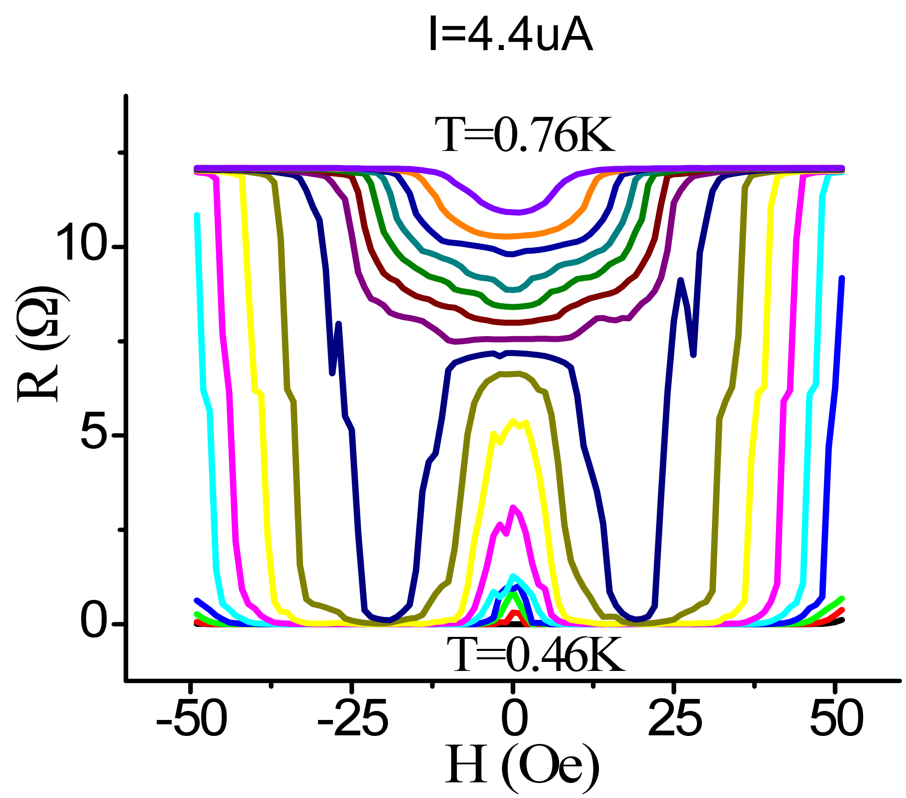


Low current: Higher T_c + Sharp Transition

High Current: Lower T_c + Broader Transition(Shoulder-like structure)

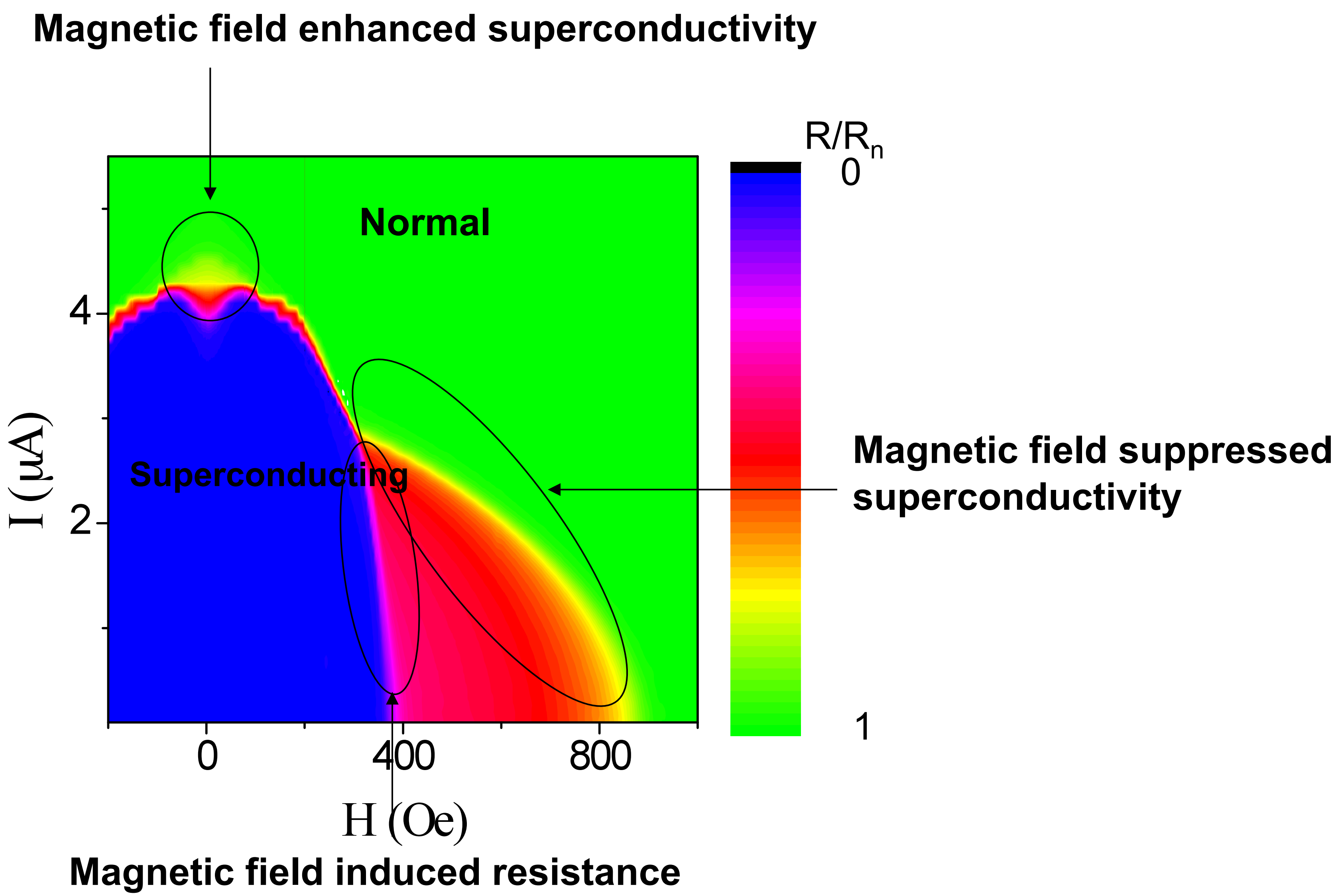
Magnetic field enhanced superconductivity



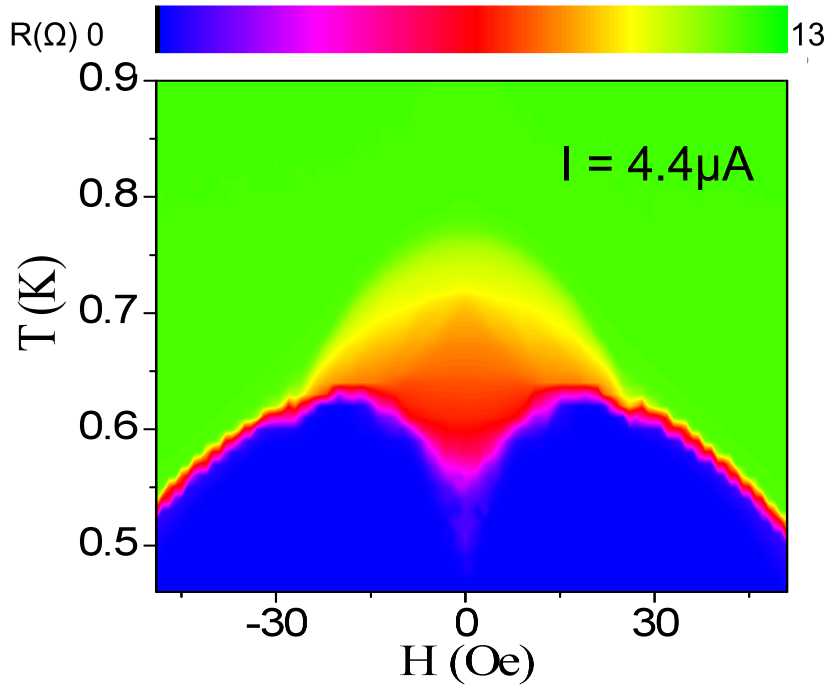


Small magnetic field ⇨ Top ↓ Bottom ↑ ⇨ Magnetic field "enhanced" superconductivity

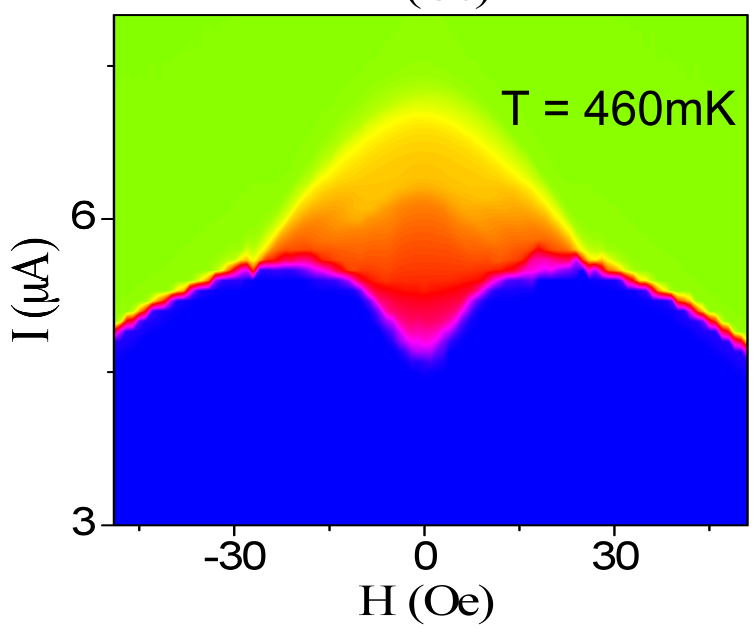
A typical phase diagram: *T = 460 mK*



Phase Diagrams: Enhancement of superconductivity in small fields

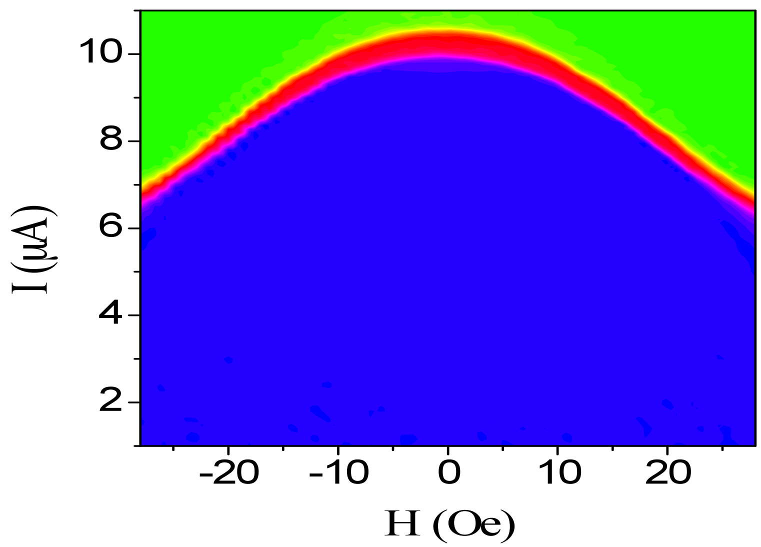


Increased critical temperatures



Increased critical currents

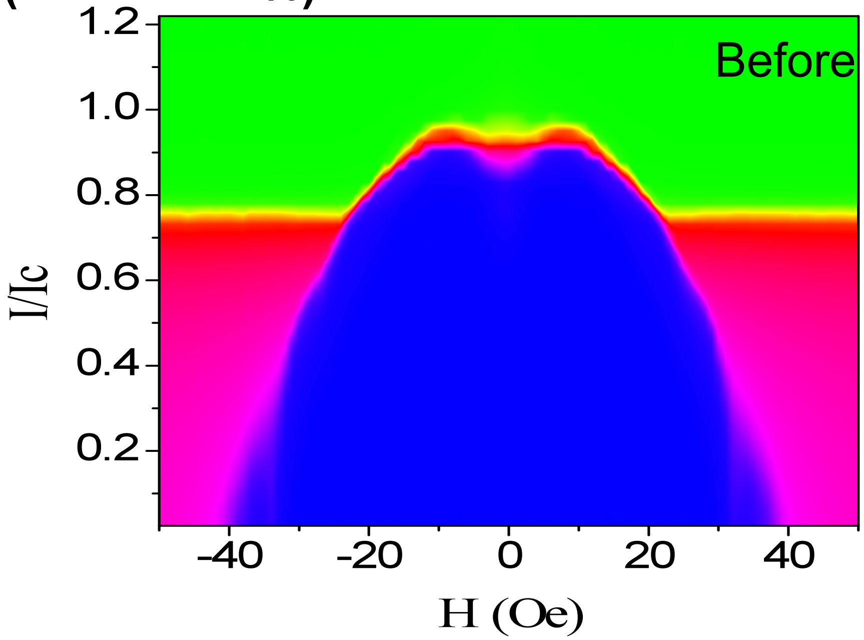
This is an effect found in quasi-one-dimensional superconductors

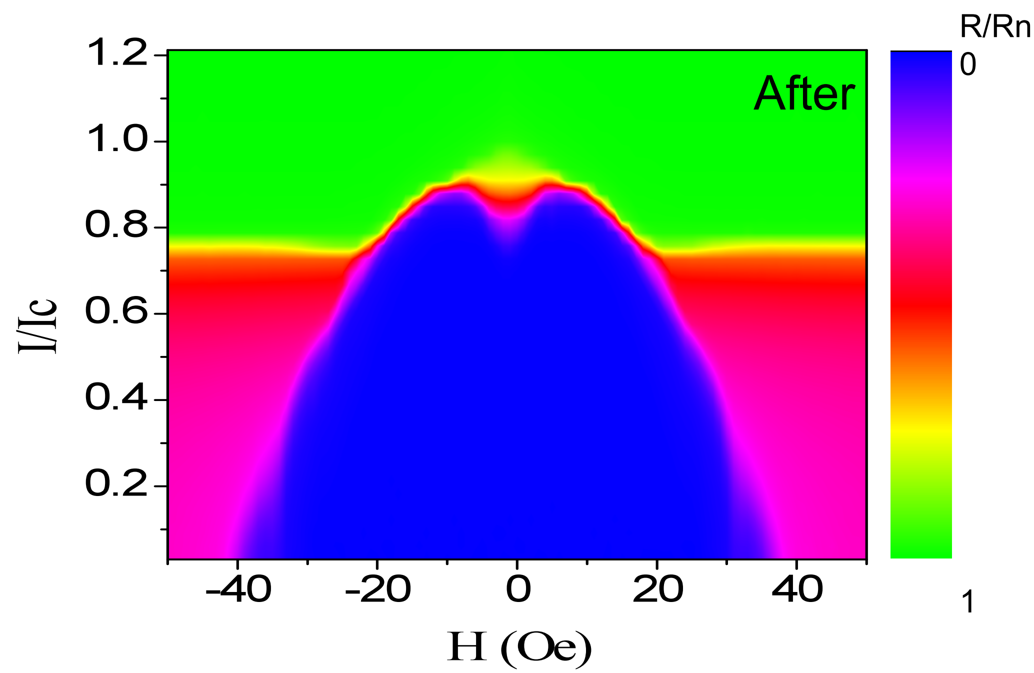


No enhancement was observed in a co-evaporated strip: w= 500nm > ξ

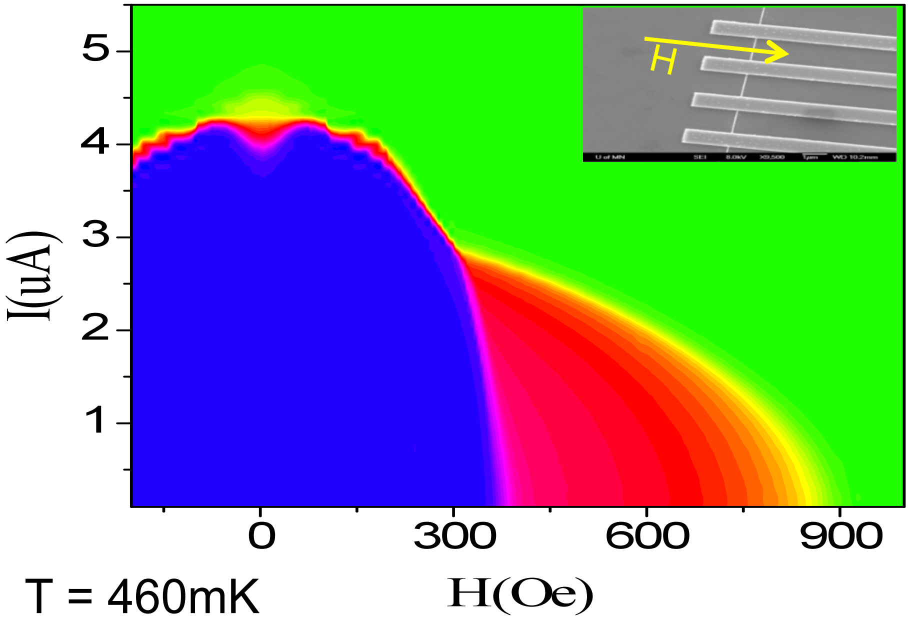
Effect seems to be stronger in a narrower wire: a weakly oxidized sample

(Δw/w ≈ 10%)



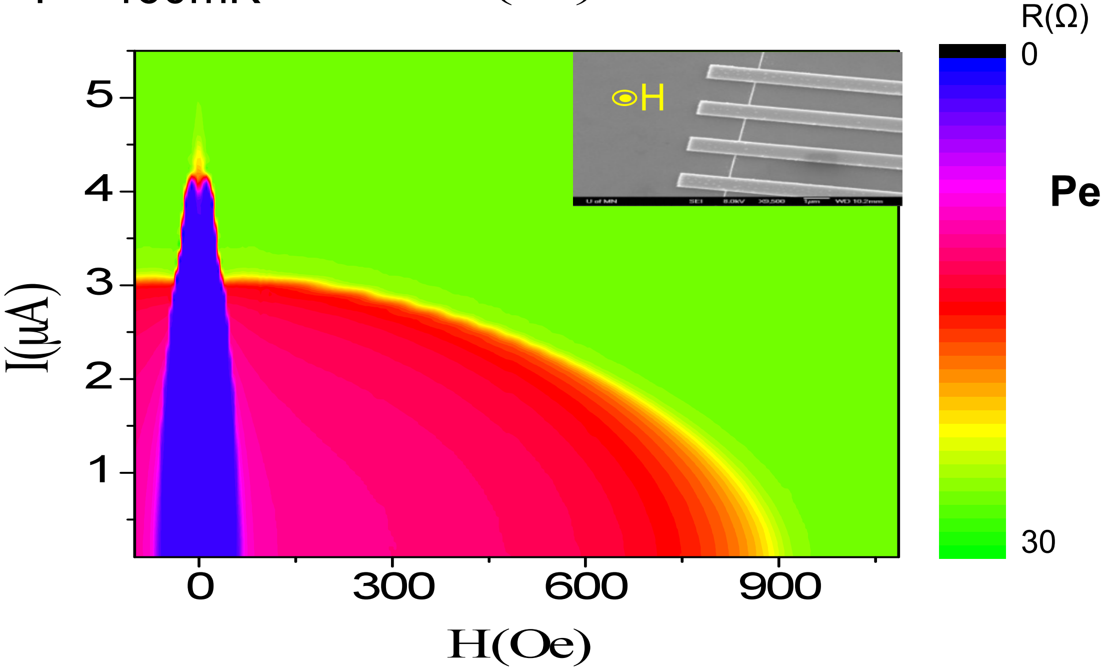


The role of the boundary electrodes



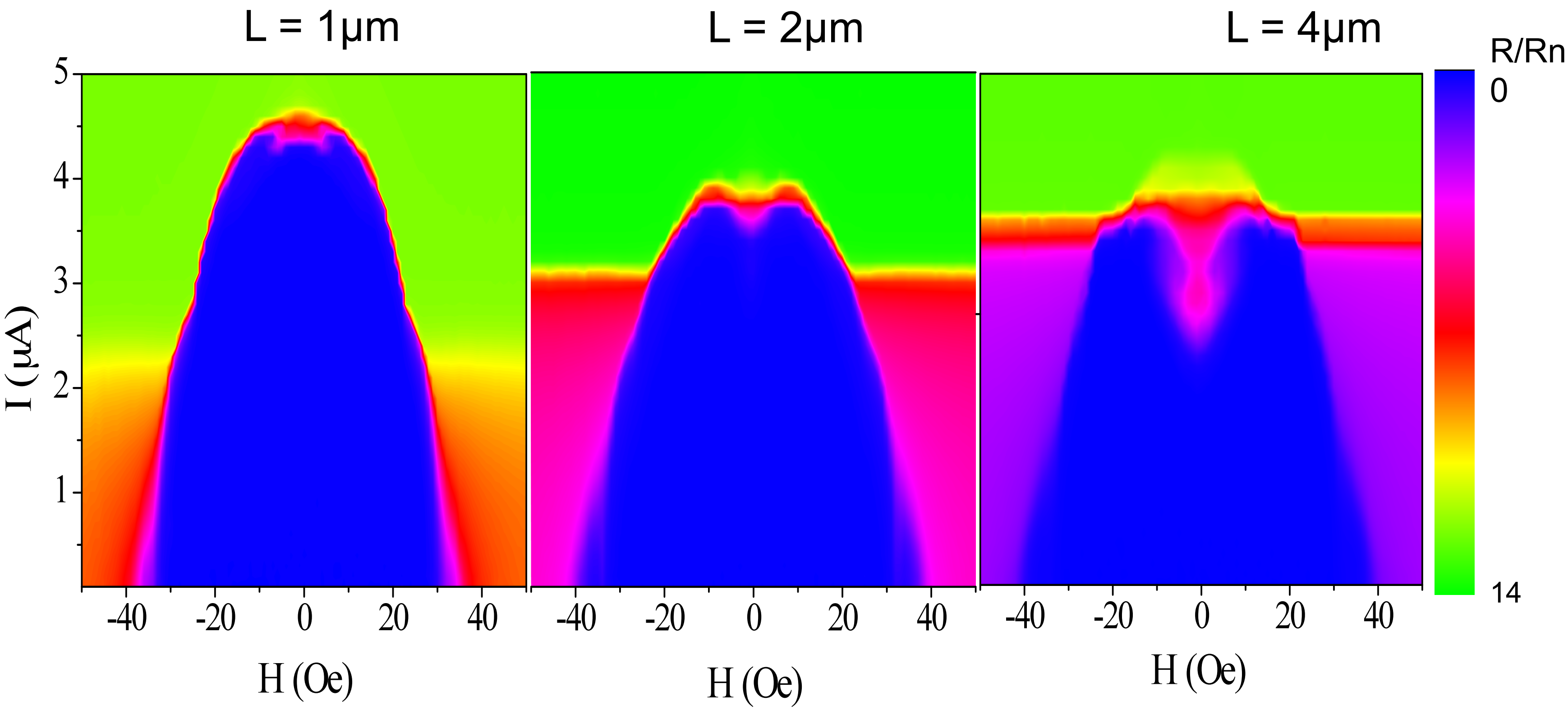
T = 460mK

Transverse : Perpendicular to the wire
Parallel to the electrodes



Perpendicular: Perpendicular to the wire
Perpendicular to the electrodes

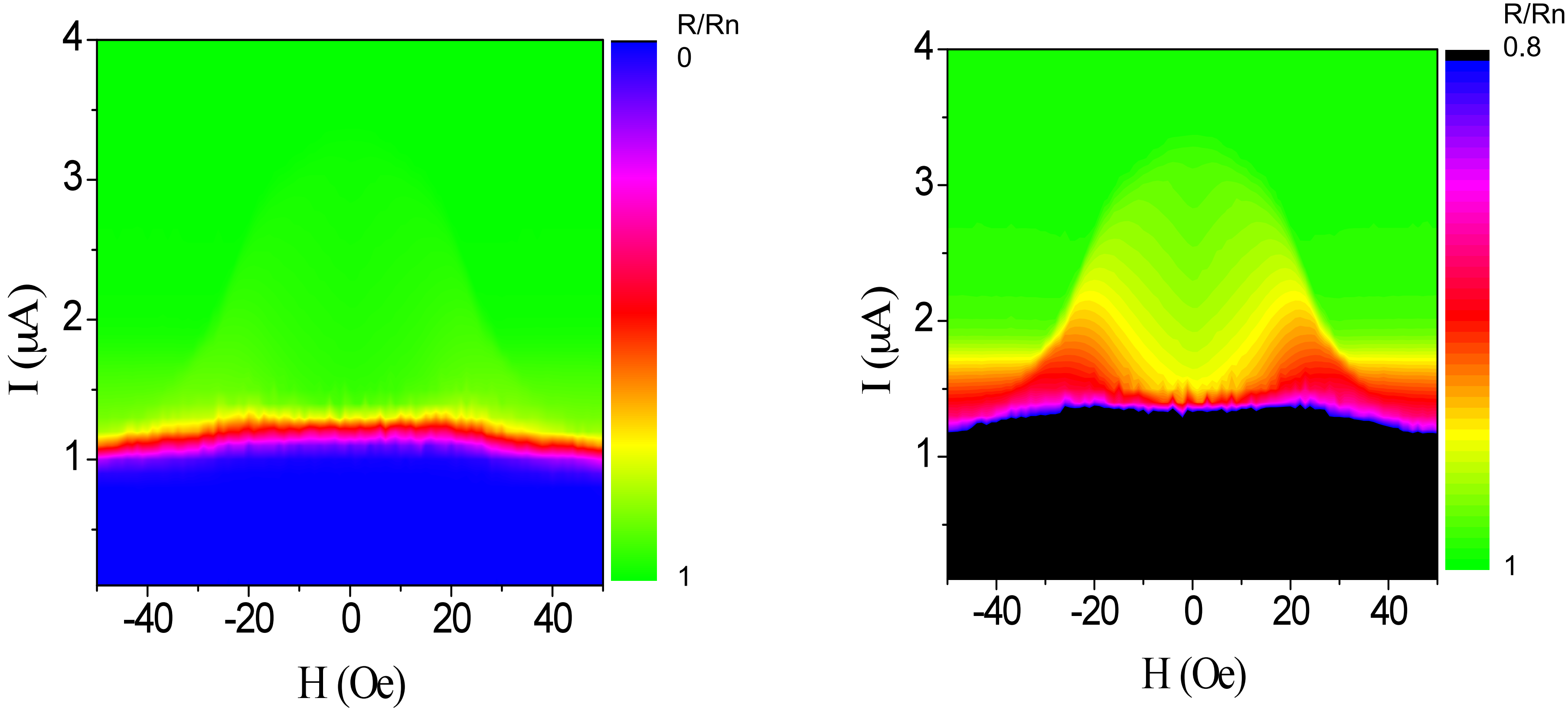
Length dependence of the effect



T = 460mK

Longer wires have stronger effect!

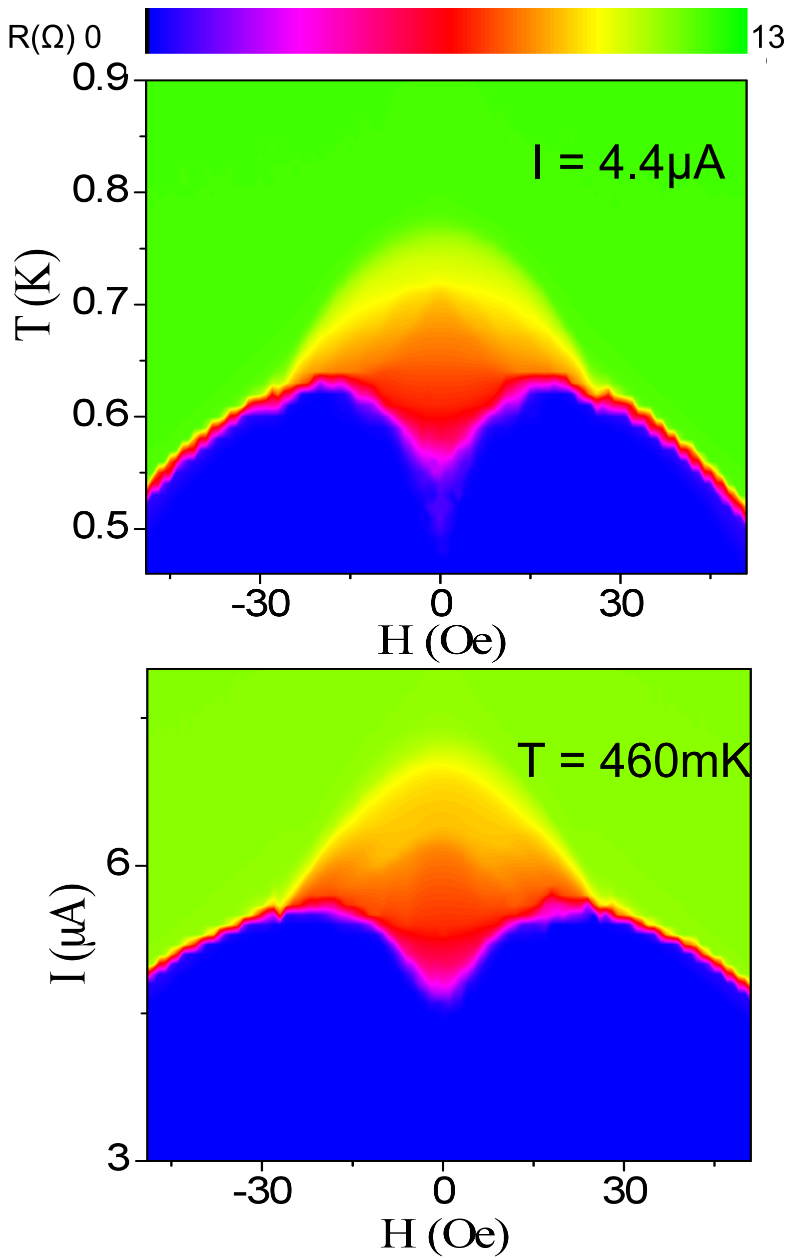
A weaker enhancement was observed in the longest wire L = 10 μm.



Two length scales play a role: ξ superconducting coherence length

L_R quasiparticle relaxation length

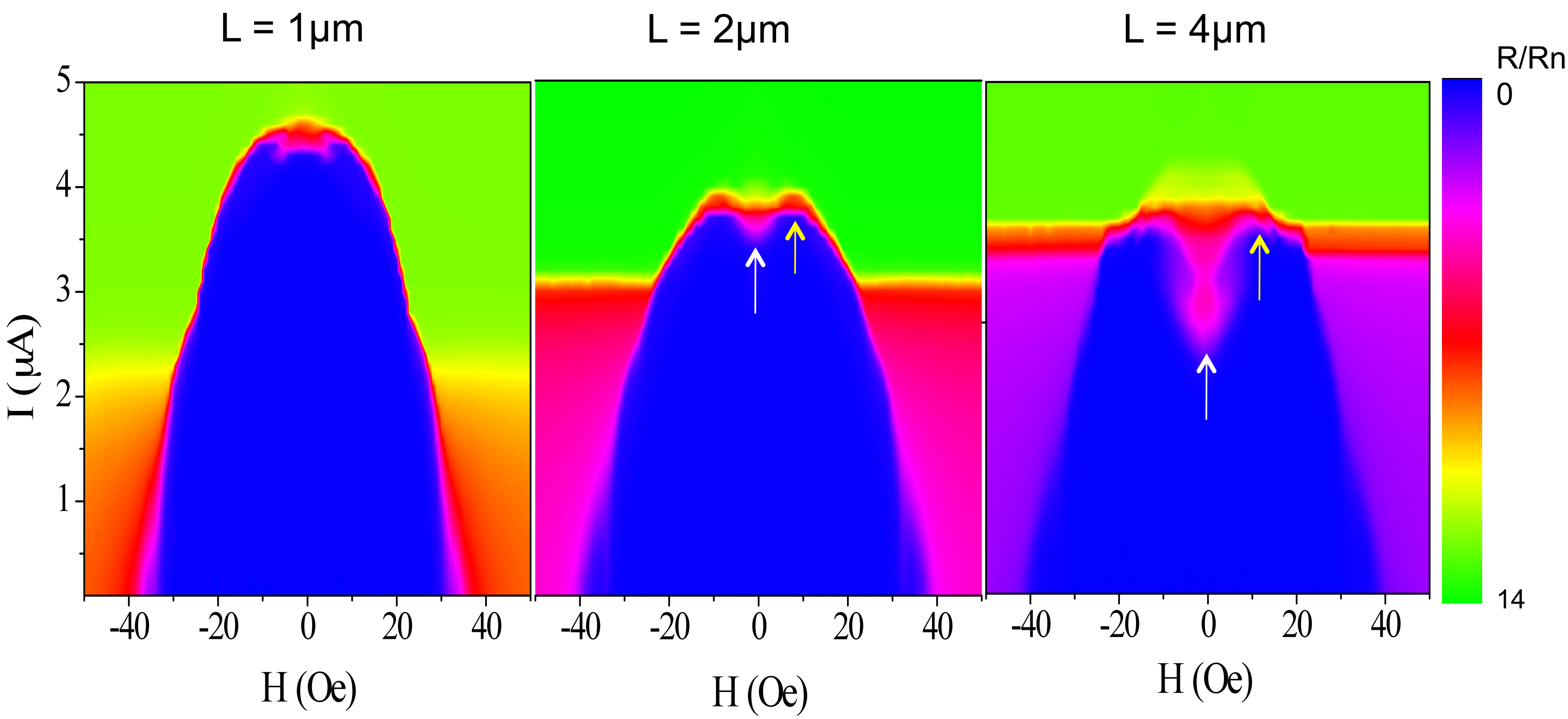
Is this really an enhancement of superconductivity by a magnetic field?



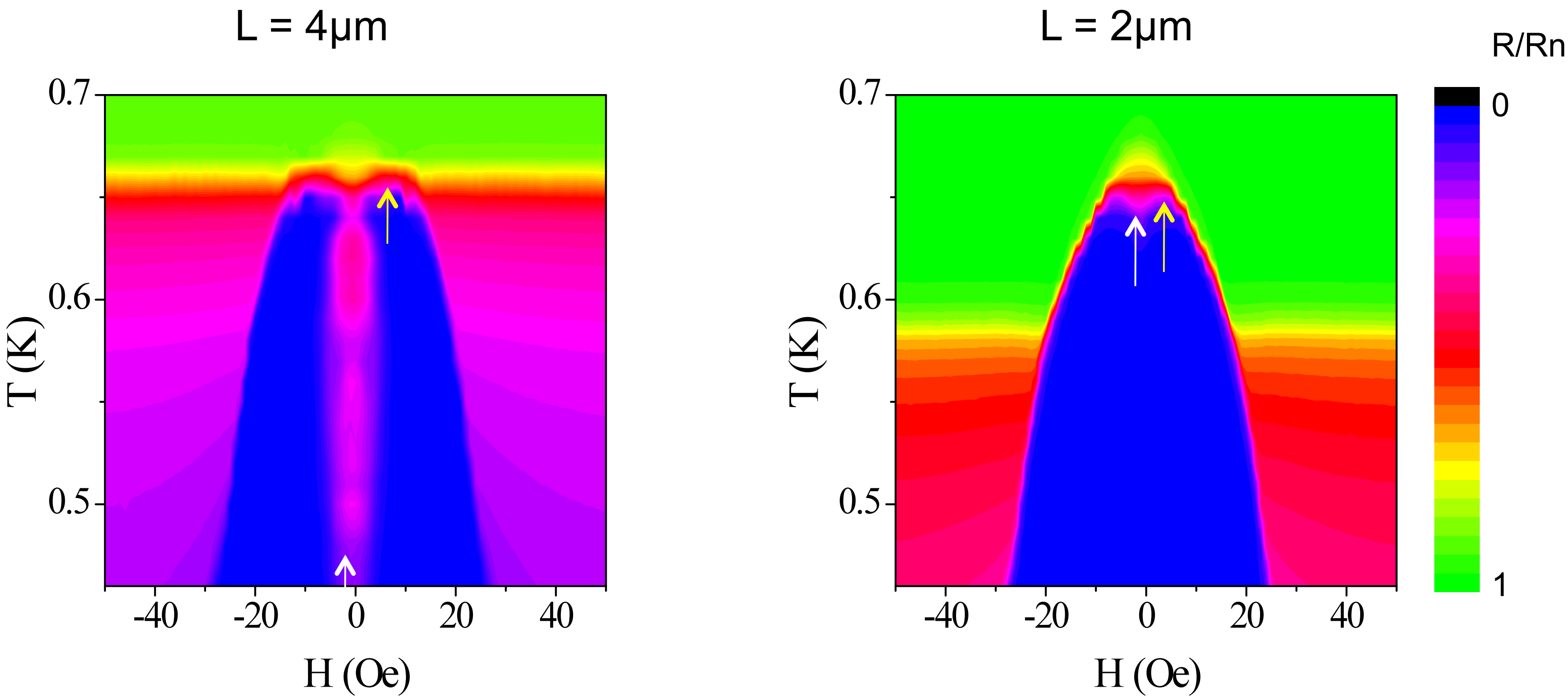
Order parameter of the wire cannot be increased by a magnetic field.

Our conjecture:
It is not an enhancement, but a recovery.

Some hint from the length dependence of the effect



T = 460mK



I = 2.5μA

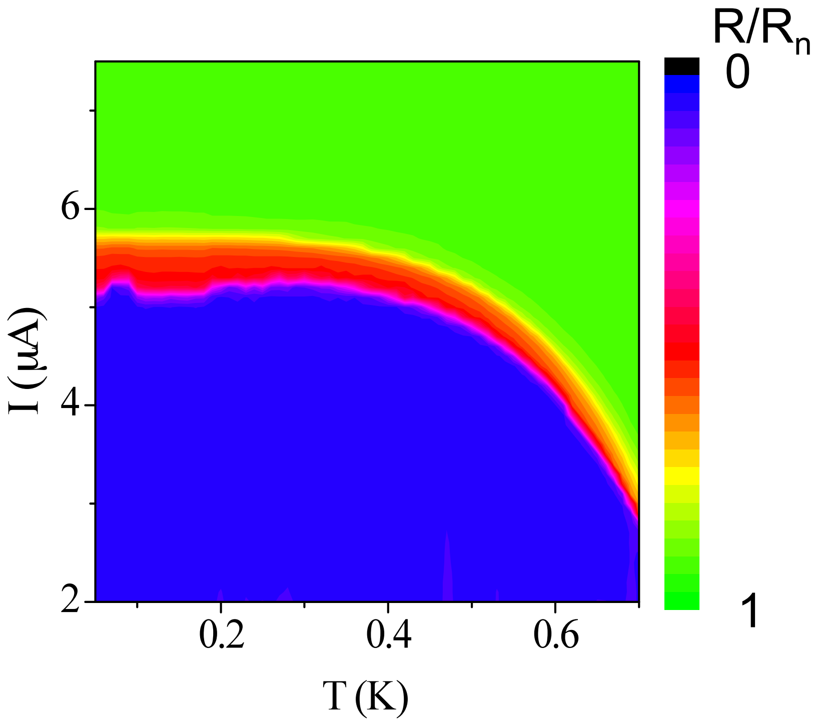
The difference between these two wires is dramatic at zero field.

Question: How can a magnetic field restore or stabilize the *suppressed* superconductivity?

Model	What is incompatible with in our results
Polarization of the magnetic impurities	*applied magnetic field is too weak*
Negative Josephson coupling	*a) not seeing any enhancement of superconductivity in the co-evaporated film. b) can not include the role of electrodes*
Reduction of charge imbalance length	*a) usually only apply to temperatures close to T_c b) needs to include of role of electrodes*
Dampening of phase slips by dissipation	Needs extension to finite temperatures and currents

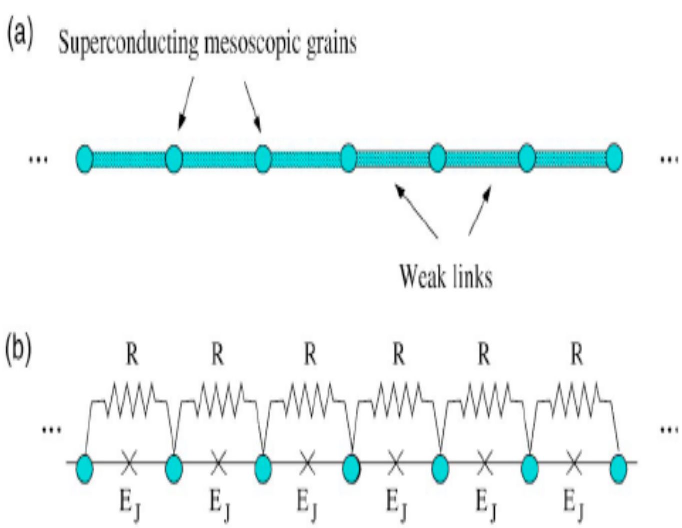
A. Rogachev et. al. PRL **97,** 137001(2006) ; K.Yu. Arutyunov, Physica C **468**, 272 (2007) ; D. Y. Vodolazov, PRB **75**, 184517 (2007); S. A. Kivelson et. al. PRB **45**, 10490 (1992); P. Xiong et. al. PRL **78** 927(1997) A.D. Zaikin et. al. Usp. Fiz. Nauk **168**, 244(1998); Henry C. Fu et. al., PRL **96**, 157005 (2007); D. S. Fisher et. al., PRB **75** 014552(2007).

Dampening of phase slips by dissipation



Broadened transition regime extends towards zero temperature.

Possible quantum phase slips?



Coupling to a dissipative environment can dampen quantum phase slips.

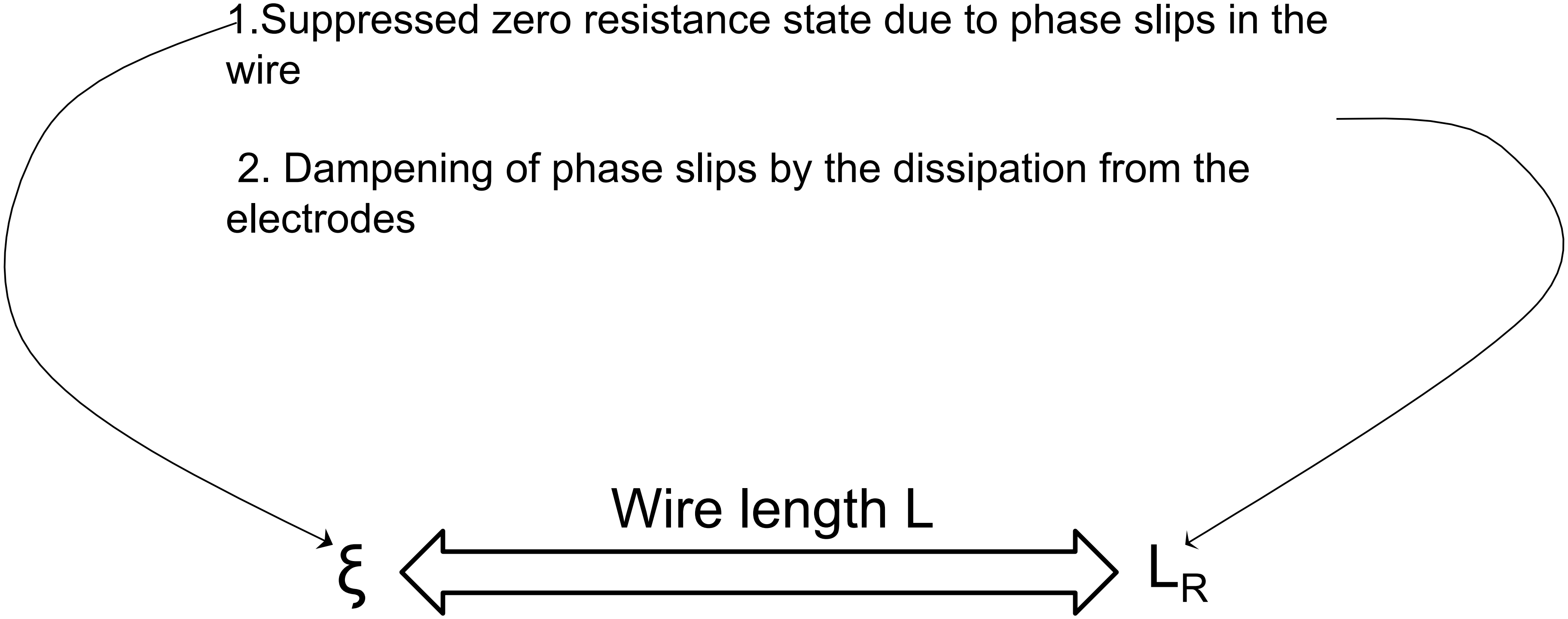
A magnetic field enhances dissipation by increasing quasiparticles in the electrodes

G. Refael *et al.*, PRB 75, 014522

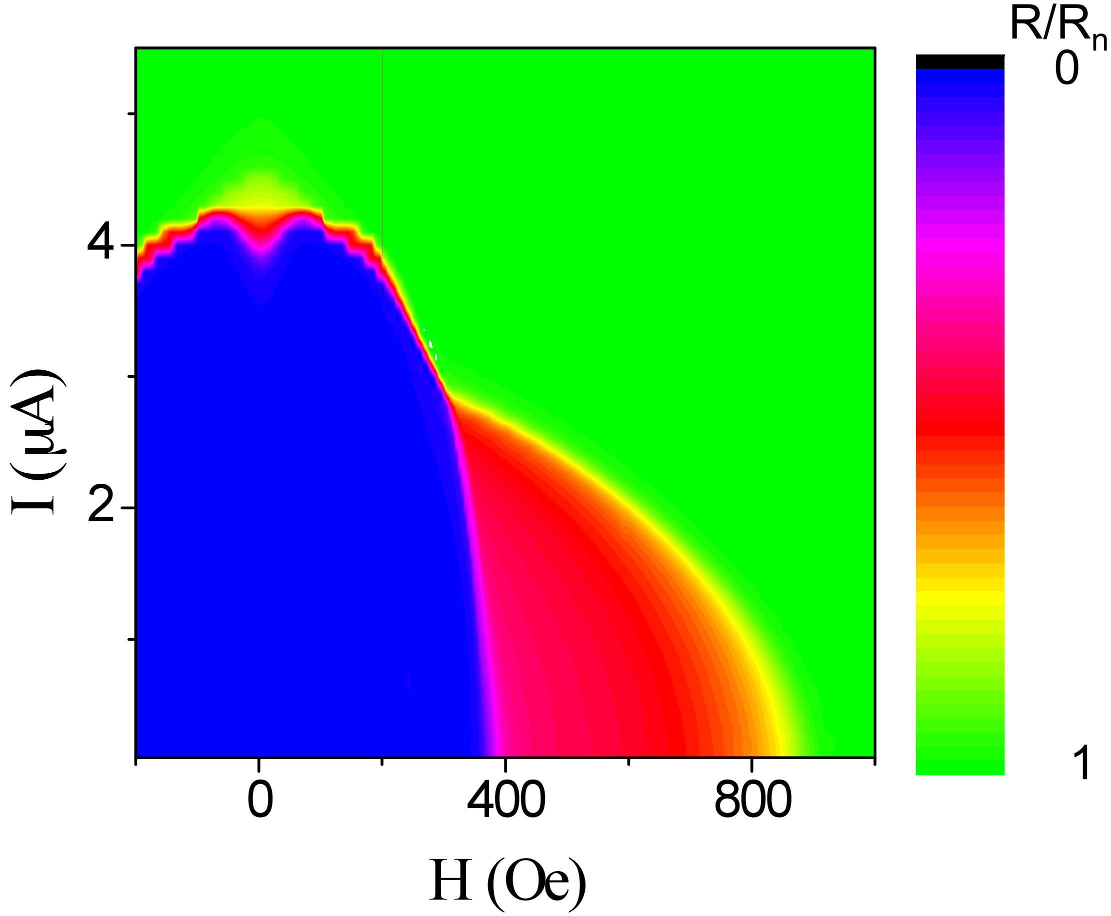
Combine the two steps

1.Suppressed zero resistance state due to phase slips in the wire

2. Dampening of phase slips by the dissipation from the electrodes



Summary



An effect found in quasi -1D superconductors.

A nonequilibrium effect influenced by the boundary electrodes.

Not an enhancement, but a recovery of superconductivity.