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Conference on Superconductor-Insulator Transitions

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The Superconductor-Insulator Transition in thin TiN films

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The Superconductor-Insulator Transition in TiN Thin Films

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Superconductor – Insulator transition

Metal – Insulator transition: driven by disorder and Coulomb interaction

delocalized wave functions | weak disorder ↔ strong disorder | localized wave functions

add superconductivity:

Cooper pairing induced by attractive interaction

collective wave function

$$\Psi = \Psi_0 \cdot \exp(i\varphi)$$

?

Outline:

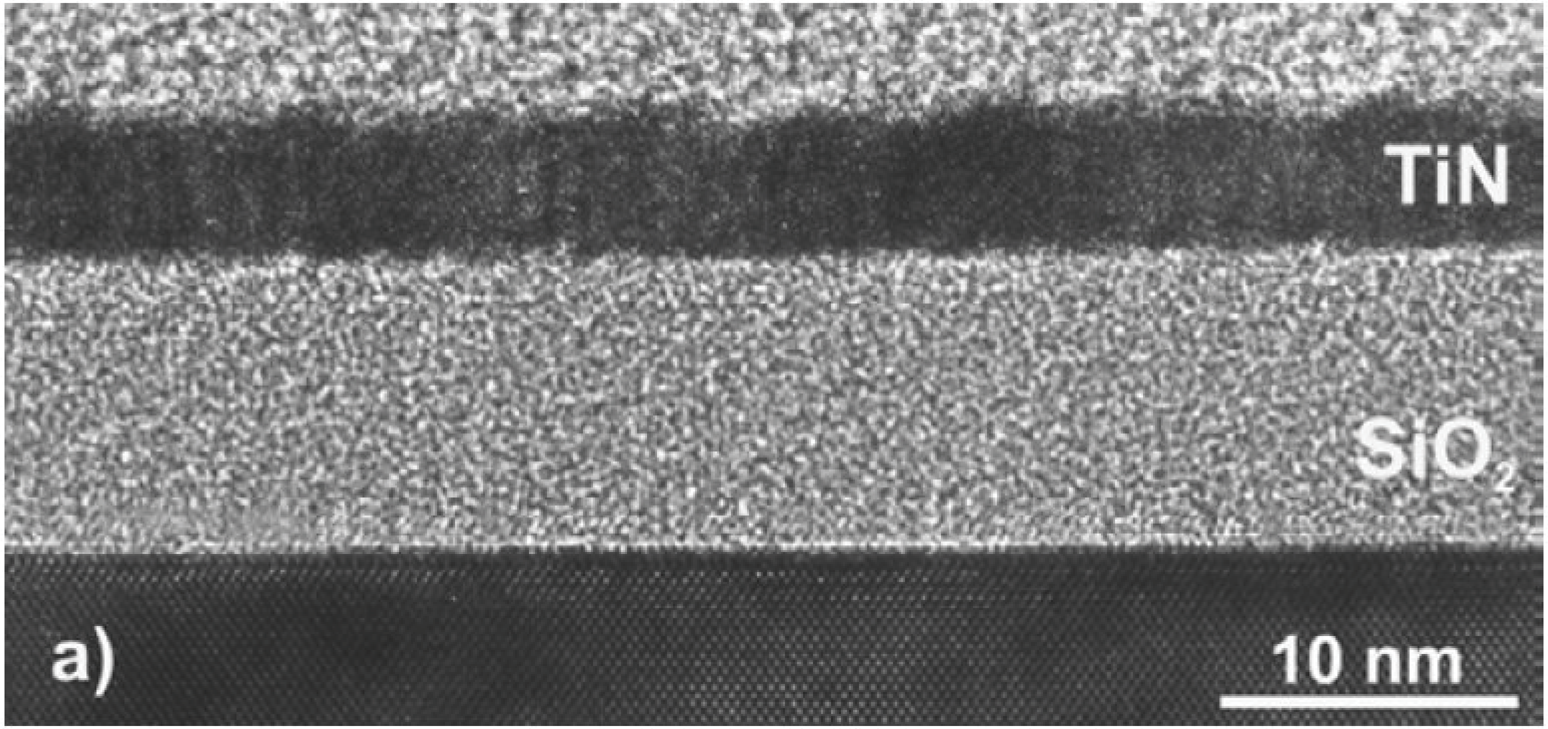
sharp superconductor/insulator transition in TiN

universal (?) metallic behavior in high magnetic fields

linear and non-linear response

super-exponential growth of R at low temperature
in insulating films

Experiments on TiN films

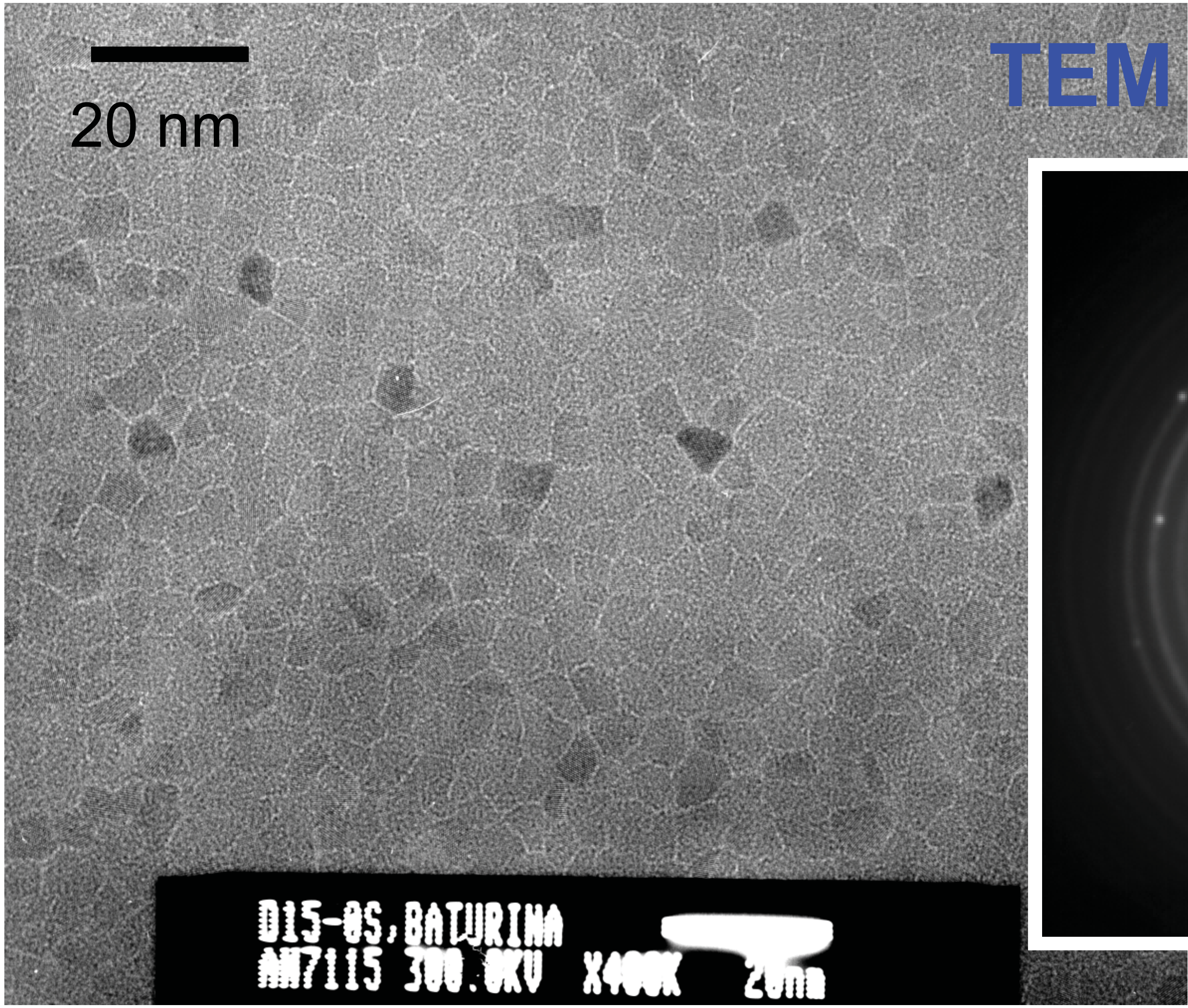


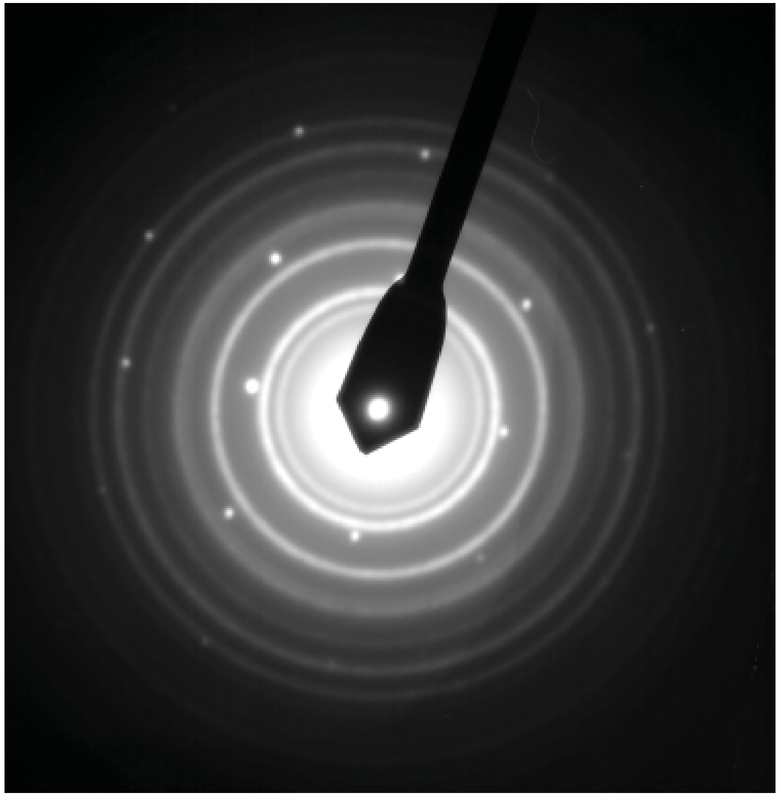
atomic layer chemical vapor deposition onto a Si/SiO_2 substrate.

Atomic layer deposition by M. Baklanov, IMEC

d = 5 nm

TEM + e^-- diffraction

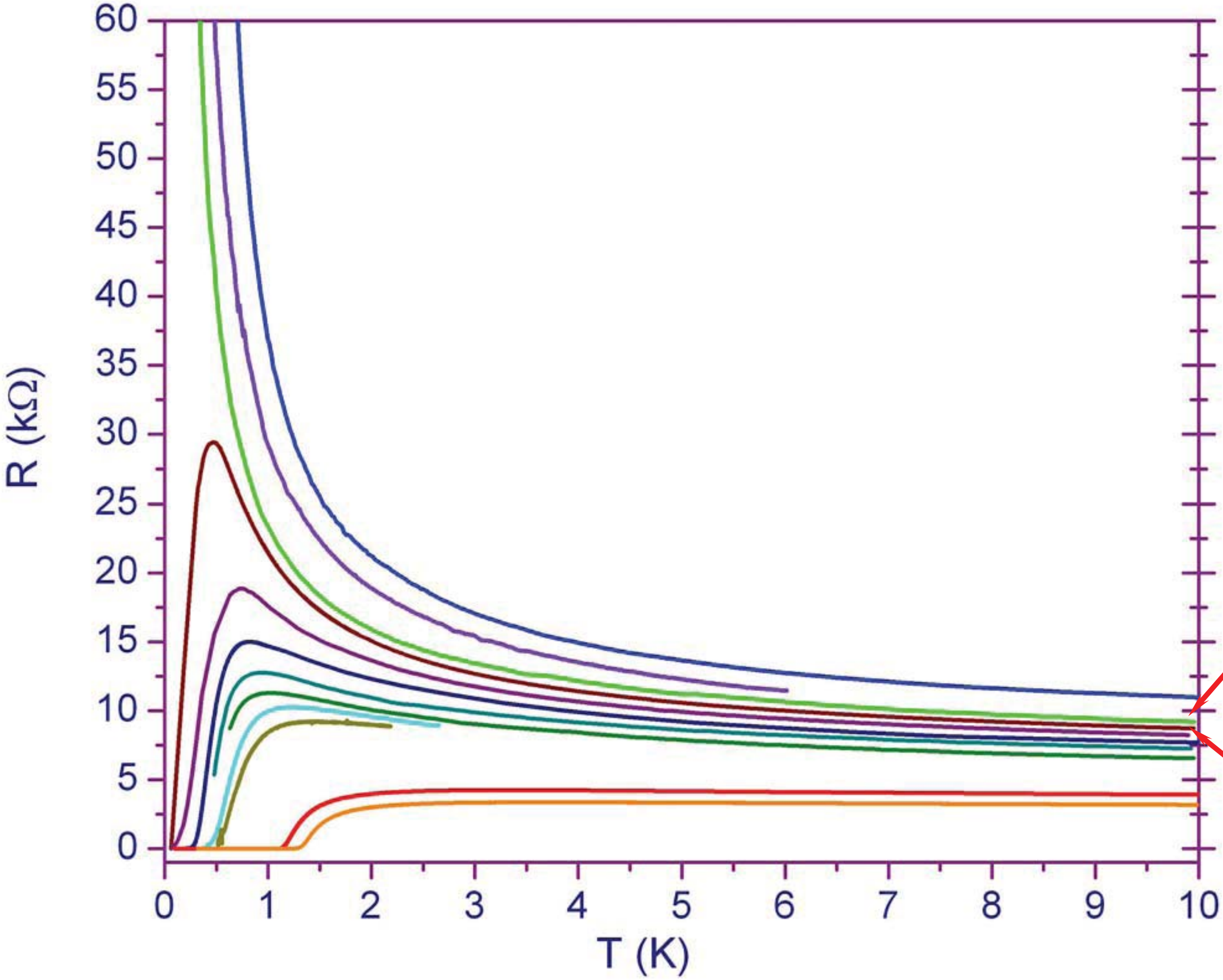




densely-packed polycrystalline structure,

interfaces between crystallites 1-2 atomic layers thick.

Disorder-induced - SIT in TiN films



T = 10 K

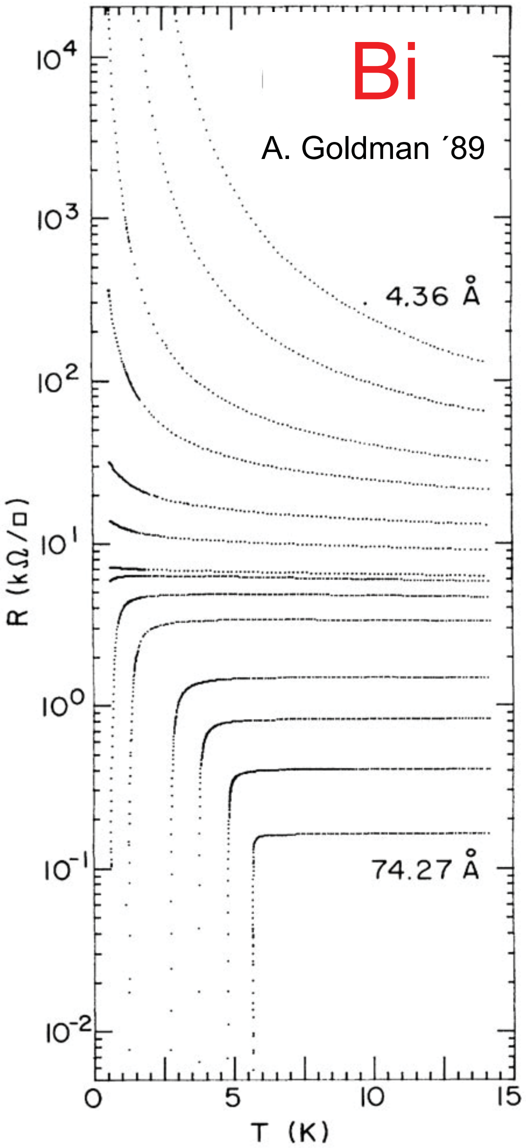
9.16 kΩ – I3

8.74 kΩ - S

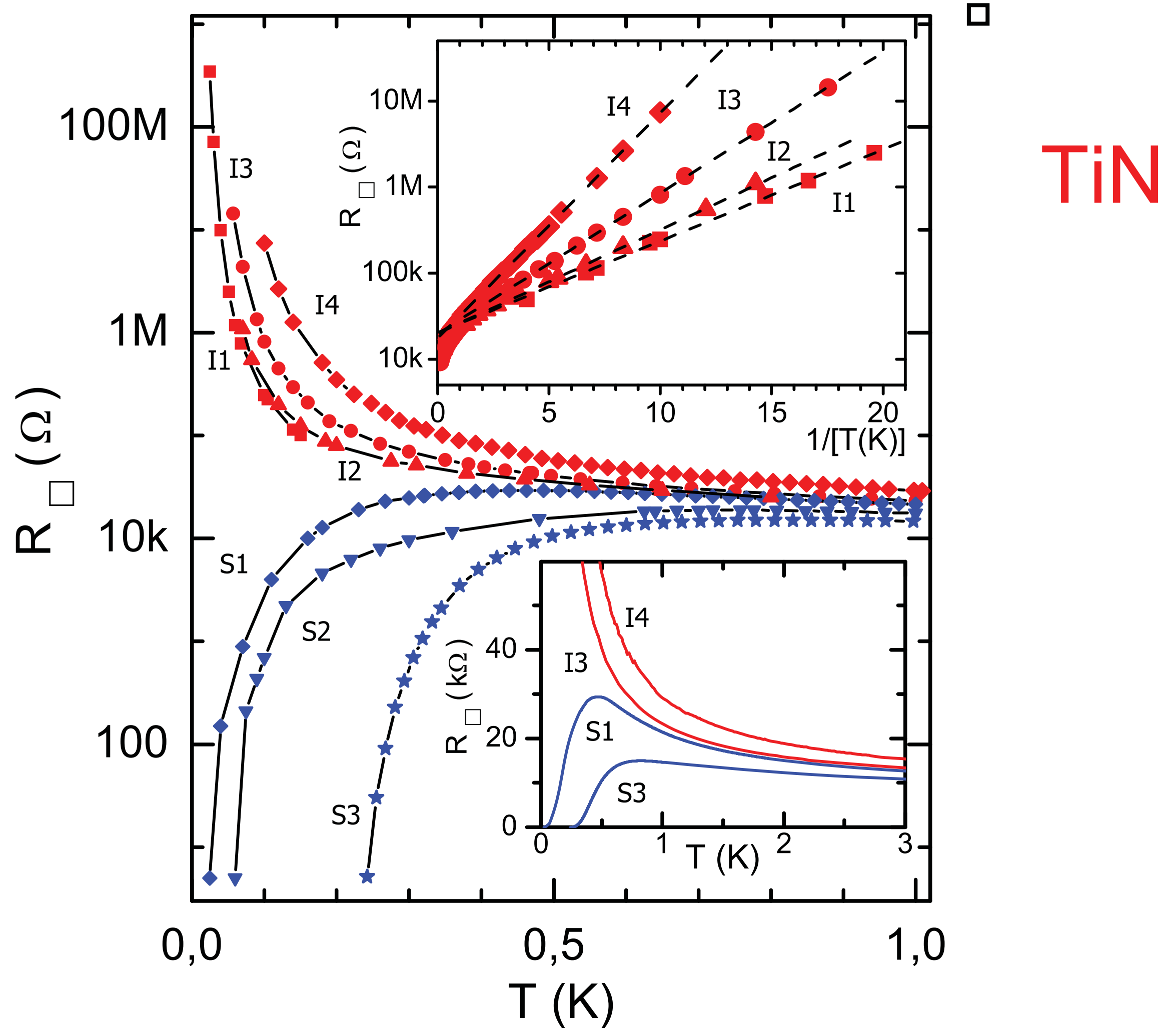
< 5% (!)

T.I. Baturina, C.S. et al., JETP Lett. 79, 337 (2004); PRL 98, 127003 (2007); PRL 99, 257003 (2007).

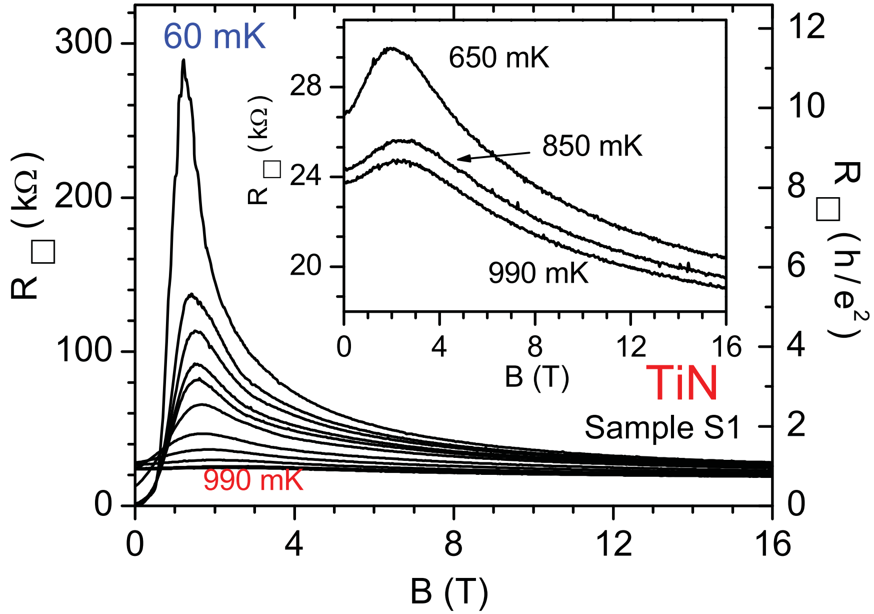
thermally activated conductance (Arrhenius) on the insulating side of the transition

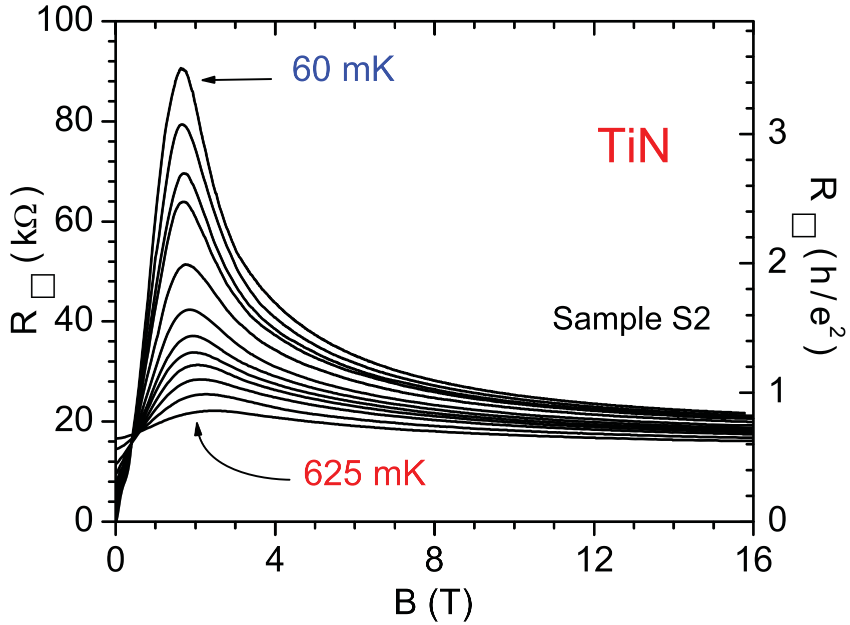


homogeneous TiN-films of 4-18 nm thickness show a disorder-induced SIT



magnetic field induced SIT (Hebard & Paalanen 1990)





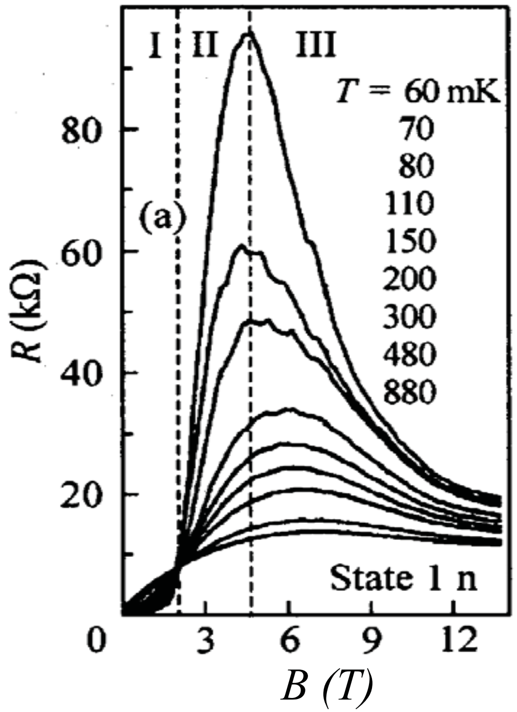
At low perpendicular fields, the global phase coherence is suppressed

→ SIT similar to that in granular films

(Skvortsov & Feigelman PRL '05)

At higher fields complete destruction of Cooper pairs

→ saturation of magnetoresistance similar to InO_x and other materials

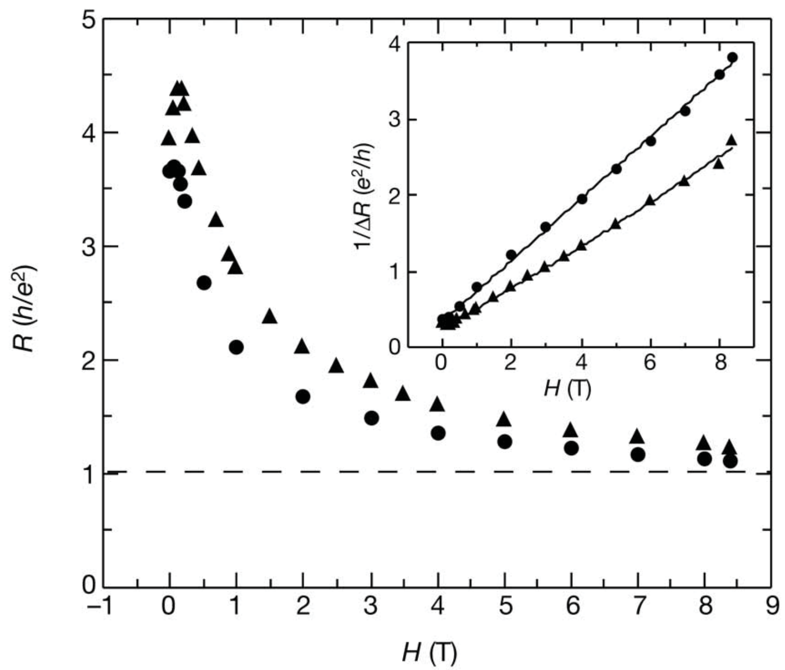


amorphous InO_X

Gantmakher et al. 2000

‚Quantum metallicity‘ at high magnetic fields?

Butko & Adams Nature 2001



different insulating Be-films
also saturate at the same resistance

$$R_{\text{sat}}(T) \gg R(10\,\text{K}, B=0)$$

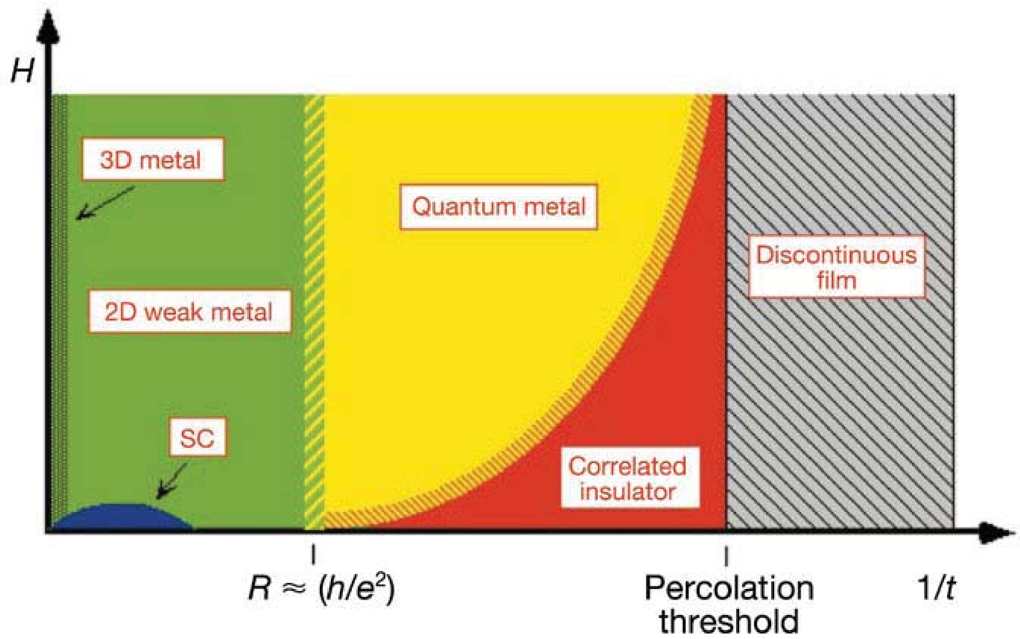
although

$$R(10\,\text{K}, B=0)$$

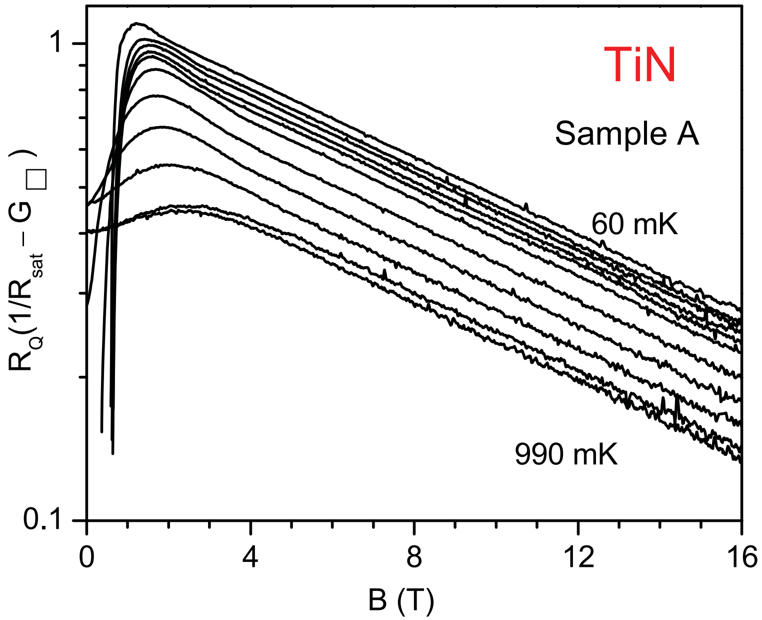
considerably varies for different films!

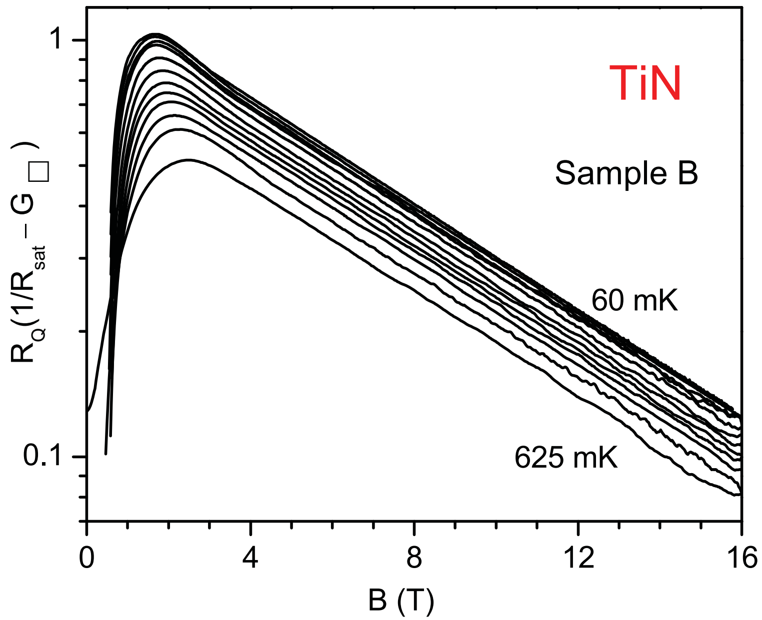
insulating Be films

proposed phase diagram



Extraction of saturation resistance



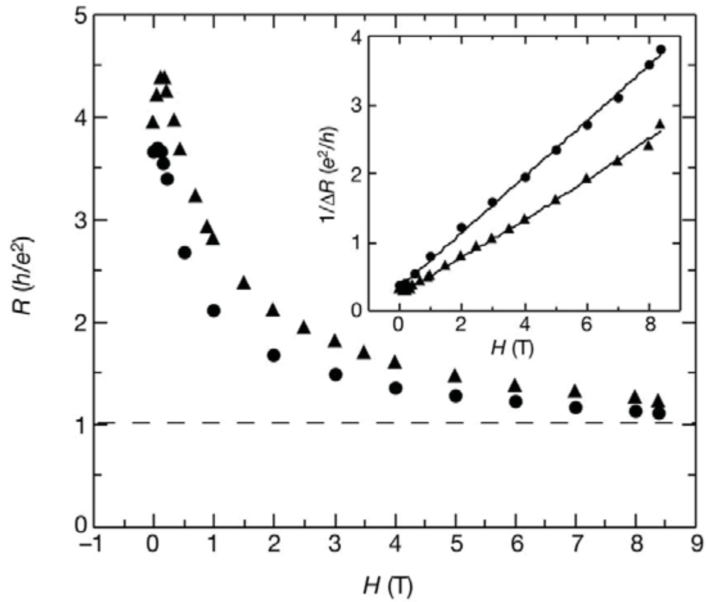


High field data follow simple scaling:

$$G_\square(T,B) = \frac{1}{R_{\mathrm{sat}}(T)} - \beta(T)\exp\left(-\frac{B}{B^*}\right)$$

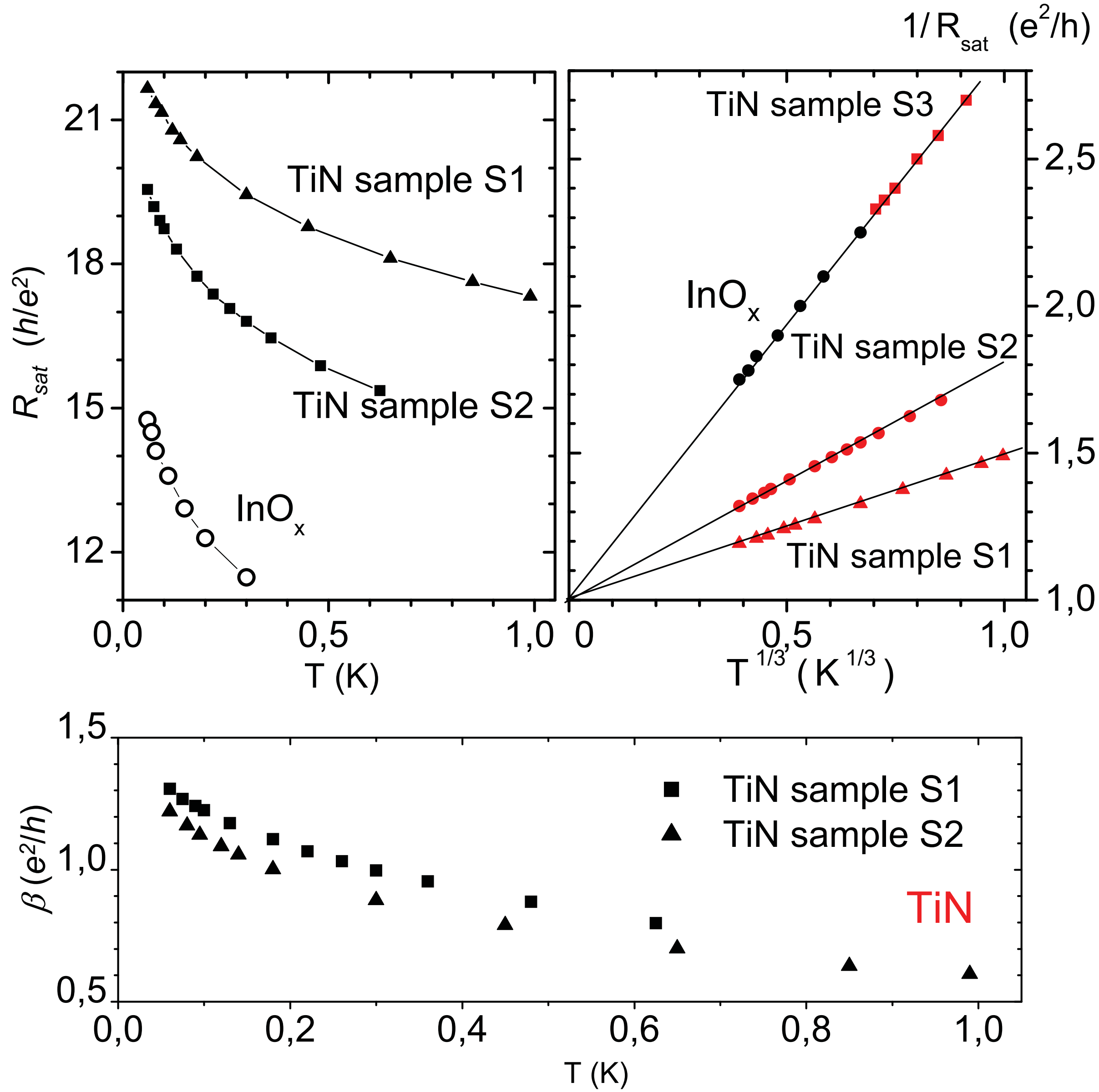
interestingly $R_{\mathrm{sat}}(T) \gg R(10\,\mathrm{K}, B=0)$

compare insulating Be films:



Butko & Adams 2001

saturation resistance extrapolates towards h/e^2 !



in the limit T ⟶ 0,
R_{sat} becomes independent of the material and normal resistance at higher *T*

generic property of thin films near the SIT?

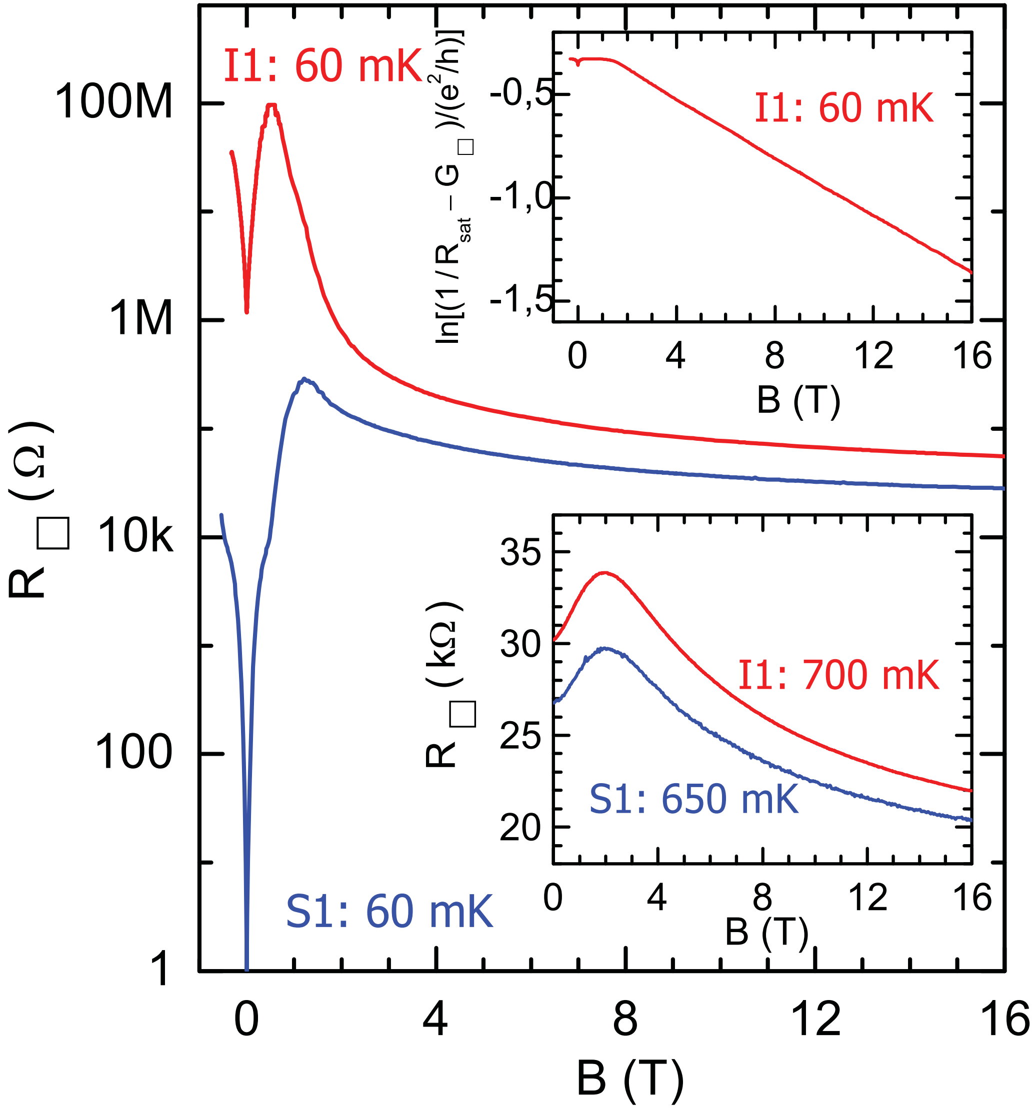
evidence for ‚quantum metallicity' at high magnetic fields?

observed before in insulating Be films:

(Butko *et al.*; Nature 2001)

T. Baturina, C.S. *et al.*
PRL **98**, 127003 (2007)

magnetic field induced resistance enhancement in both: insulating and metallic state



Qualitatively similar behavoir for insulating and superconducting films already in small magnetic fields

Exponential decay of magneto-resistance at high fields:

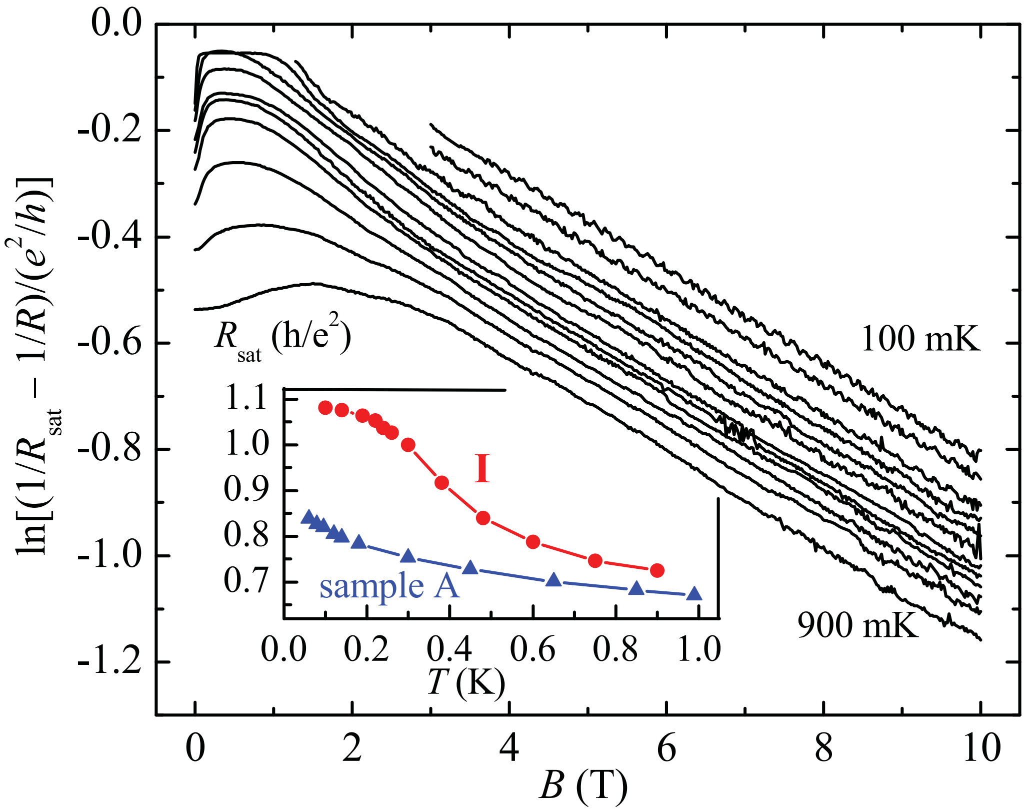
→ gradual suppression of superconducting OP

Very similar behavior of insulating and superconducting films for T > 600 mK

quasi-metallic phase at high B

low B: ‚Cooper-pair' - insulator !

magnetic field induced resistance enhancement in both: insulating and metallic state



Similar behavoir for insulating and superconducting films also in large magnetic fields:

Similar saturation resistance

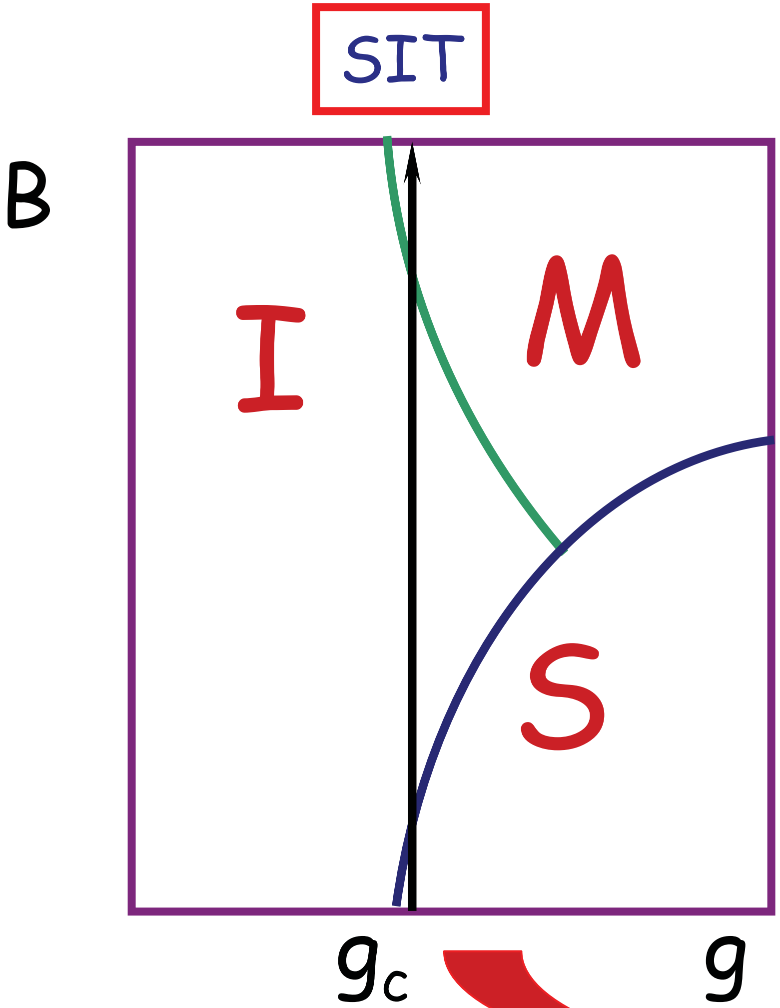
Again exponential decay of magneto-resistance at high fields:

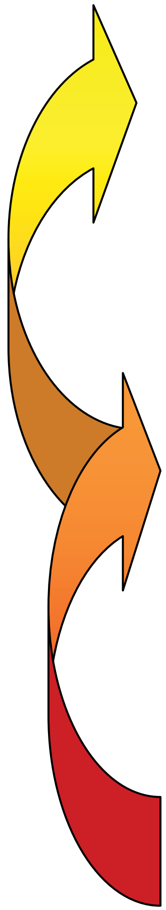
→ also caused by suppression of superconducting OP ?

quasi-metallic phase at high *B* occurs also in samples *insulating* at *B*=0 !

schematic phase diagram

InO_x, Be, and TiN films





Quantum metallicity at a high-field side of SIT

Magnetic-field-tuned superconductor-insulator transition

Disorder-driven superconductor-insulator transition

Compare

nonlinear transport (IV-characteristics)

on the

superconducting and insulating

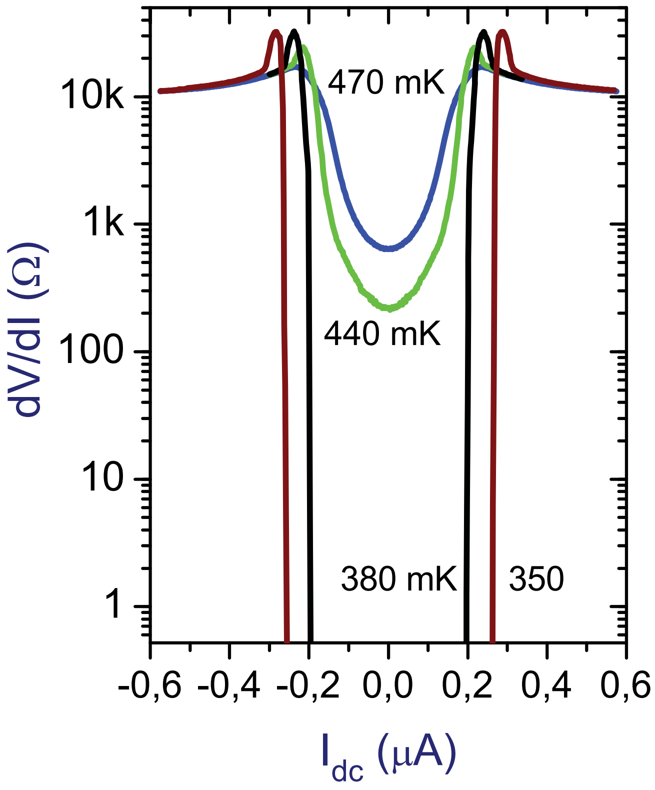
sides of the SIT:

Superconducting state:
Current-Voltage Characteristics

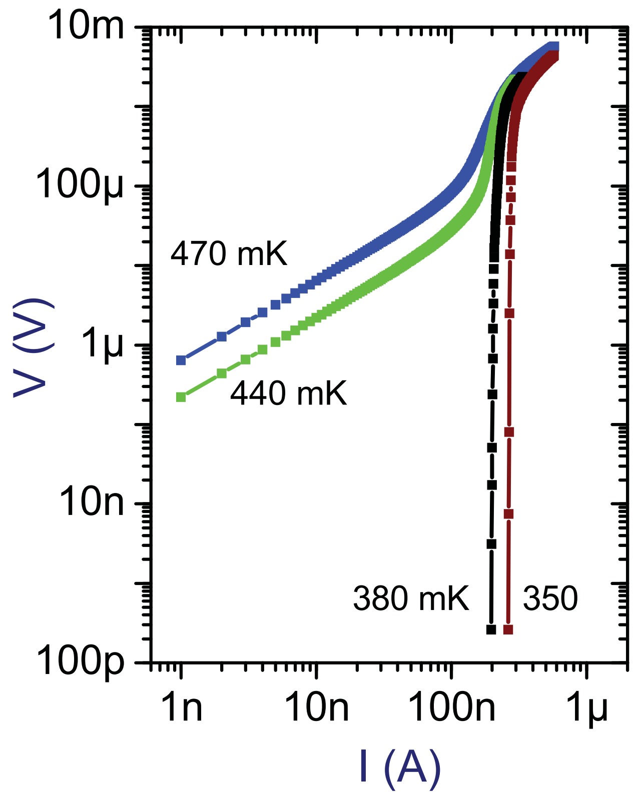
TiN films

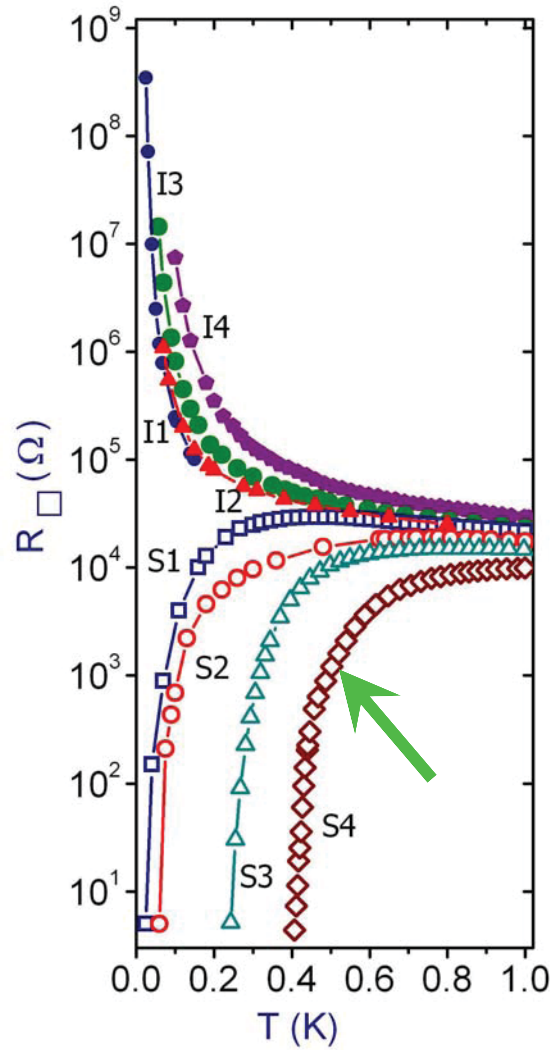
S4 at B = 0T

dV/dI vs I



V vs I





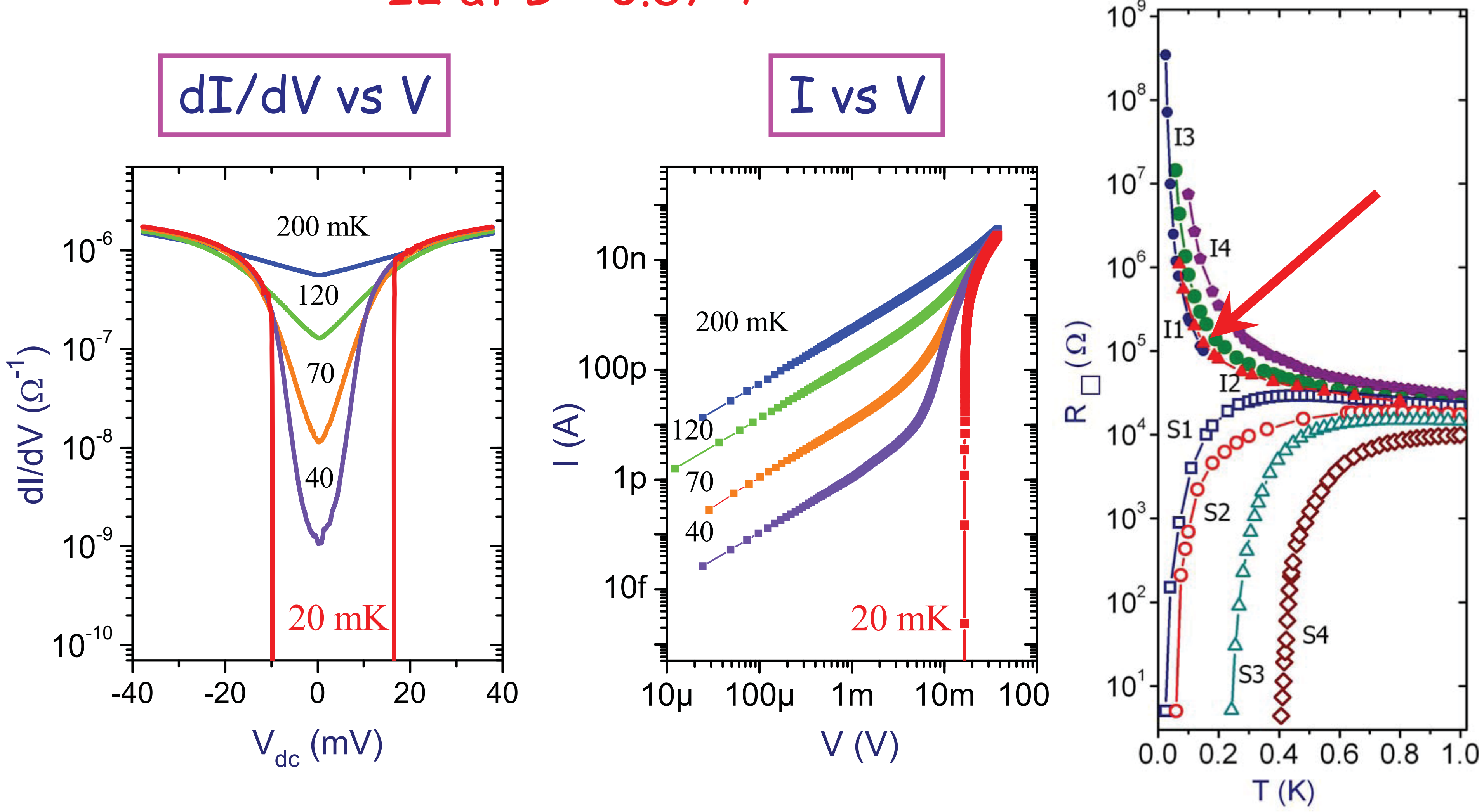
Insulating state:
Current-Voltage Characteristics

TiN films

I2 at B = 0.87 T

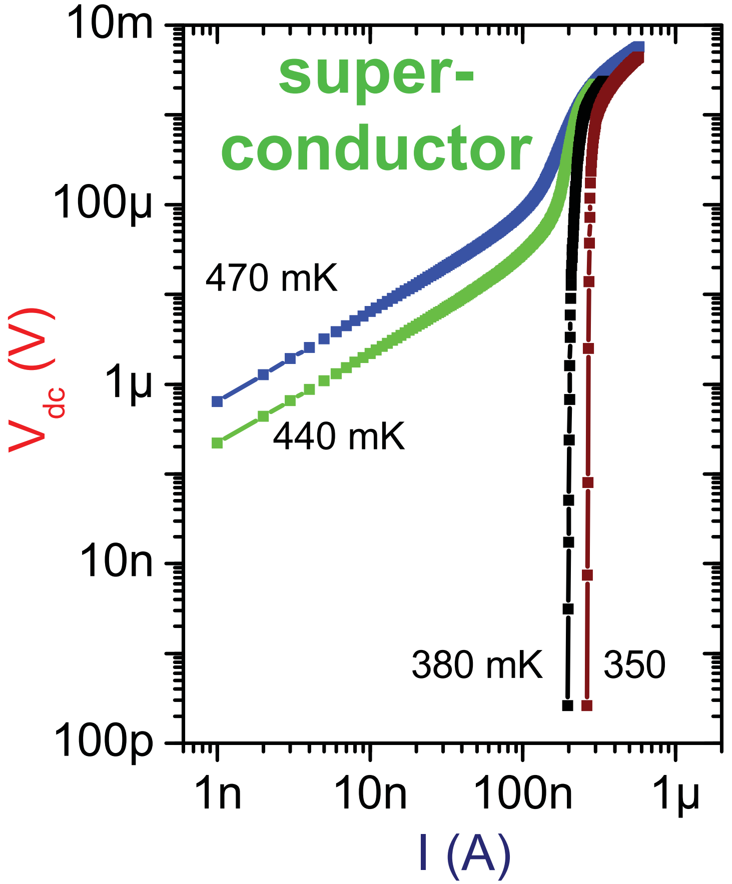
dI/dV vs V

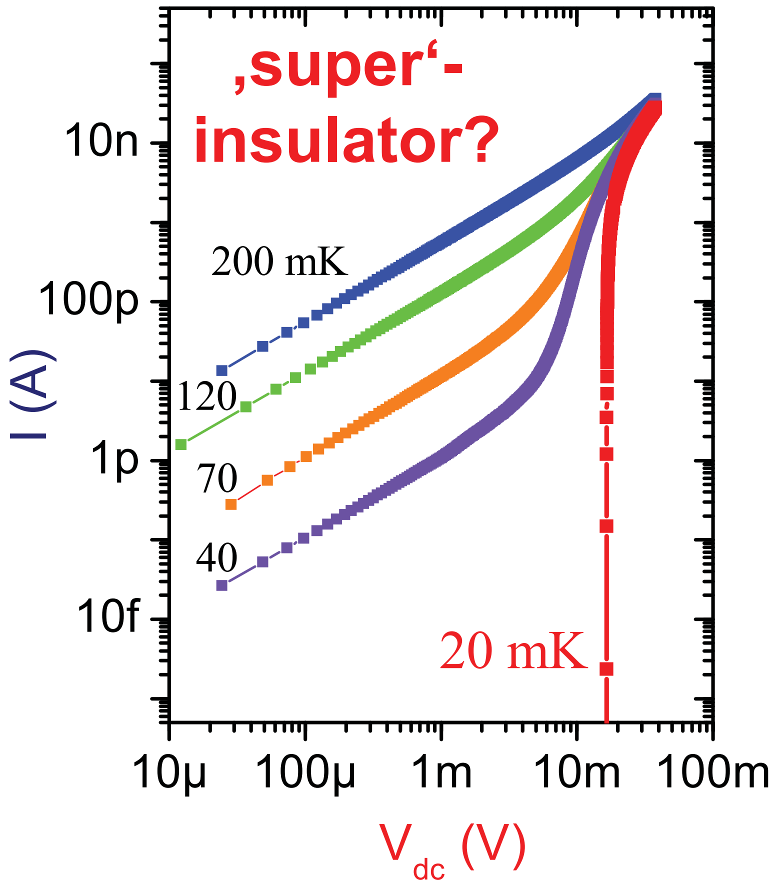
I vs V



Berezhinskii-Kosterlitz-Thouless transition

thermally activated vortex-antivortex pairs	thermally activated charge-antichange pairs ??





A similar phenomenology has been seen before:

Sambandamurthy et al. (Shahar group, Weizmann)

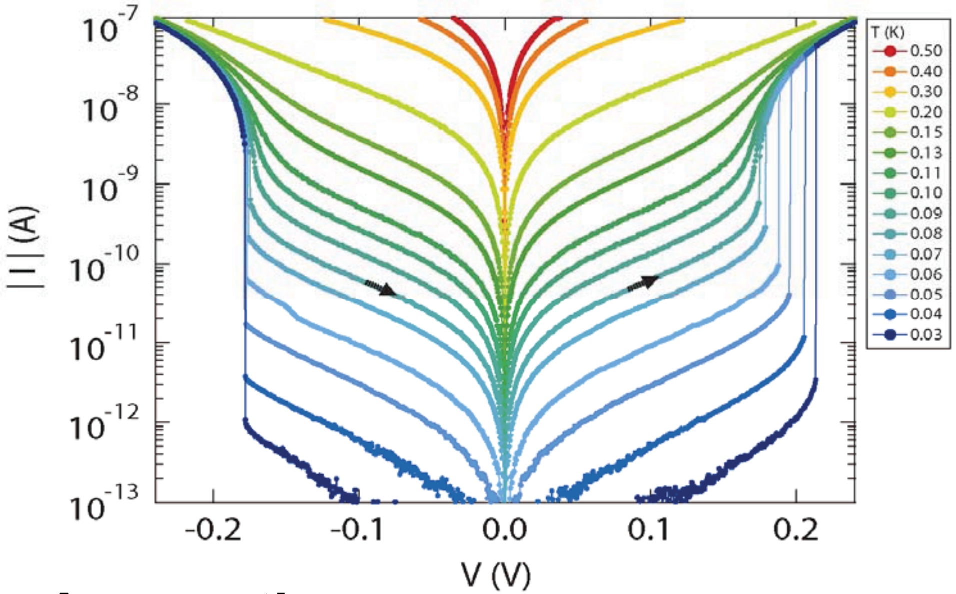
have observed a zero-conductance state in amorphous InO_x films in magnetic field

Sambandamurthy et al. PRL **92**, 107005 (2004)

PRL **94**, 17003 (2005)

no clear interpretation at that time

A more recent interpretation of the current jumps: electron heating effects



Ovadia, Sacepe & Shahar
PRL **102**, 176802 (2009)

Altshuler, Kravtsov, Lerner & Aleiner,
PRL **102**, 176803 (2009)

similar to YSi-films (Mott-insulator):

F. Ladieu, M. Sanquer & J. Bouchaud,
PRB **53**, 973 (1996)

Assumptions:

- I(V) is linear – no internal energy scales induce non-linearity
- strongly varying R(T) produces heating instability
- decoupling between electrons and phonons (right power law IV ~ T^6)

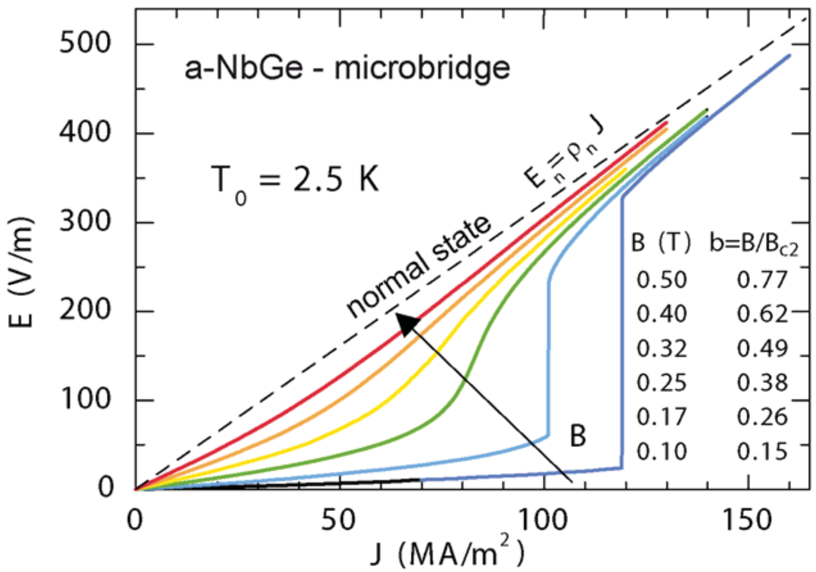
Questions:

- power level 3 orders of magnitude higher than in our TiN-films
- is there really only one energy scale involved (linearity of IC's ?)
- where is superconductivity coming in ?

Caution: there may be different types of jumps

Example: Larkin-Ovchinnikov instability
in strongly driven vortex flows

quasiparticles boil off from strongly driven vortex cores
- shrinking of the vortex core
- decrease of vortex viscosity
- incease of vortex velocity and dissipation



ön

D. Babic, C.S. et al.
PRB 65, 645 - 648 (2004)

completely different mechanism for jumps in V(I) than BKT superconductivity provides additional energy scales (Δ)

- what mechanisms are there to drive a SC insulating?

- what about the repulsive part of ee-interaction?

Ovadyahu, Paalanen, Trivedi and others:

the superconducting film may develop spatial inhomogeneities!

$\longrightarrow$ model system as a granular superconductor

charging energy produces another energy scale

similarity to granular systems?

DISORDER INDUCED GRANULARITY IN AN AMORPHOUS SUPERCONDUCTOR

David Kowal and Zvi Ovadyahu

Solid State Communications, Vol. 90, No. 12, pp. 783-786, 1994

In this Communication we present data relevant for the SIT in an amorphous metal which, from the structural standpoint may be termed "homogeneous". The electronic transport data, however, show features that are well known to occur in *granular* systems near their SIT. This is ascribed to the appearance of superconducting droplets in regions where the local disorder is weaker than the "average" value. We argue that this behavior is inherent to the problem and results from the fluctuations in the local conductivity which are expected to be very large near the Anderson transition. Such a scenario may be generic to all uniformly disordered superconductors, especially for those made from a relatively low T_c material, where moderate disorder actually *enhances* T_c.

Role of Spatial Amplitude Fluctuations in Highly Disordered *s*-Wave Superconductors

Amit Ghosal, Mohit Randeria, and Nandini Trivedi
Department of Theoretical Physics, Tata Institute of Fundamental Research, Mumbai 400005, India
(Received 4 June 1998)

The effect of nonmagnetic impurities on 2D *s*-wave superconductors is studied beyond the weak disorder regime. Within the Bogoliubov–de Gennes (BdG) framework, the local pairing amplitude develops a broad distribution with significant weight near zero with increasing disorder. Surprisingly, the density of states continues to show a finite spectral gap. The persistence of the spectral gap at large disorder is shown to arise from the breakup of the system into superconducting "islands." Superfluid density and off-diagonal correlations show a substantial reduction at high disorder. A simple analysis of phase fluctuations about the highly inhomogeneous BdG state is shown to lead to a transition to a nonsuperconducting state. [S0031-9007(98)07517-6]

Another implication of our results for experiments is that SC insulator transitions in disordered films are often described in terms of two different paradigms: homogeneously disordered films (driven insulating by the vanishing of the gap) and granular films (driven by vanishing of the phase stiffness). In our simple model, although the system was homogeneously disordered at the microscopic level, granular SC-like structures developed in so far as the pairing amplitude was concerned. It would be very interesting to use scanning tunneling microscopy measurements to study variations in the local density states to shed more light on this question.

numerical simulations
by Ghosal , Randeria & Trivedi

see also
Dubi, Meir & Avishai
Nature **449**, 876 (2007)

Is there a granular structure of the SC OP ?

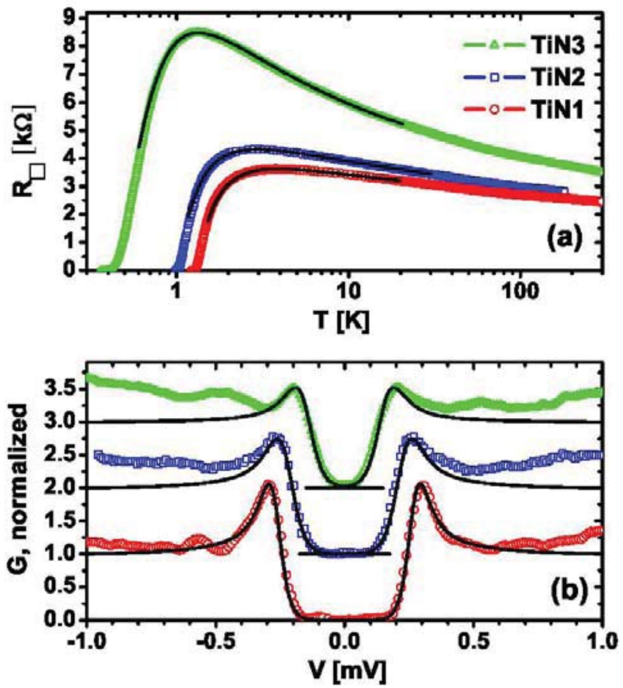


FIG. 1: (a) Sheet resistance $R_\square$ versus temperature for three samples. The solid lines are fits according to localization-interaction and superconducting fluctuations corrections. The legend of panel (a) describes the two panels. (b) Normalized differential tunneling conductance measured at $T = 50\,\mathrm{mK}$ (dots). Spectra are shifted for clarity. The BCS fits (solid lines) were calculated with the following parameters: TiN1 - $\Delta = 260\ \mu\mathrm{eV}$ and an effective temperature $T_{eff} = 0.25\,\mathrm{K}$; TiN2 - $\Delta = 225\ \mu\mathrm{eV}$, $T_{eff} = 0.32\,\mathrm{K}$; TiN3 - $\Delta = 154\ \mu\mathrm{eV}$, $T_{eff} = 0.35\,\mathrm{K}$.

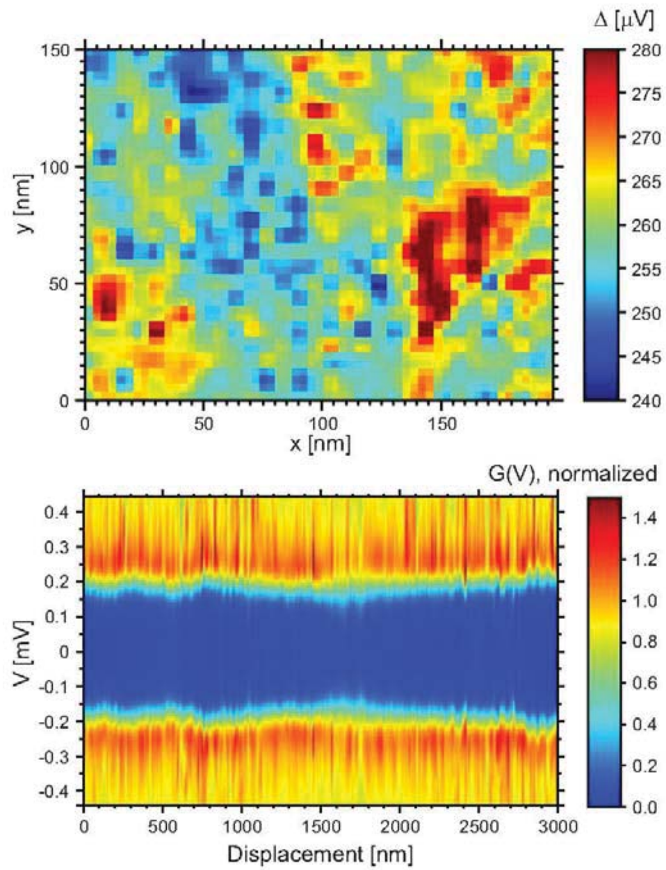


FIG. 2: Top: The colour map of spatial fluctuations of Δ on TiN1. Inhomogeneities of the superconducting properties show up on a scale of a few tens of nanometers. Bottom: Spectra measured along a straight line on TiN2. The BCS-like LDOS fluctuates symmetrically around the Fermi level.

Theory predictions:

Ghosal, Randeria, Trivedi,

PRL ('98), PRB ('01)

Dubi, Meir, Avishai

Nature ('07)

Experiment on TiN: PRL 101, 157006 (2008)

B. Sacepe, C. Chapelier, T. I. Baturina, V.M. Vinokur, M.R. Baklanov, and M. Sanquer

Phenomenology of Josephson networks

conductance of an artificial Josephson junction array

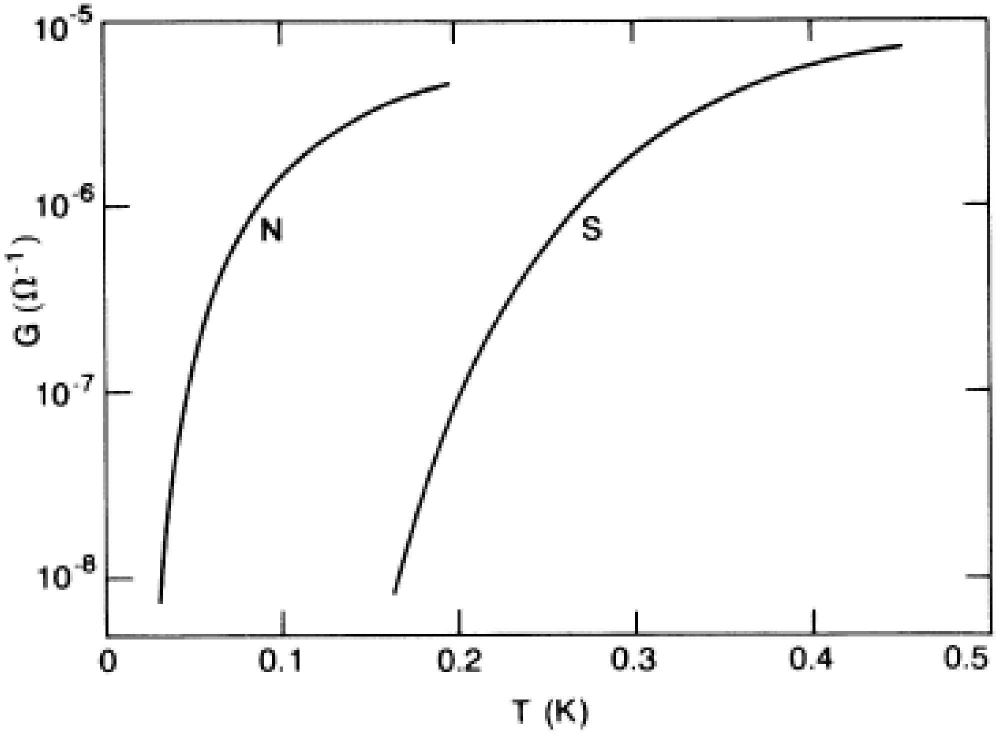


FIG. 3. Measured conductance of an array of $(100\ \text{nm})^2$ aluminum tunnel junctions, 190 cells long and 60 cells wide. *N* is in the normal state (magnetic field of 3T applied); *S* in the superconducting state.

The superconducting array turns insulating at higher temperatures !

J. Mooij, B.J. van Wees, L.J. Geerlings, M. Peters, R. Fazio and G. Schön

Phys. Rev. Lett. 65, 645 - 648 (1990)

E. Chow, P. Delsing, D.B. Haviland, PRL 81, 204 (1998).

One-dimensional arrays of small-capacitance Josephson junctions (255, 127, and 63 junctions)

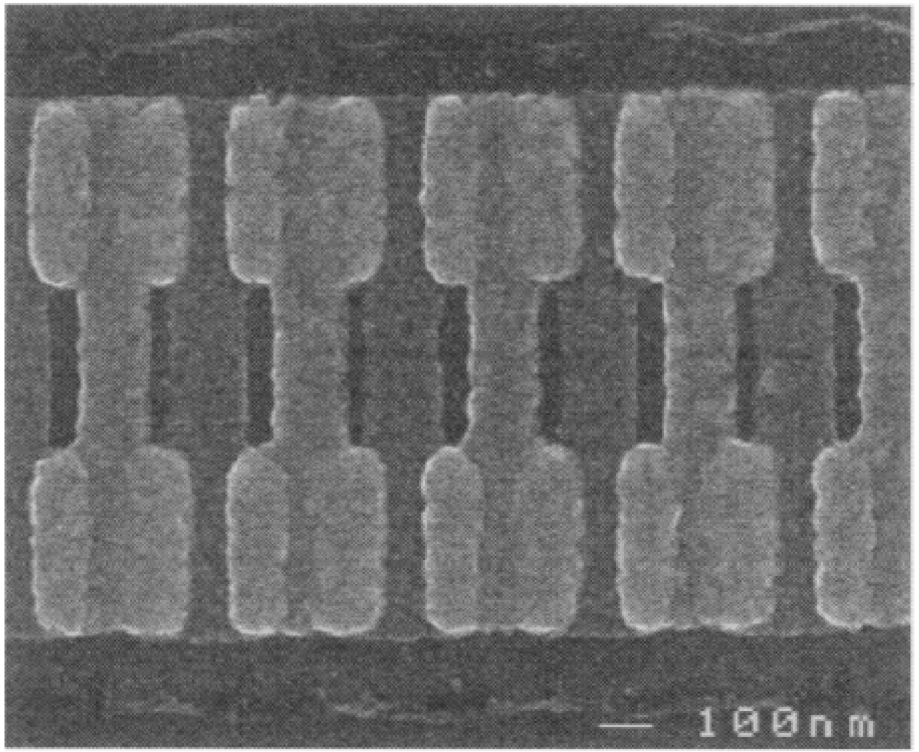


FIG. 1. A scanning electron micrograph of a section of the Josephson junction array. Tunnel junctions are formed at the overlap between the base electrode (darker gray) and the top electrode (lighter gray). The hole between neighboring electrodes forms the SQUID geometry.

$Al/Al_2O_3/Al$ tunnel junctions

$A_{\text{loop}} = 0.12\ \mu\text{m}^2$ is the effective area of the SQUID loop.

$A \simeq 0.039\ \mu\text{m}^2$ is junction area

$R_T = 4.9\ \text{k}\Omega \pm 6\%$

$C \simeq 3.5\ \text{fF}$

electrostatic screening length

$\Lambda \equiv (C/C_0)^{1/2} \simeq 10$

$E_{J0}/E_C \simeq 142\ \mu\text{eV}/23\ \mu\text{eV} = 6.1$

$E_J = E_{J0}|\cos \pi B A_{\text{loop}}/\Phi_0|$

1-d JJ – arrays show similar phenomenology !

super-conducting state at low B-fields

insulating state at intermediate B-fields

cusp-like B-dependence of threshold voltage in insulating regime

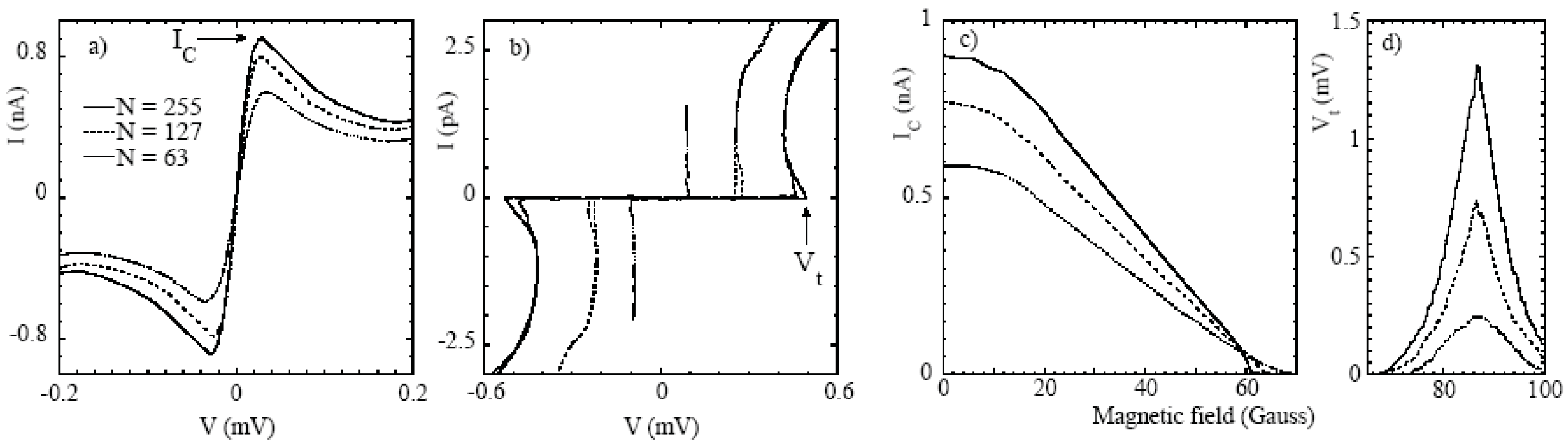
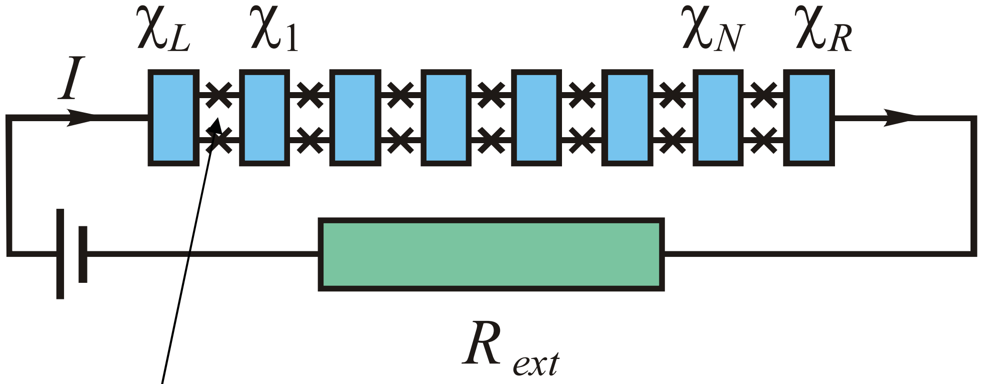


FIG. 2. Dependence of the I-V curves on array length, N, $T = 50$ mK. (a) The I-V curves at $B = 0$ G showing Josephson-like behavior and the critical current I_C. (b) The I-V curves at $B = 71$ G showing the Coulomb blockade of Cooper-pair tunneling and the threshold voltage V_t. (c) The magnetic field dependence of I_C. (d) The magnetic field dependence of V_t.

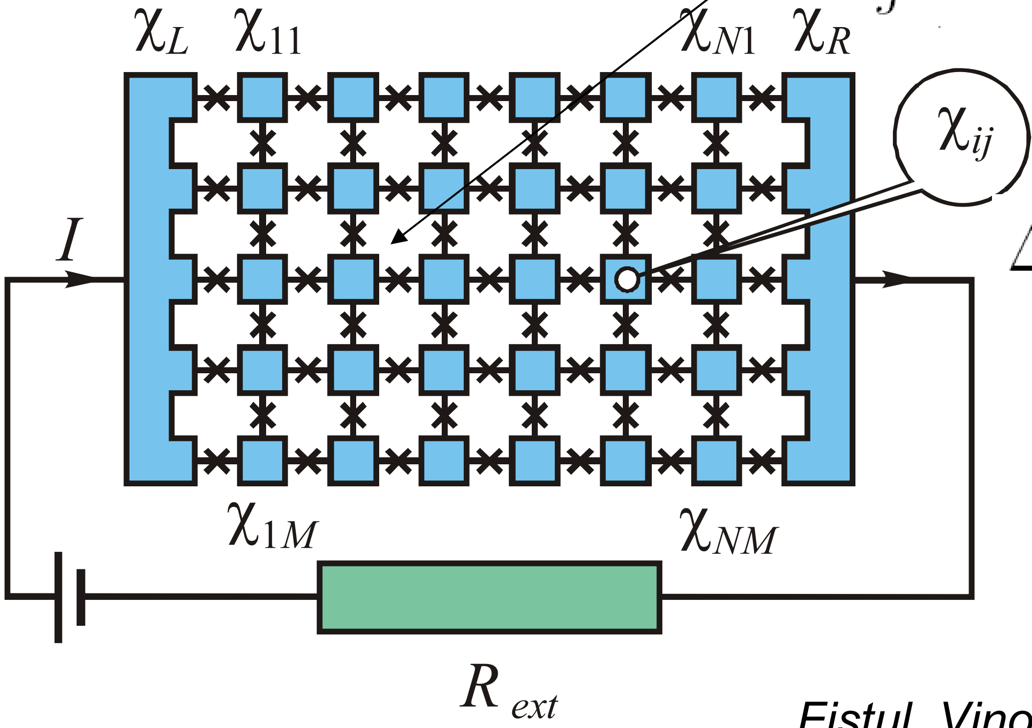
formation of a collective charging energy?

$$E_J^{1D} = E_{J0}|\cos(\pi f)|$$



$$f = eBA_{loop}/\pi h$$

$$E_J^{2D} = E_{J0}\{1 - 4f\sin^2[\pi(1-f)/4]\}$$



$$\Delta_c(B) = \Delta_c[1 - \alpha E_J(B)/E_c]$$
$$\alpha E_{J0}/E_c = 0.8$$

Δ_c : collective charging energy

Fistul, Vinokur, Baturina, PRL **100**, 086805 (2008)

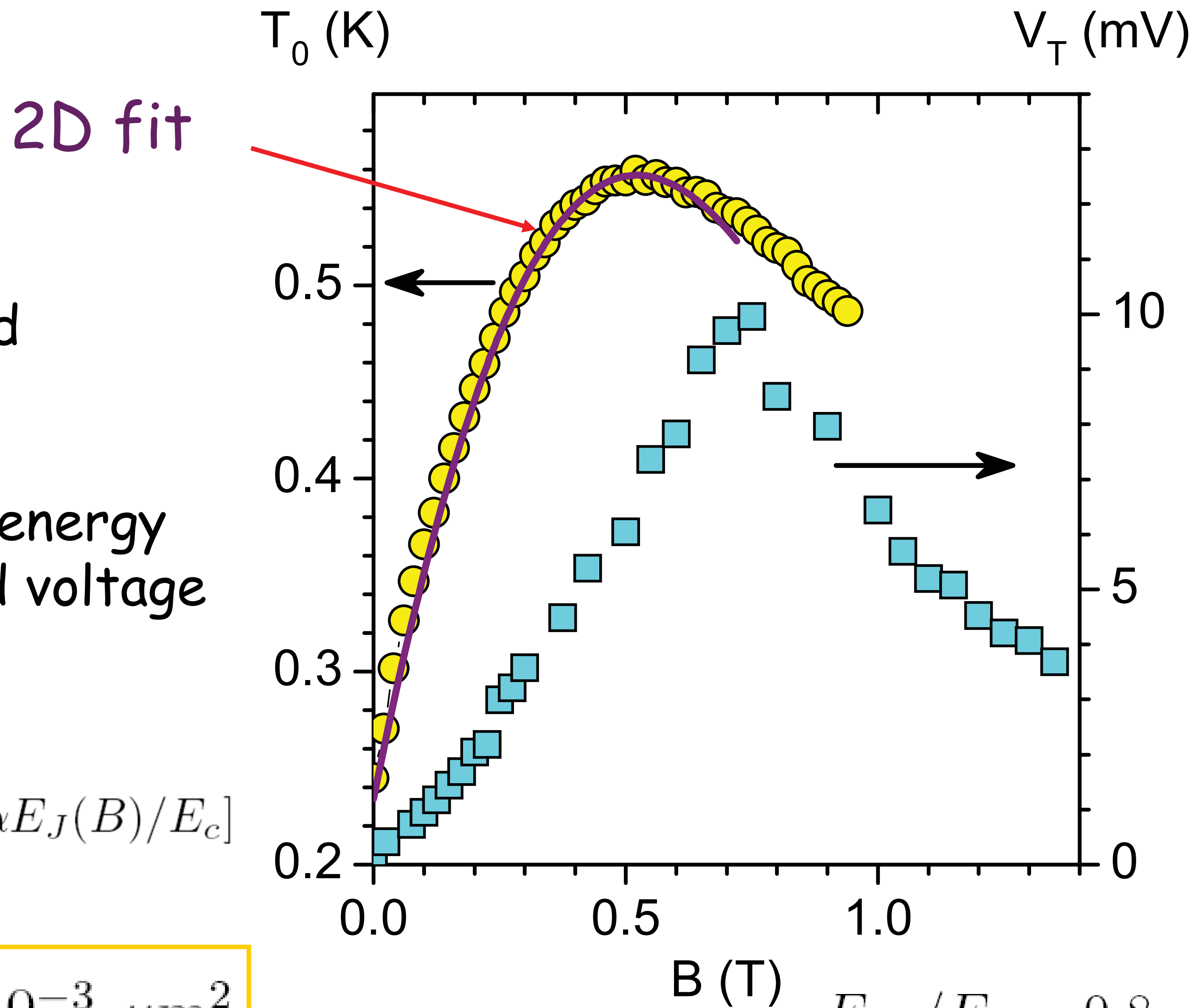
Data on TiN

magnetic field dependence

of activation energy and threshold voltage

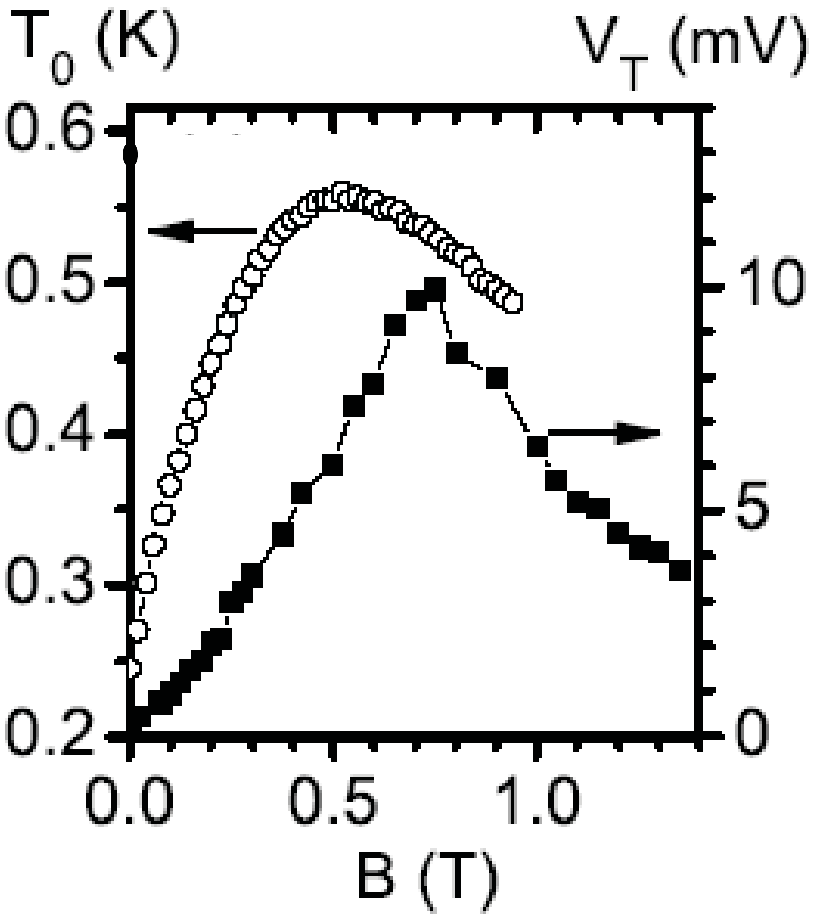
$$\Delta_c(B) = \Delta_c[1 - \alpha E_J(B)/E_c]$$

$$A_{loop} = 1.4 \cdot 10^{-3}\ \mu\text{m}^2$$



$$\alpha E_{J0}/E_c = 0.8$$

Observation:
threshold voltage much larger than activation energy



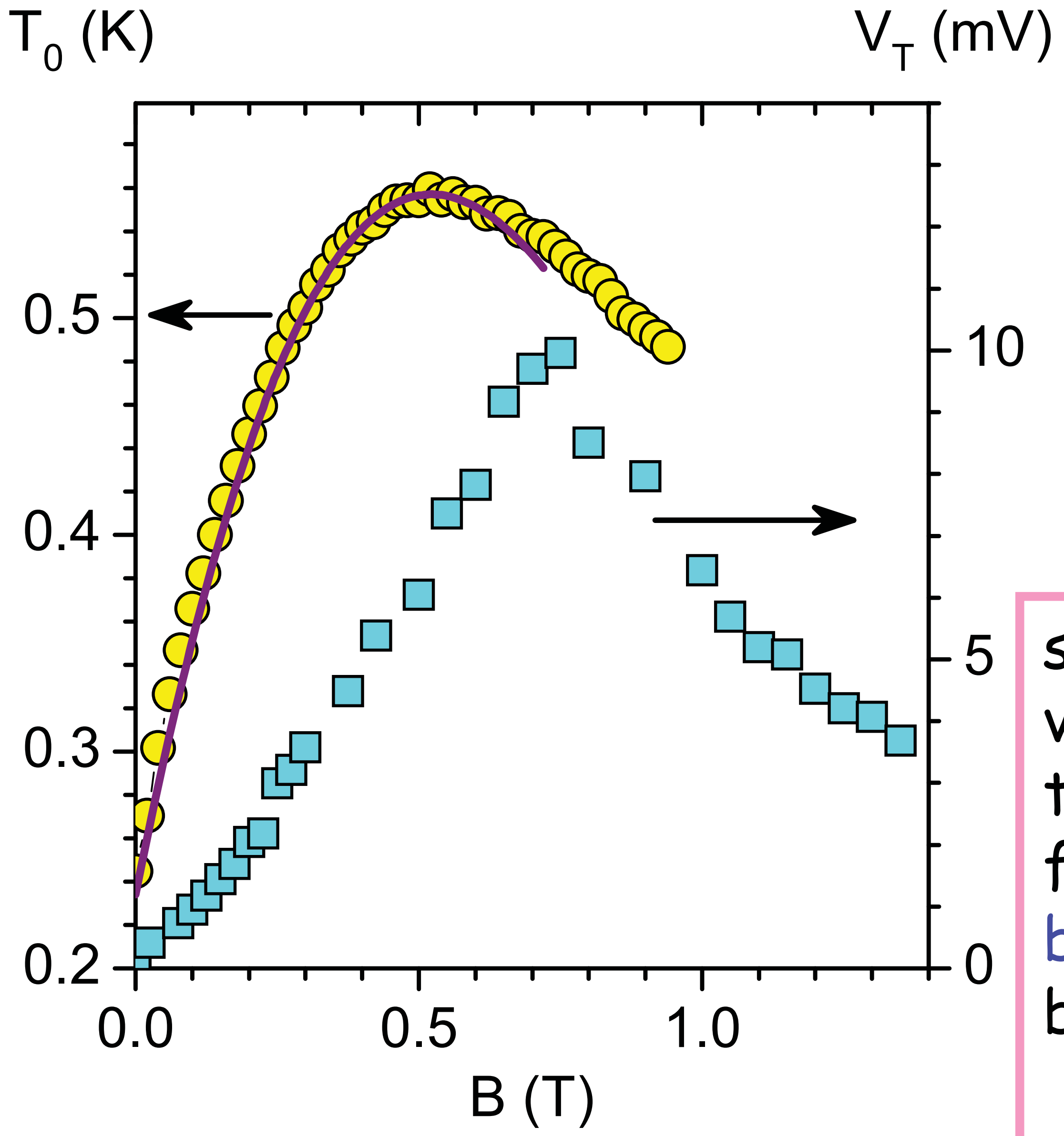
$$\frac{eV_T}{k_B T} \approx 220 \quad \text{at B=0.7T}$$

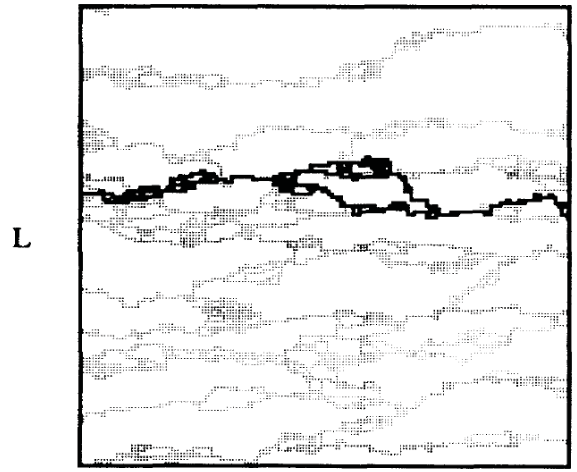
does V_T result from electron heating?

Why do maxima occur at different B-field then?

Magnetic field dependence

$$\Delta_c(B) = \Delta_c[1 - \alpha E_J(B)/E_c]$$





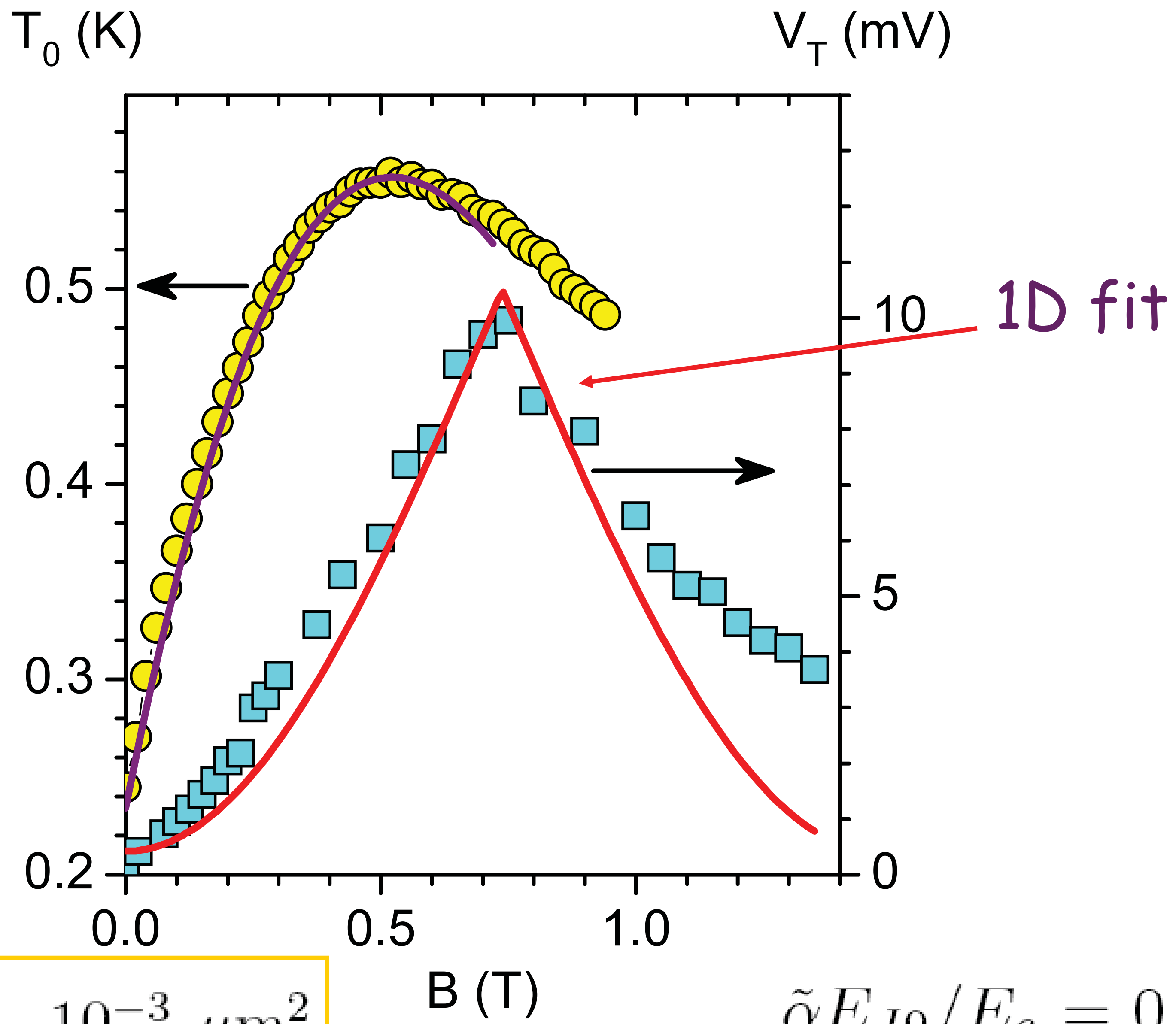
A. Middleton et al., PRL ,94

second possibility: voltage depinning threshold results from dielectric breakdown determined by the weakest path.

1D behavior!

Magnetic field dependence

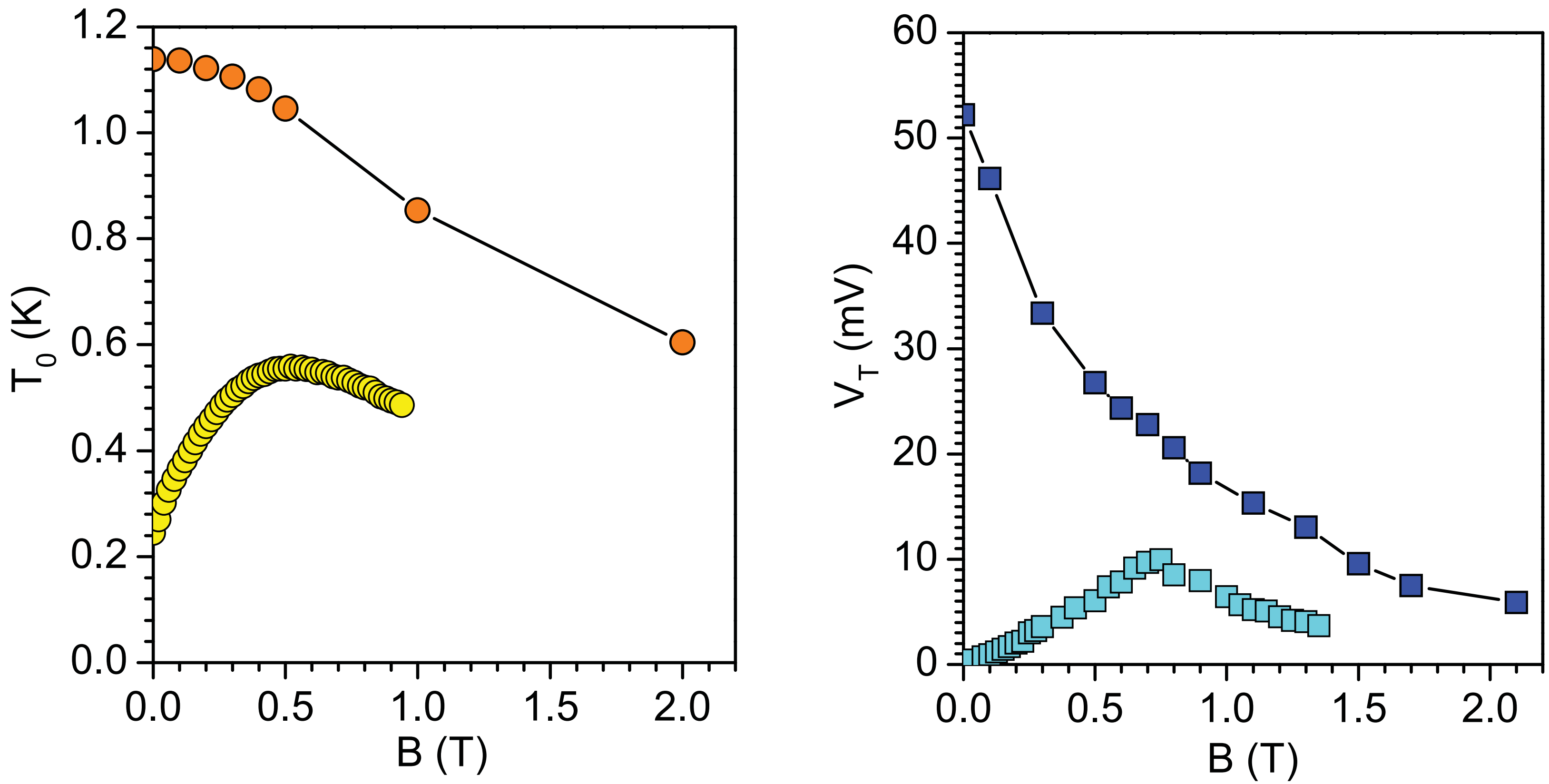
$$\Delta_c(B) = \Delta_c[1 - \alpha E_J(B)/E_c]$$



$$A_{loop} = 1.4 \cdot 10^{-3}\ \mu\mathrm{m}^2$$

$$\tilde{\alpha} E_{J0}/E_c = 0.96$$

Compare samples deeper in the insulating regime



positive magnetoresistance and initial rise of T_0 and V_T disappear

$T_0(B)$: horizontal slope; $V_T(B)$: finite slope

Characteristics of the JJ-network model

- activated conductivity

$$T > T_{SI} = E_c / k_B$$

$$R \propto \exp[\Delta_c / (2k_B T)]$$

- collective Coulomb energy:

$$\Delta_c = \begin{cases} E_c N/2, & 1D \\ E_c \log N, & 2D \end{cases}$$

N : number of islands

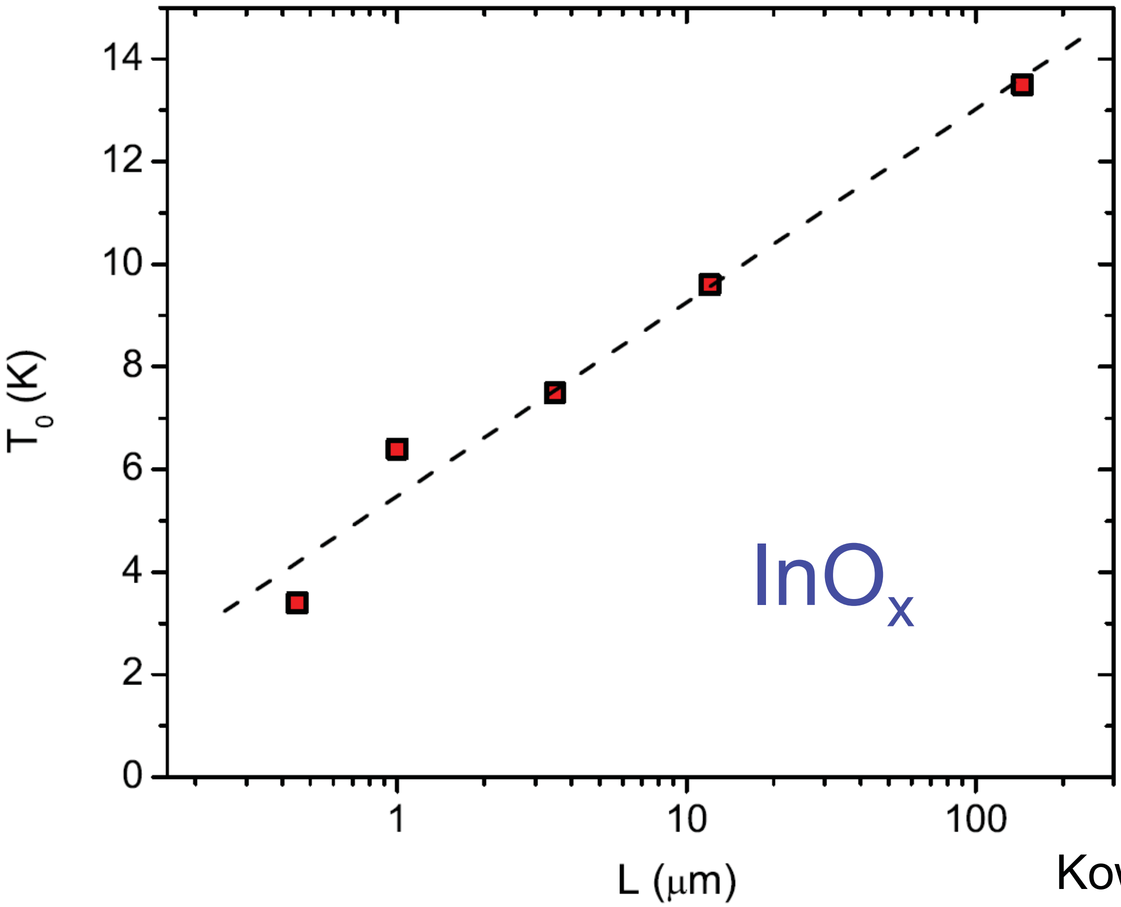
$$N = \min\left\{\frac{L}{d}, \frac{\lambda}{d}\right\}$$

where λ is screening length

- Threshold voltage depinning, $eV_T \sim E_c L/d$

Fistul, Vinokur, Baturina, PRL **100**, 086805 (2008)

size dependence of thermal activation energy already observed in InO_x-films



Kowal & Ovadyahu (2007)

$$\Delta_c = E_c \log N, \text{ for 2D}$$

At very low temperatures, $T < E_c / k_B$, calculations yield:

$$R \propto \exp\left\{\frac{\Delta_c}{E_c}\exp\left(\frac{E_c}{2k_B T}\right)\right\}$$

What carries the current?

– thermally activated pairs of charge/anti-charge solitons

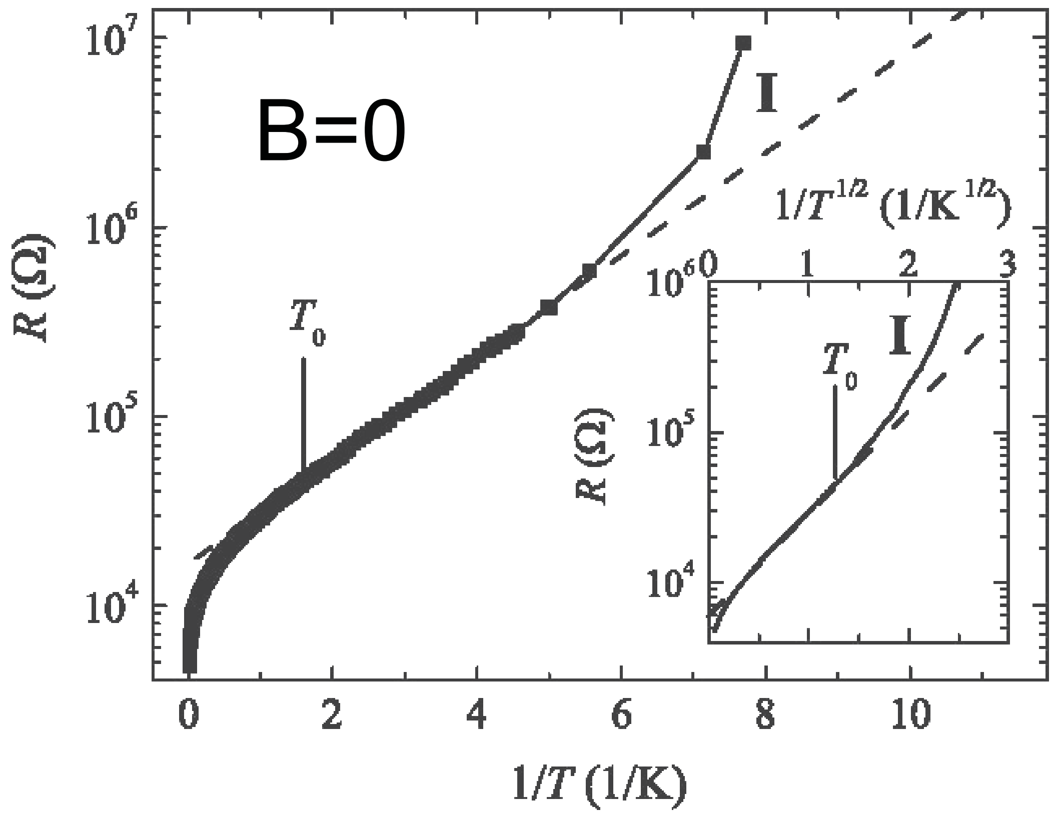
(Josephson coupling smeares charges over several islands)

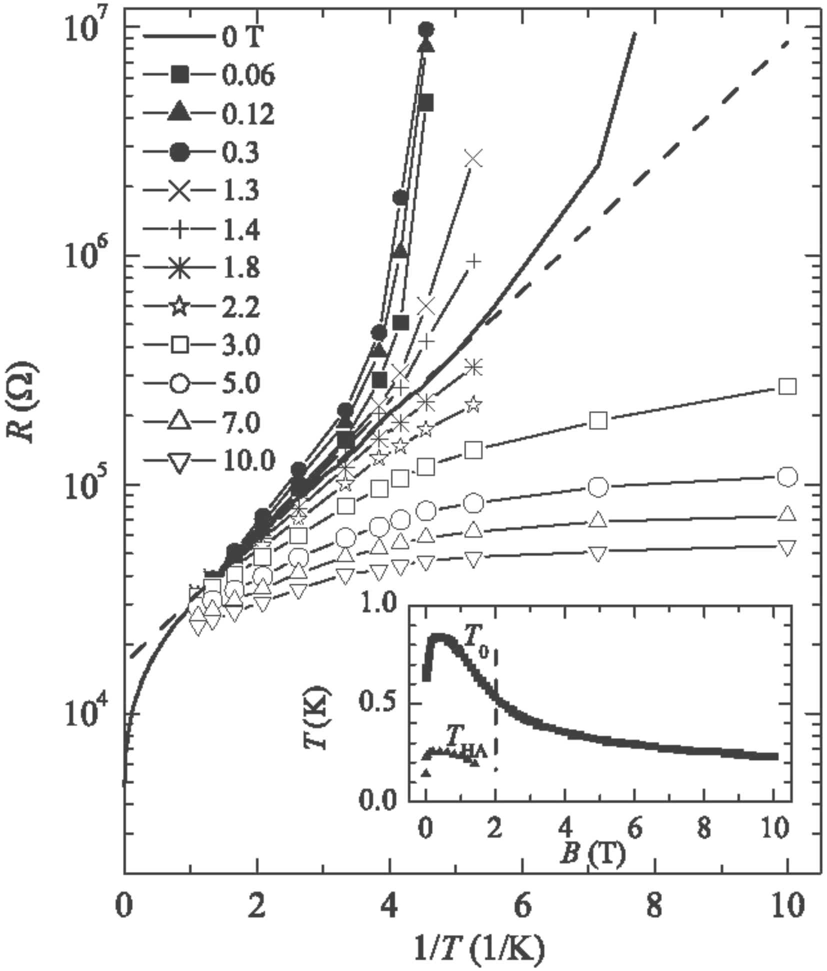
jumps in IV provide no safe evidence

→ search for signatures in linear response regime!

V. M. Vinokur, T. I. Baturina, M. Fistul, A. Yu. Mironov, M. R. Baklanov, and C. Strunk, Nature **452**, 613 (2008)

Experimental evidence for super-exponential behavior





resistance at low T and B grows faster than expected from an Ahrrenius law!

super-exponential behavior in JJ-Arrays

Journal of the Physical Society of Japan
Vol. 64, No. 1, January, 1995, pp. 19–21

Precursor of Charge KTB Transition in Normal and Superconducting Tunnel Junction Array

Akinobu KANDA and Shun-ichi KOBAYASHI

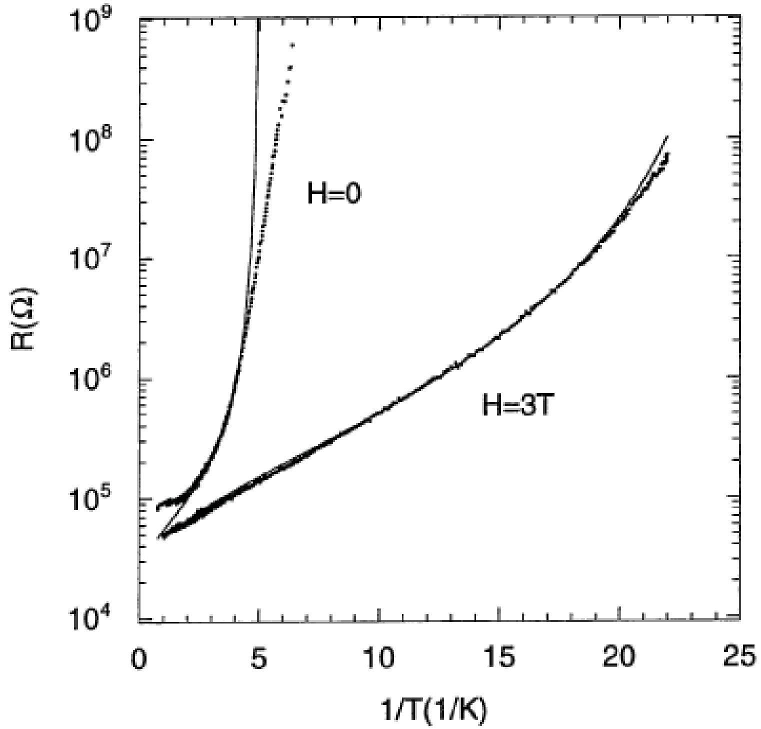


Fig. 1. Resistance at $V=50\,\mu$V as a function of $1/T$ in $H=0$ and 3 T. Solid lines are results of fitting with eq. (1). The values of fitting parameters are $K=1.6$ and $b=1.0$ in $H=0$, and $K=1.6$ and $b=2.2$ in $H=$ 3 T. For the values of T_{KT}, see the text.

The array was 380 junctions in length and 331 junctions in width. Each junction had an area of 0.0072 $(\mu m)^2$, normal-state tunneling resistance $R_N=32\,k\Omega$ and the capacitance $C=1.1\times10^{-15}$ F. The self-capacitance of the island electrode was 5.1×10^{-17} F. The method to estimate these values is described in ref. 7. Consequently, the charging energy $E_C=e^2/2C=0.81$ K, the Josephson coupling energy $E_J=0.31$ K and $\Lambda=5.7$ junctions.

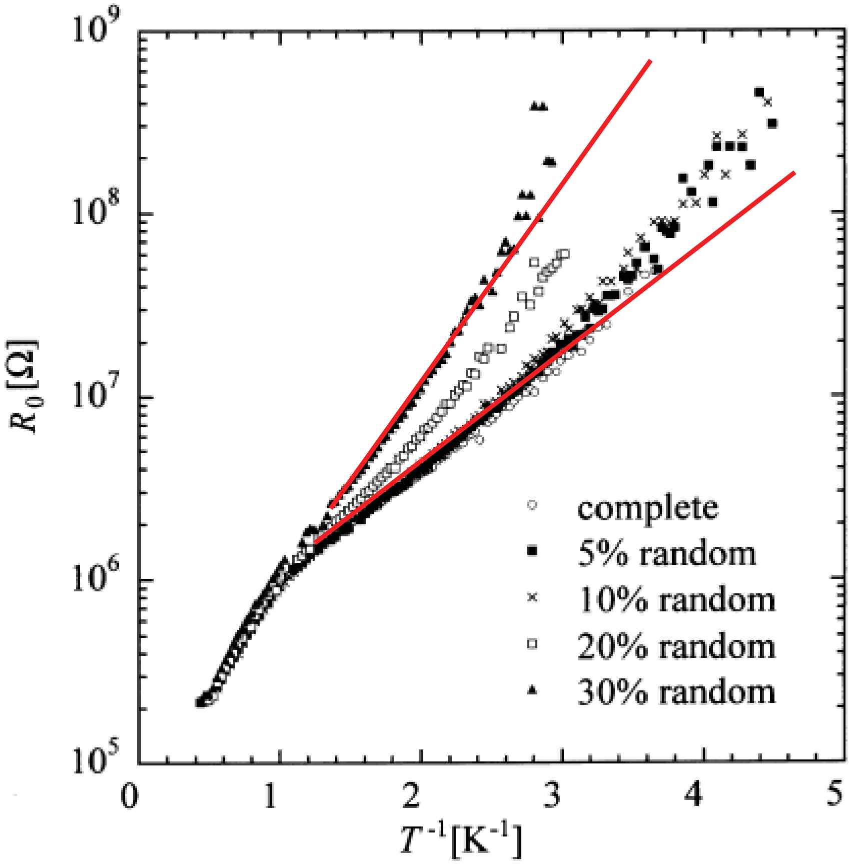
Resistance at low T grows faster than expected from an Ahrrenius law!

Journal of the Physical Society of Japan
Vol. 67, No. 3, March, 1998, pp. 729-731

super-exponential behavior in JJ-arrays

Two-Dimensional Arrays of Small Josephson Junctions with Regular and Random Defects

Takahide YAMAGUCHI, Ryuta YAGI, Shun-ichi KOBAYASHI and Youiti OOTUKA[1]



In the present experiments we also confirmed that the temperature dependence of the array resistance is stronger than the thermal-activation type.

Resistance at low T grows faster than expected from an Ahrrenius law!

Conclusions

- universal ‘quantum metallic’ behavior at high B

- insulating state driven by *collective* charging energy of Cooper-pairs

- evolution from a regular insulator with hopping conductance to novel zero conductance (‘superinsulating’) state at very low T

- non-trivial dependence on magnetic field and sample size

Open Questions

- complete phase diagram?

- existence/origin of island formation ?

- other features complementary to the superconducting state ?

Supported by the DFG

GK 638