Фонд Дмитрия Зимина
Династия

Летняя школа
«Нанофизика низких температур»
20-30 августа 2007

Superconductivity on the Localization Threshold & Superconductor-Insulator quantum phase transition

Experiment

Tatyana Baturina

Concrete address

- ✓ Superconducting
- ✓ Disordered

$$T\tau \ll 1$$

- ✓ Two-dimensional systems

quasi-2D → electronic spectrum is 3D

$$l,\ \lambda_F < d < \xi,\ l_T$$

- ✓ Disordered Superconducting Ultra-thin Films

Evolution

weak disorder ↔ strong disorder

metal

Drude conductivity
+
quantum corrections

insulator

thermally activated
or Mott-Efros-Shklovskii-like
behavior of conductivity

+
superconductivity
Cooper pairing
attractive interaction

Outline

✓ Quantum corrections to conductivity at $T > T_c$

✓ Fermionic and Bosonic Models

✓ Suppression of Superconductivity by Disorder

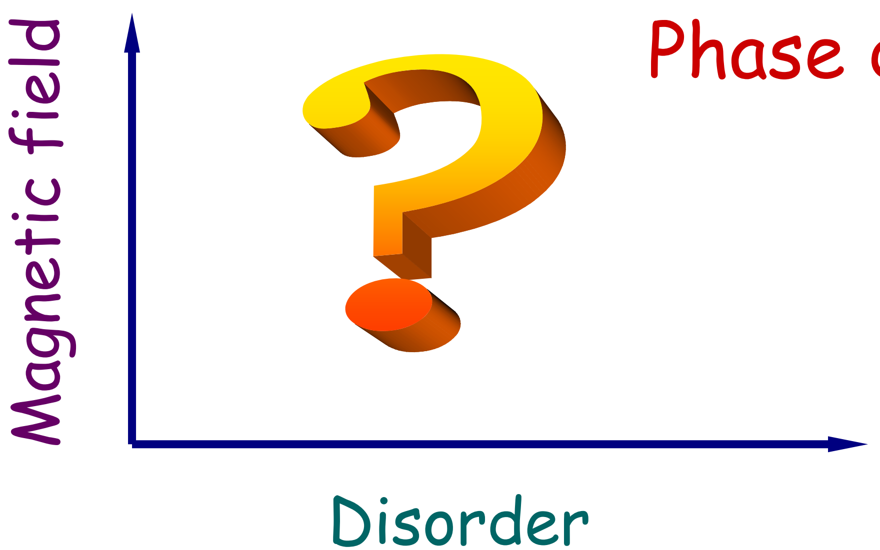
- Superconductor – Metal – Insulator transition (SMIT)

- Superconductor – Insulator transition (SIT)

✓ Suppression of Superconductivity by Magnetic field

- Evolution from Superconductor – Metal transition (SMT) to Superconductor – Insulator transition (SIT)

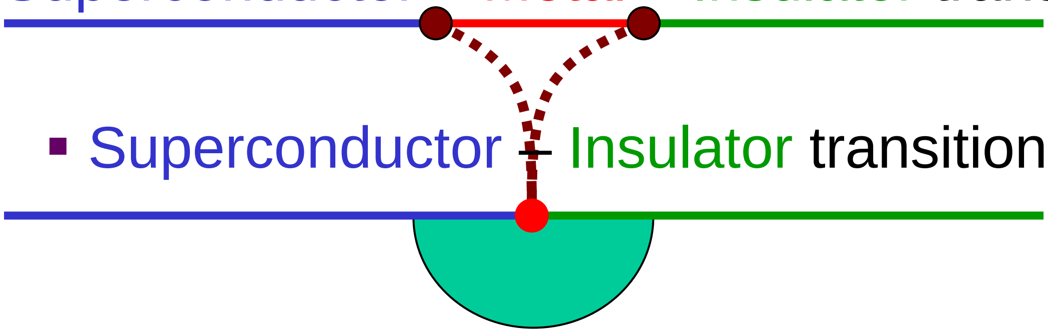
Phase diagram



Outline

✓ Suppression of Superconductivity by Disorder

- Superconductor – Metal – Insulator transition (SMIT)



- Superconductor – Insulator transition (SIT)

Critical Region
of the Disorder-Driven
Superconductor-Insulator
quantum phase transition

Quantum corrections to conductivity

one-particle interference

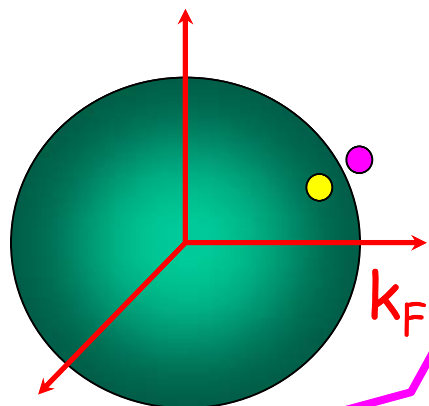
Weak Localization

Aronov - Altshuler

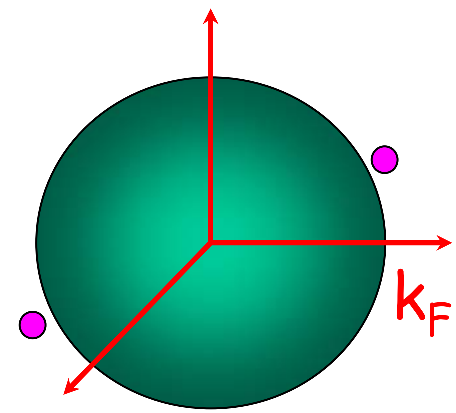
two-particle interference

(e-e interaction)

Diffusion Channel



Cooper Channel



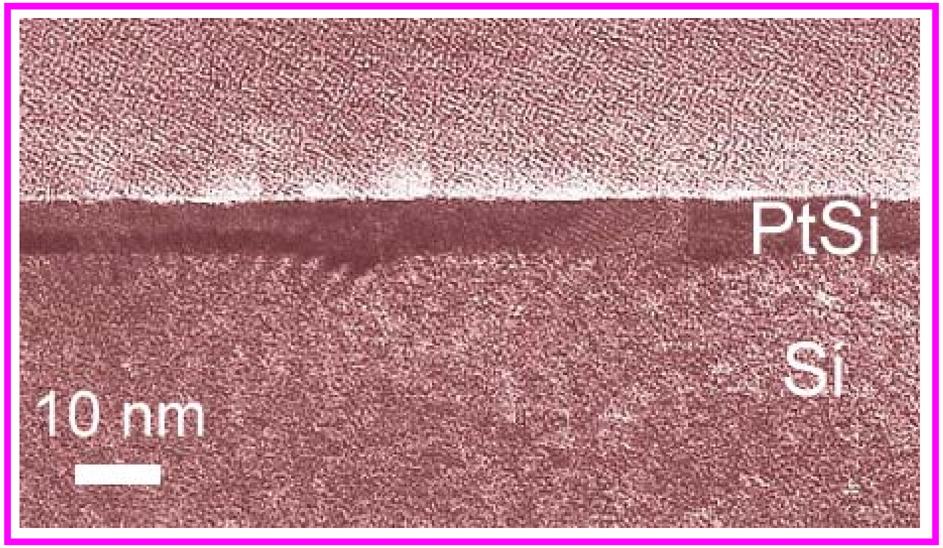
Aslamasov - Larkin

Density–Of-States

Maki - Thompson

Superconducting fluctuations

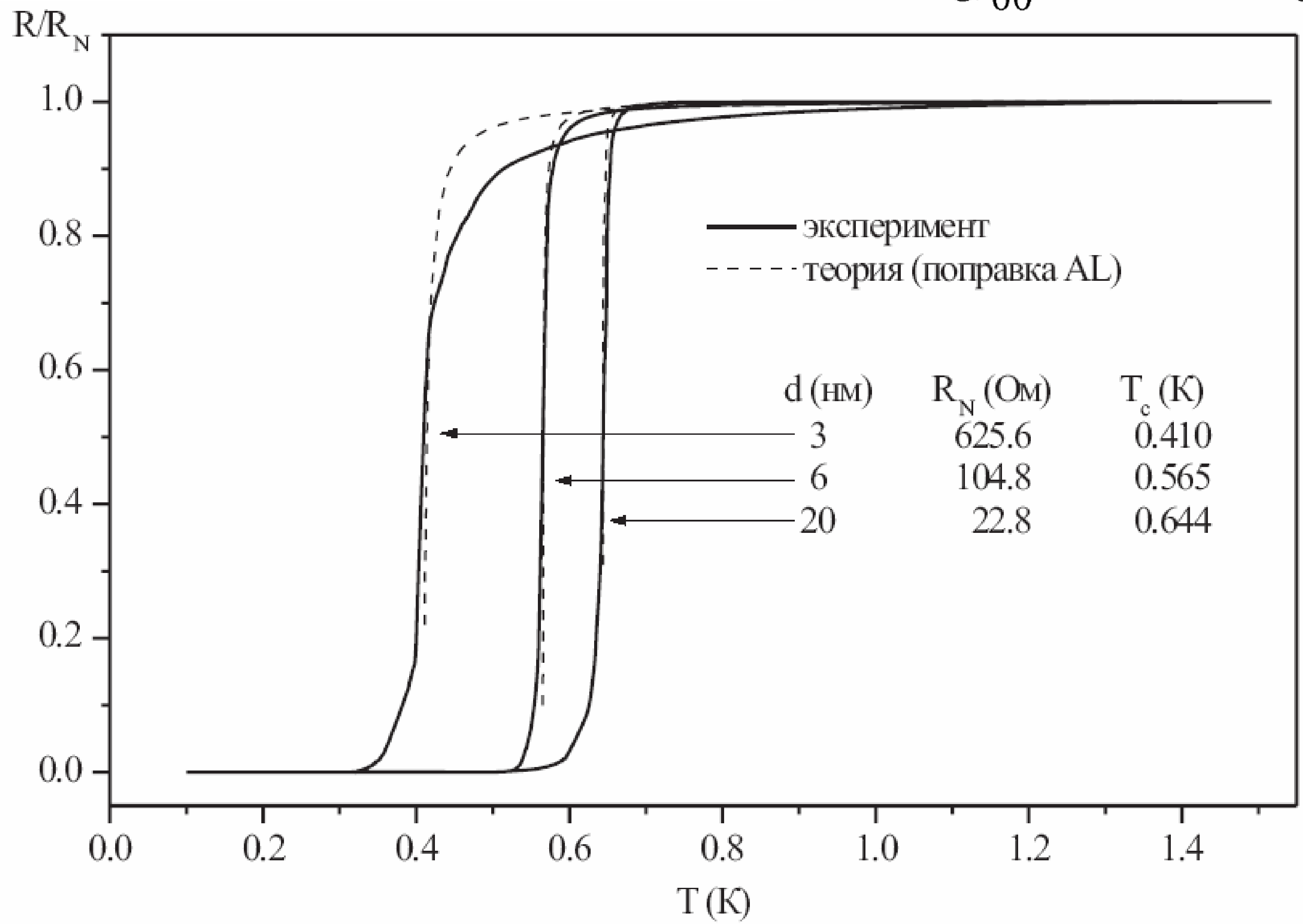
The basic parameters of the PtSi films



d нм	$R_\square$ Ом	n 10^{22} см$^{-3}$	k_F 10^8 см$^{-1}$	E_F эВ	$\rho(E_F)$ 10^{46} Дж$^{-1}$м$^{-3}$	τ 10^{-16} с	$k_F l$	l нм	D см^2/с
3	625.6	3.6	1.0	4.0	8.5	5.3	6.4	0.6	2.5
6	104.8	7.0	1.3	6.1	10.7	8.2	15.4	1.2	5.9
20	22.8	9.4	1.4	7.5	11.7	8.2	18.7	1.3	7.2

R(T) at B = 0

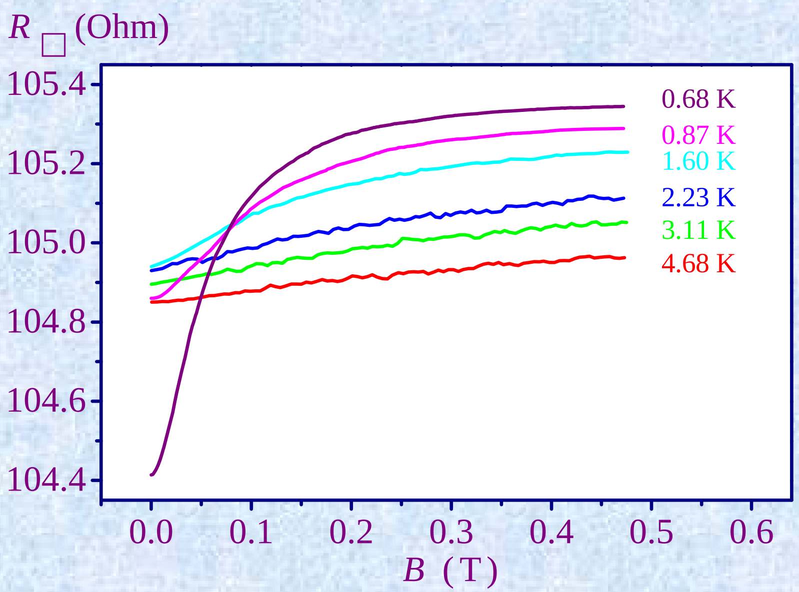
$$\frac{\Delta G^{AL}(T)|_{T\to T_c}}{G_{00}} = \frac{\pi^2}{8}\frac{T}{T - T_c}$$



$$G_{00} = e^2/(2\pi^2\hbar)$$

$$\Delta R(T) \approx R^2 \Delta G(T)$$

Magnetoresistance $R(B, T = T_i)$



WL

$$\frac{\Delta G^{WL}(B)}{G_{00}} = \alpha \cdot Y\left(\frac{4eB}{\hbar} l_\varphi^2\right)$$

$$G_{00} = e^2 / 2\pi^2\hbar$$

$$Y(x) = \ln(x) + \Psi\left(\frac{1}{2} + \frac{1}{x}\right)$$

where $\Psi(z)$ is the digamma function

$\alpha = 1$, if $\tau_\varphi << \tau_{so}$ → negative MR

$\alpha = -1/2$, if $\tau_\varphi >> \tau_{so}$ → positive MR

MT

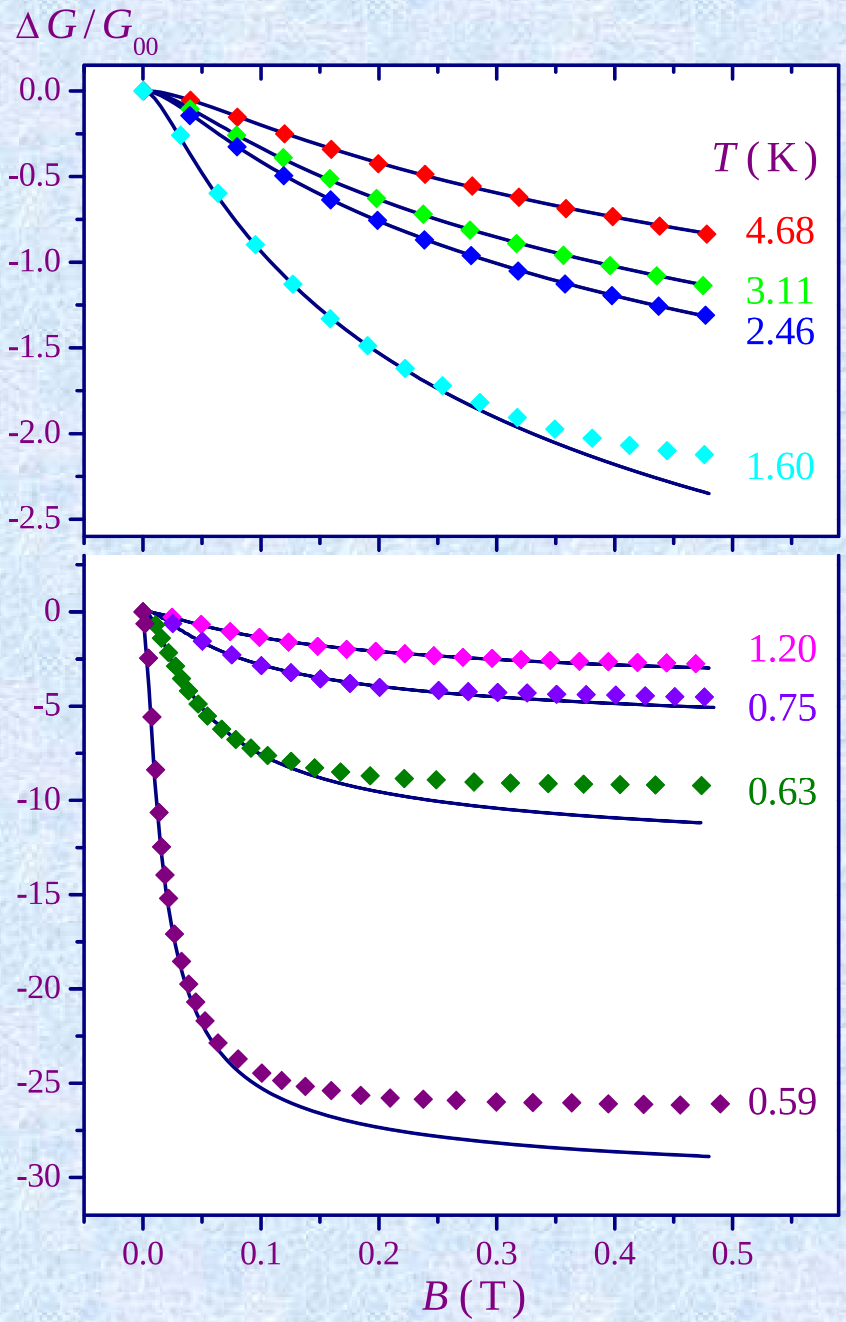
A.I. Larkin (1980)

$$\frac{\Delta G^{MT}(B)}{G_{00}} = -\beta(T) \cdot Y\left(\frac{4eB}{\hbar} l_\varphi^2\right)$$

Restrictions: $\ln\frac{T}{T_c} \gg \frac{\hbar}{k_B T \tau_\varphi}$, $B \ll \frac{k_B T}{4De} \ln\frac{T}{T_c}$

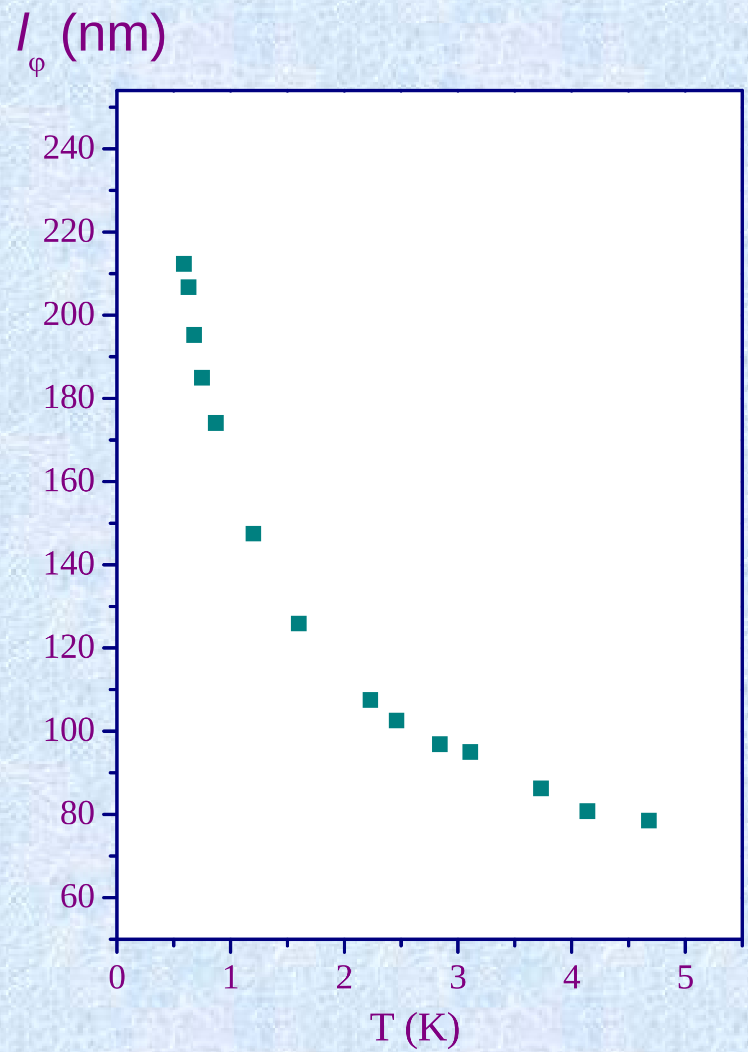
Lopes dos Santos and Abrahams (1985)

$$\frac{\Delta G^{MT}(B)}{G_{00}} = -\beta(T, \tau_\varphi) \cdot \left[Y\left(\frac{4eB}{\hbar} l_\varphi^2\right) - Y\left(\frac{\pi DeB}{2k_B T \ln(T/T_c)}\right) \right]$$

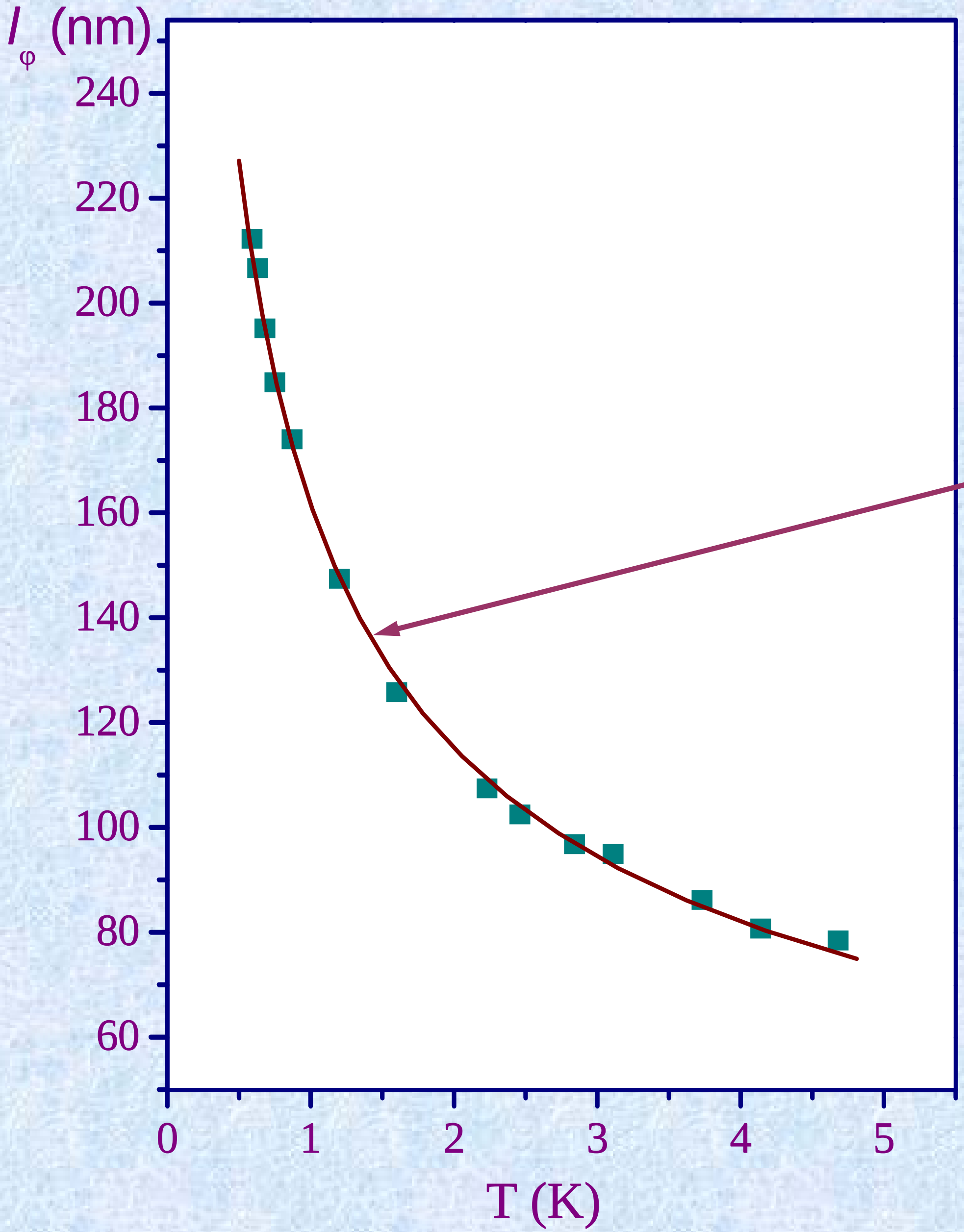


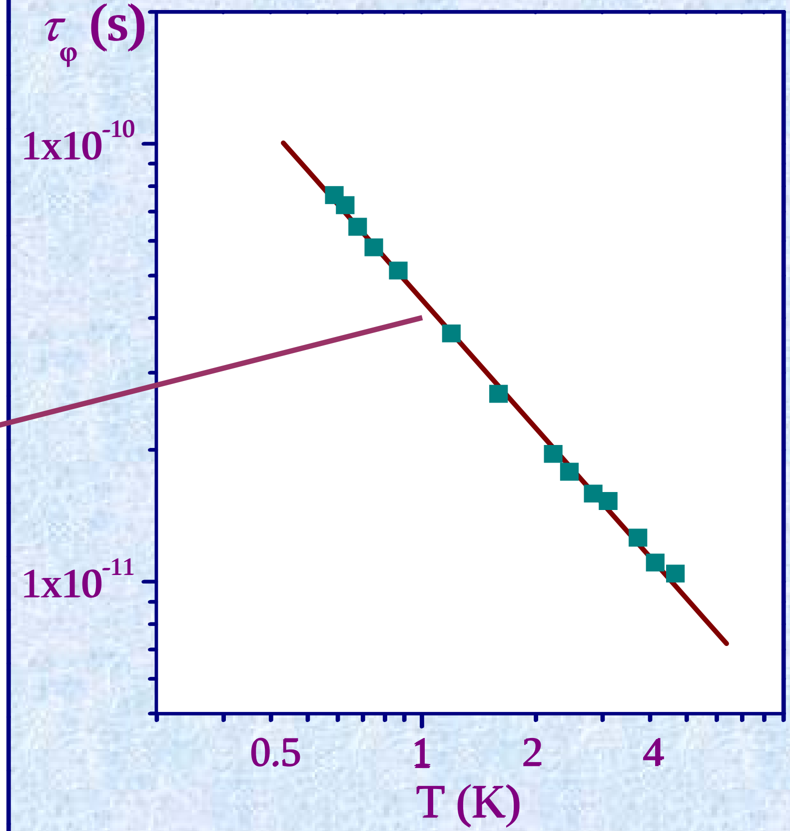
$$\Delta G(B) / G_{00} = (2\pi^2\hbar / e^2)[1/R(B) - 1/R(0)]$$

$$G_{00} = e^2 / 2\pi^2\hbar$$



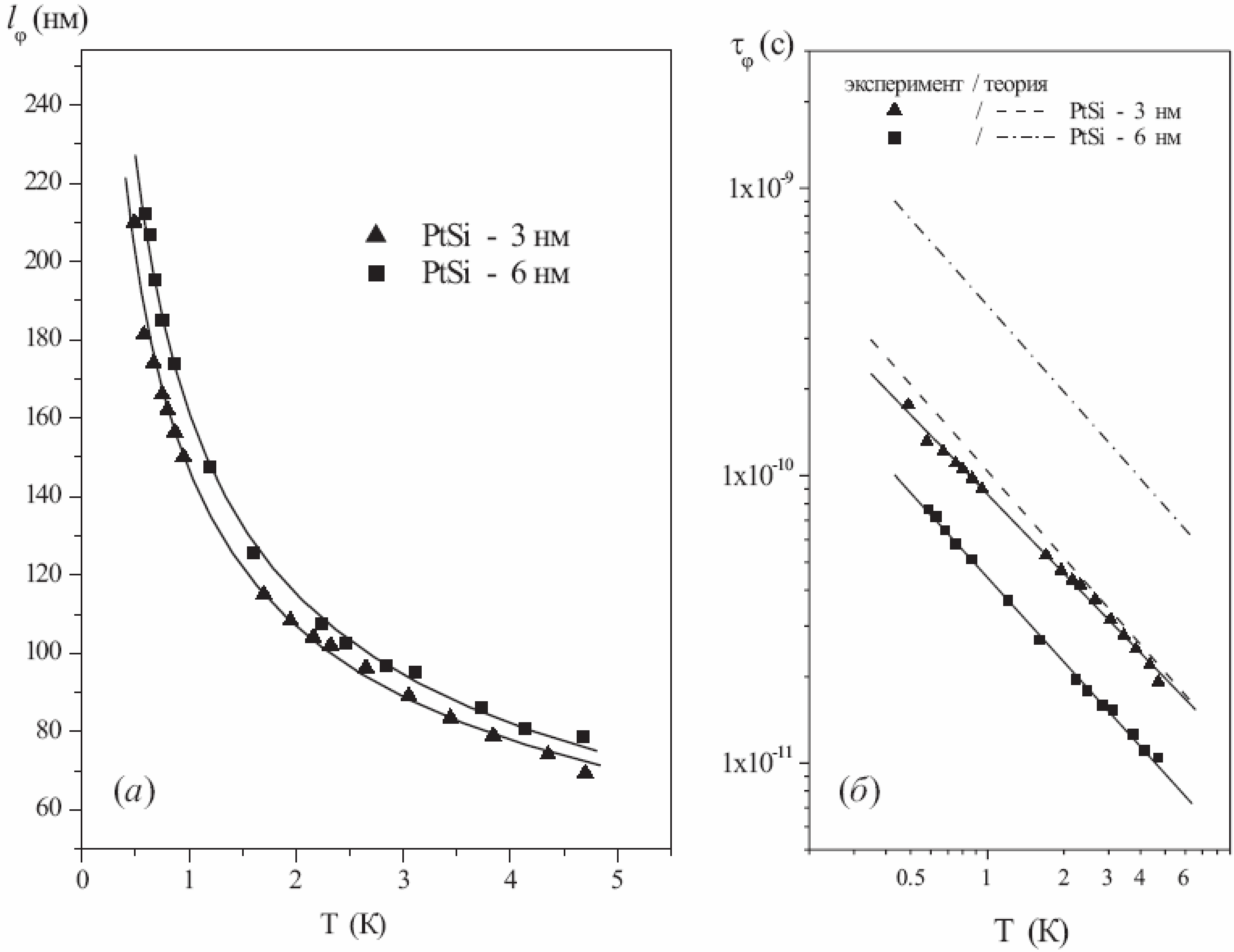
$$\tau_\varphi = l_\varphi^2 / D$$





$$\tau_\varphi \propto T^{-p} \rightarrow p = 0.98$$

$$\tau_\varphi^{-1} = \frac{\pi k T}{\hbar} \frac{e^2 R_\square}{2\pi^2 \hbar} \ln \frac{\pi \hbar}{e^2 R_\square}$$



l_φ (нм)
240
220
200
180
160
140
120
100
80
60
0
1
2
3
4
5
T (K)
PtSi - 3 нм
PtSi - 6 нм
(а)
τ_φ (с)
эксперимент / теория
/ PtSi - 3 нм
/ PtSi - 6 нм
1x10^{-9}
1x10^{-10}
1x10^{-11}
0.5
1
2
3
4
6
T (K)
(б)

R(T) at B = 0

$$G_{00} = e^2/(2\pi^2\hbar)$$

$$\frac{\Delta G^{WL}(T)}{G_{00}} = \alpha p \ln\left(\frac{kT\tau}{\hbar}\right) \qquad \frac{\Delta G^{ID}(T)}{G_{00}} = \left[4 - 3\frac{2+F}{F}\ln\left(1+\frac{F}{2}\right)\right]\ln\left(\frac{kT\tau}{\hbar}\right)$$

$$\frac{\Delta G^{WL+ID}(T)}{G_{00}} = A\ln\left(\frac{kT\tau}{\hbar}\right)$$

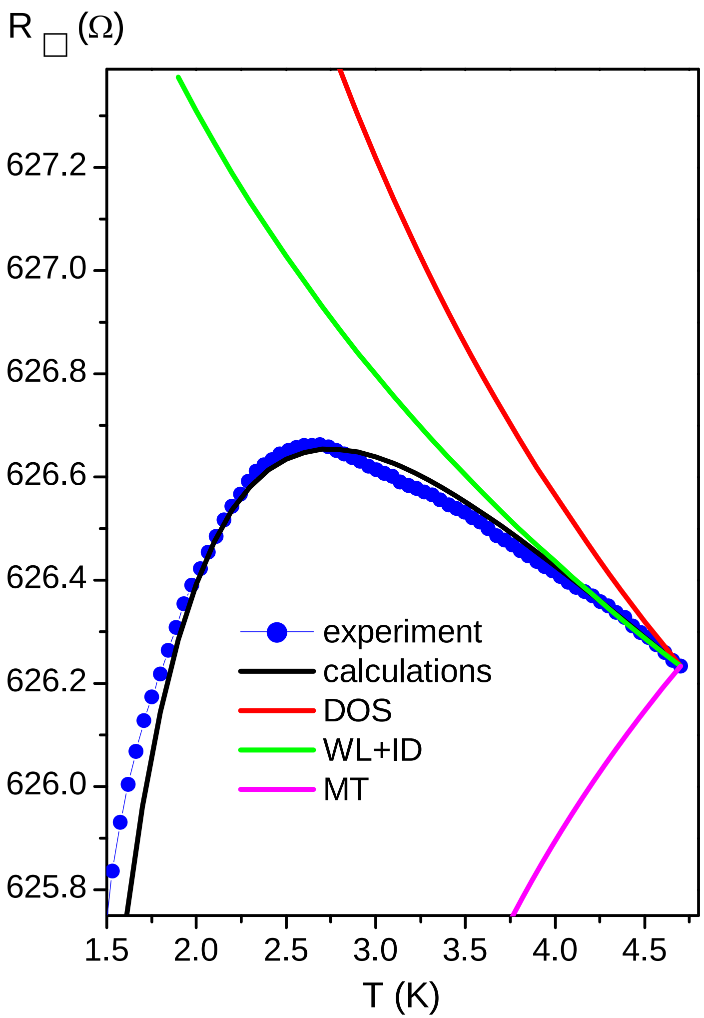
$$\frac{\Delta G^{DOS}(T)}{G_{00}} = \ln\left[\frac{\ln(T_c/T)}{\ln(kT_c\tau/\hbar)}\right] \qquad \frac{\Delta G^{AL}(T)|_{T\to T_c}}{G_{00}} = \frac{\pi^2}{8}\frac{T}{T-T_c}$$

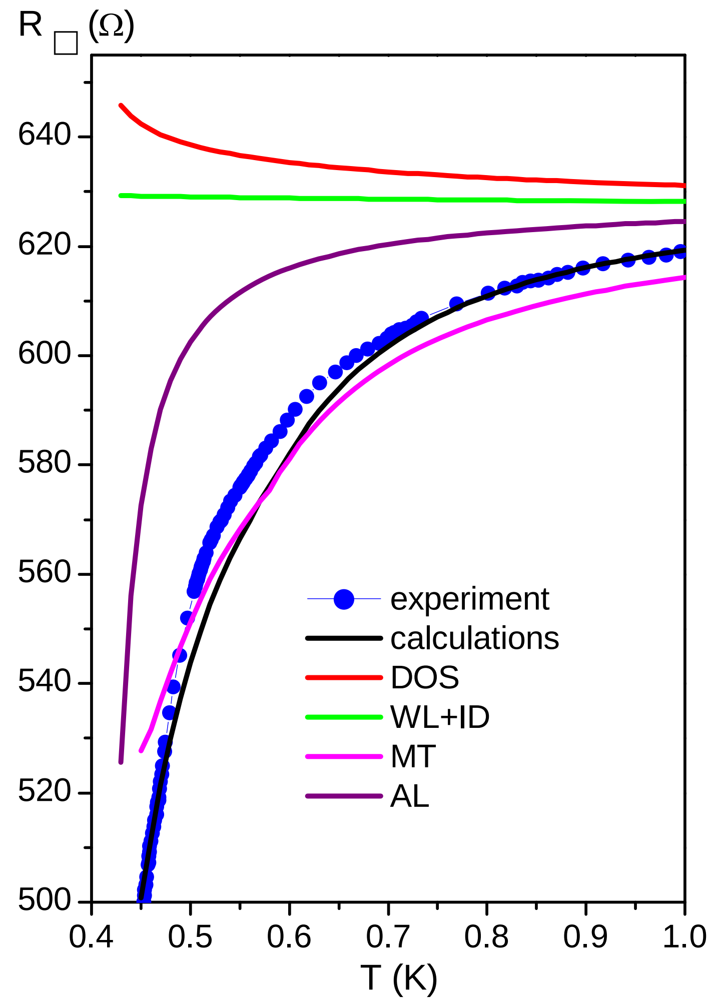
$$\frac{\Delta G^{MT}(T)|_{T\gg T_c}}{G_{00}} = \beta(T)\ln\left(\frac{kT\tau_\varphi}{\hbar}\right) \qquad \frac{\Delta G^{MT}(T)}{G_{00}} = \beta(T,\tau_\varphi)\ln\left(\frac{\ln(T/T_c)}{\delta}\right)$$

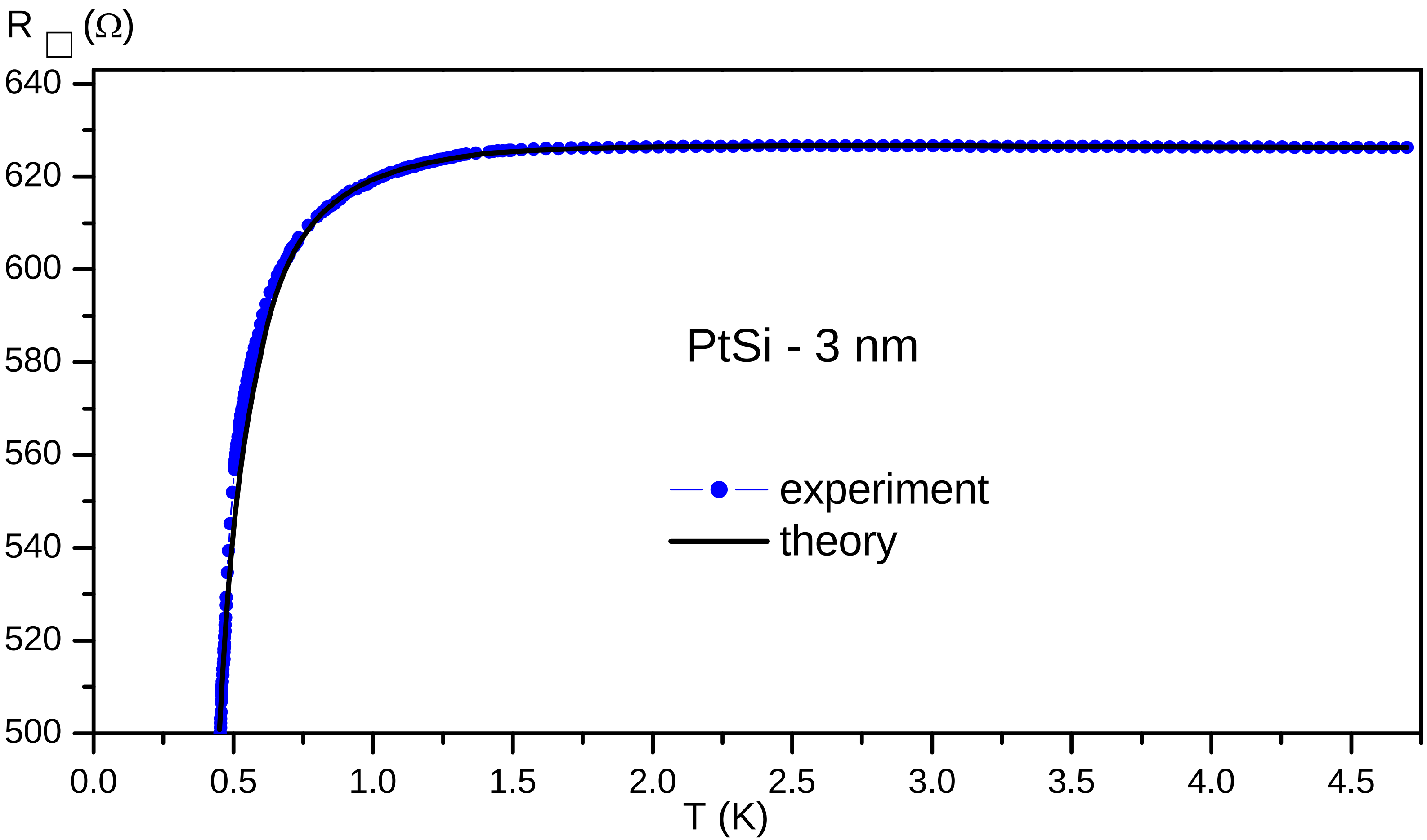
$$\delta = \frac{\pi\hbar}{8kT\tau_\varphi}$$

$T_c < T < \hbar(k\tau_\varphi)^{-1}$	|	AL
$\hbar(k\tau_\varphi)^{-1} < T < 2T_c$	|	MT, AL, DOS, ID, WL
$T > 2T_c$	|	$ID, WL, DOS, MT.$

$$
\begin{array}{rcl}
T_c < T < \hbar(k\tau_\varphi)^{-1} & | & AL \\
\hbar(k\tau_\varphi)^{-1} < T < 2T_c & | & MT, AL, DOS, ID, WL \\
T > 2T_c & | & ID, WL, DOS, MT.
\end{array}
$$

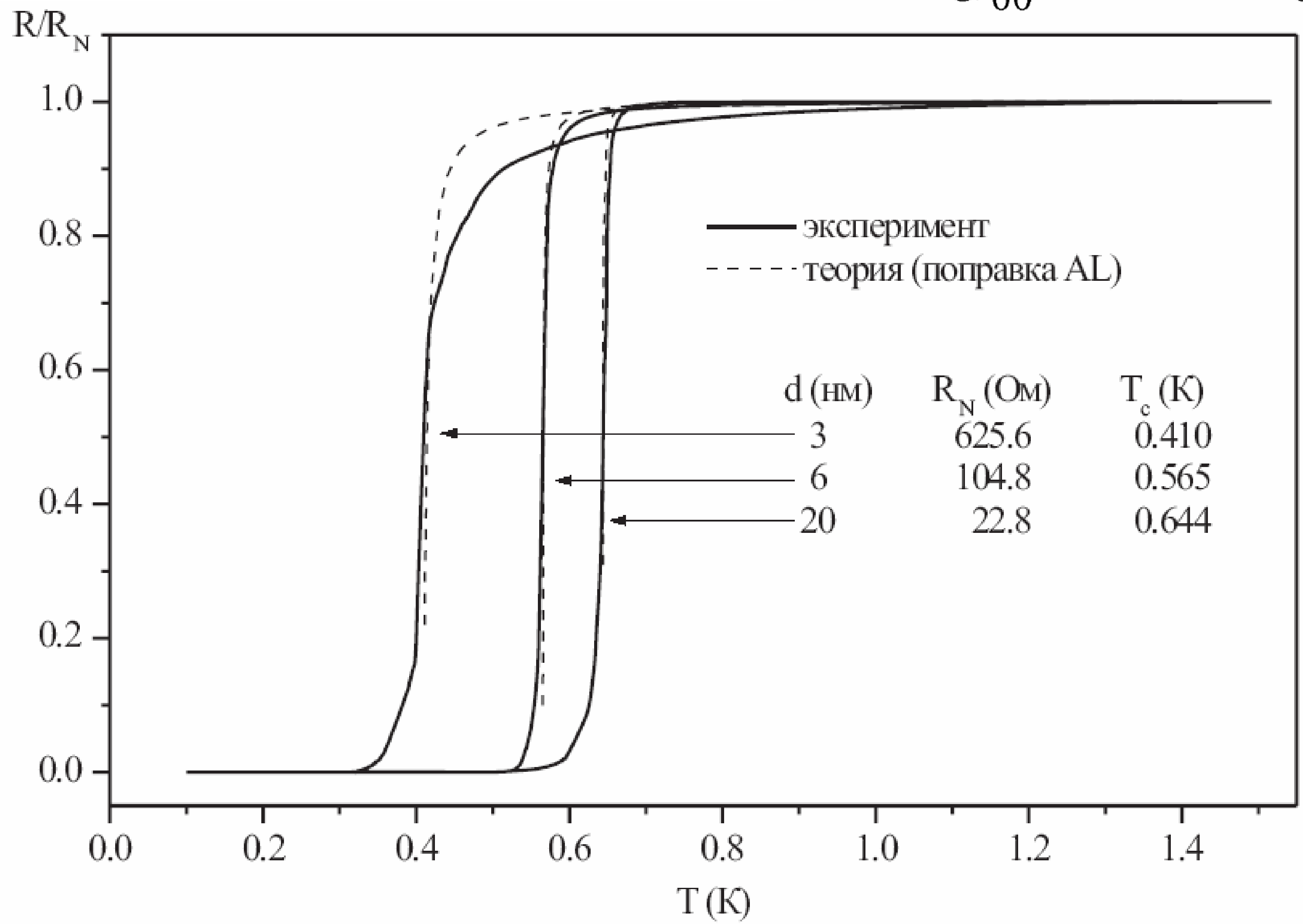





R □ (Ω)
640
620
600
580
560
540
520
500
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
T (K)
PtSi - 3 nm
experiment
theory

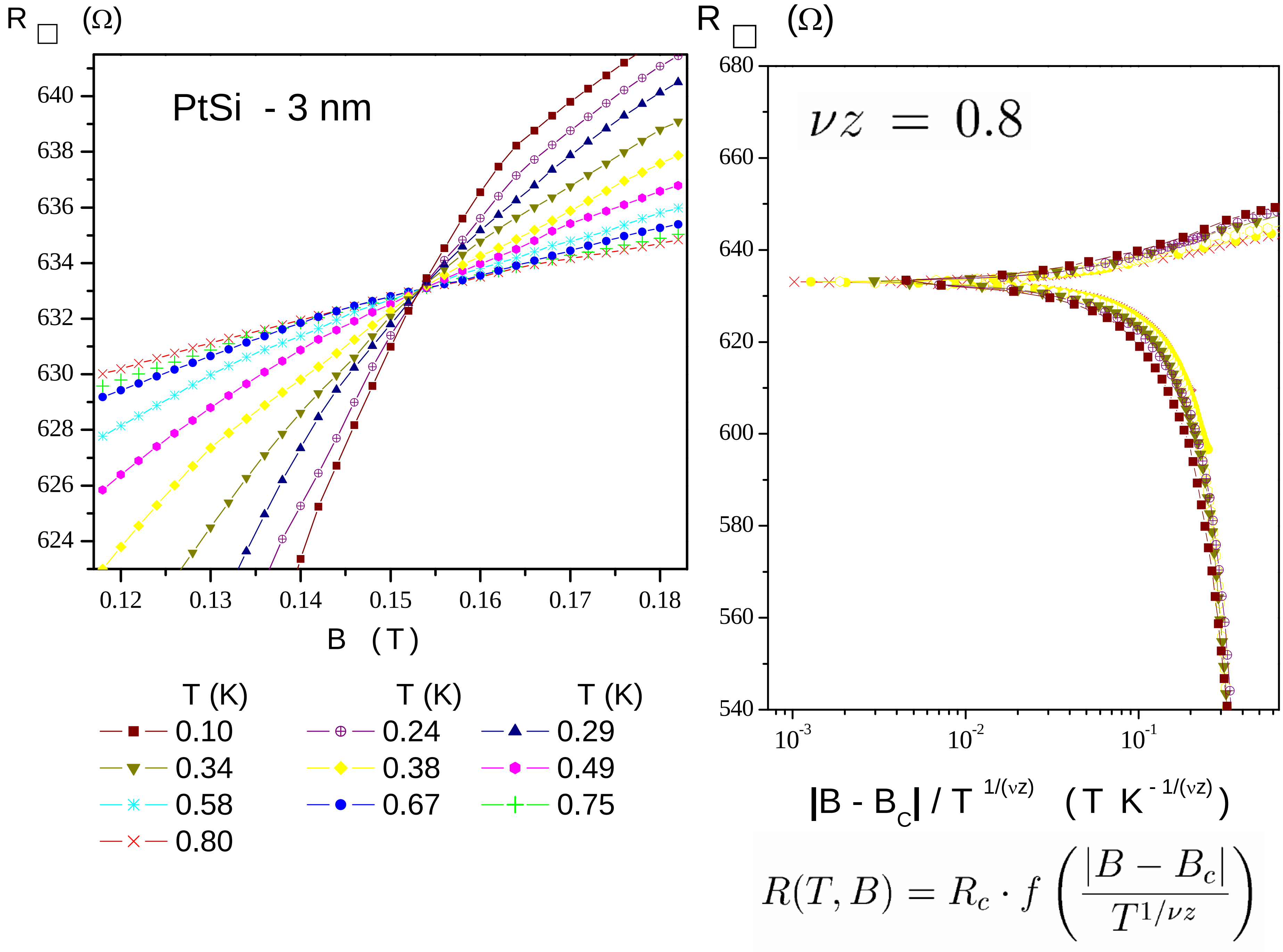
R(T) at B = 0

$$\frac{\Delta G^{AL}(T)|_{T\to T_c}}{G_{00}} = \frac{\pi^2}{8}\frac{T}{T-T_c}$$



$$G_{00} = e^2/(2\pi^2\hbar)$$

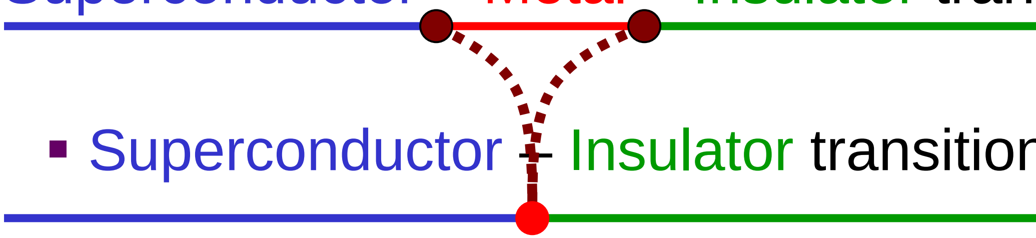
$$\Delta R(T) \approx R^2 \Delta G(T)$$



R□ (Ω)
PtSi - 3 nm
640
638
636
634
632
630
628
626
624
0.12
0.13
0.14
0.15
0.16
0.17
0.18
B (T)
T (K)
0.10
0.24
0.29
0.34
0.38
0.49
0.58
0.67
0.75
0.80
R□ (Ω)
$\nu z = 0.8$
680
660
640
620
600
580
560
540
10^{-3}
10^{-2}
10^{-1}
$|B - B_c| / T^{1/(\nu z)}$ $(T\ K^{-1/(\nu z)})$
$R(T,B) = R_c \cdot f\left(\frac{|B-B_c|}{T^{1/\nu z}}\right)$

✓ Suppression of Superconductivity by Disorder

- Superconductor – Metal – Insulator transition (SMIT)



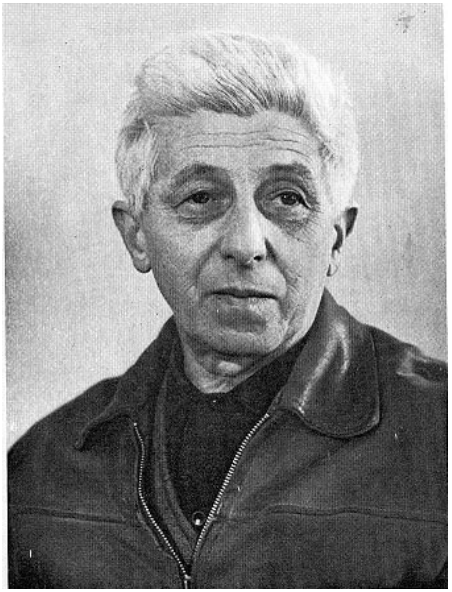
- Superconductor – Insulator transition (SIT)

Suppression of Superconductivity by Disorder

The first studies of superconductivity in the presence of disorder were performed by A.I. Shalnikov (Institute for Physical Problems, Russia).

A. Shalnikov, Nature **142**, 74 (1938).

A.I. Shalnikov, ZhETF **10**, 630 (1940).



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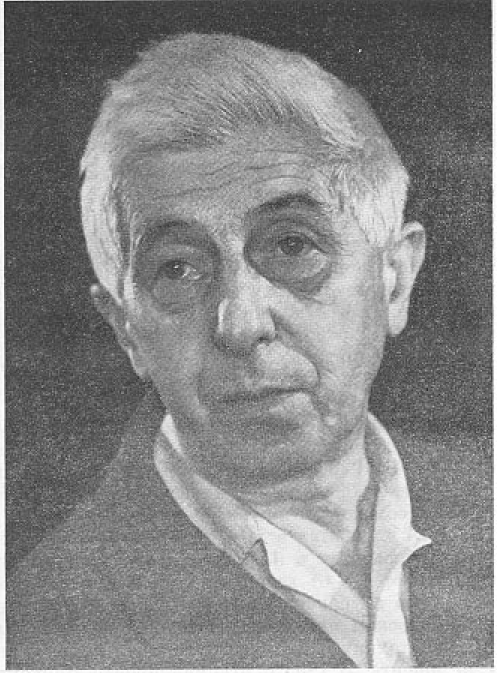
A.I. Shalnikov, ZhETF **10**, 630 (1940).

Amorphous metals:
lead (Pb), tin (Sn) and thallium (Tl) films
with thickness between 1 (!) and 200 nanometers

This was the first observation of suppression of T_c with decreasing thickness in thin superconducting films



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A.I. Shalnikov, ZhETF **10**, 630 (1940)

Мы не можем привести зависимости, характеризующей влияние толщины пленки на критическую температуру перехода. Нами были сделаны качественные эксперименты, в которых мы получали пленки различных толщин, последовательно испаряя все новые и новые количества металла в одном и том же приборе. Первая, самая тонкая пленка ($d \sim 10^{-7}$ см) оказалась сверхпроводящей при $\sim 4.1°$ K. Следующая, более толстая ($d = 10^{-6}$ см) при $4.5°$ K и, наконец, пленка толщиной около $3 \cdot 10^{-5}$ см при $4.9°$ K.

Anderson´s theorem

predicts that nonmagnetic impurities have no effect on superconductivity

A.A. Abrikosov and L.P. Gorkov, Sov. Phys. JETP 8, 1090 (1958).
P.W. Anderson, J. Phys. Chem. Solid 11, 26 (1959).

at relatively weak disorder $l >> v_F / \omega_D$

This theorem does not consider

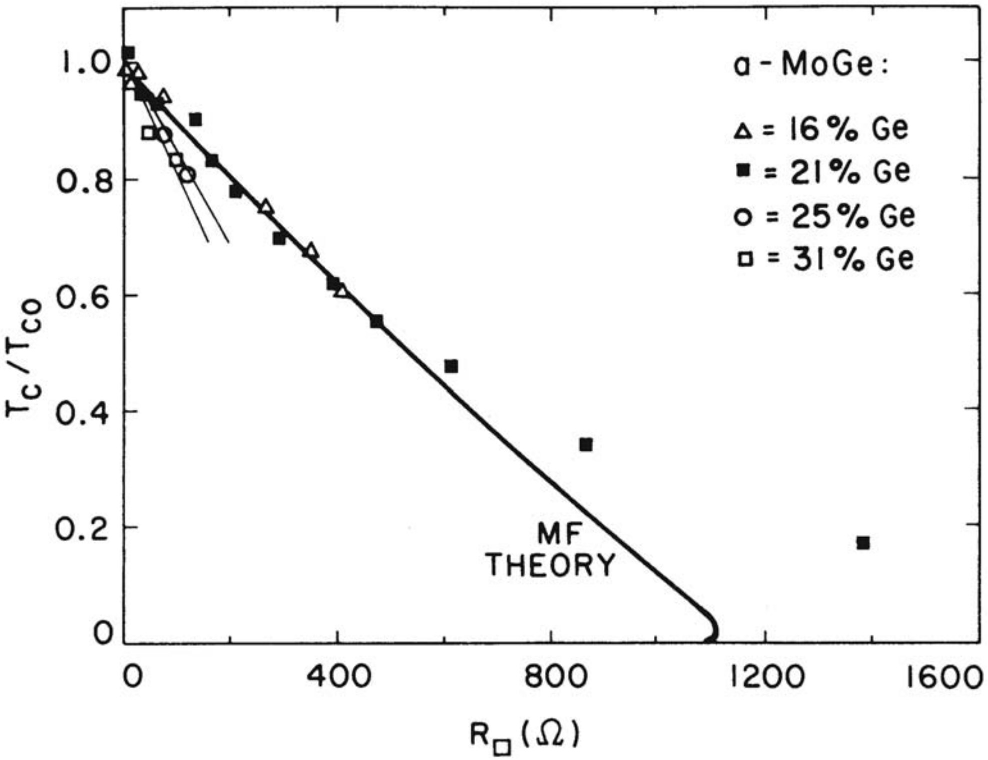
the strengthening of electron-electron interaction with increasing disorder

the effect of Anderson localization

weak disorder ⟷ strong disorder

Suppression of Superconductivity by Disorder

weak disorder



Theory

S. Maekawa, H. Fukuyama, J. Phys. Soc. Jpn. **51**, 1380 (1982).

S. Maekawa, H. Ebisawa, H. Fukuyama, J. Phys. Soc. Jpn. **52**, 1352 (1983).

H. Takagi and Y. Kuroda, Solid State Comm. **41**, 643 (1982).

Experiment

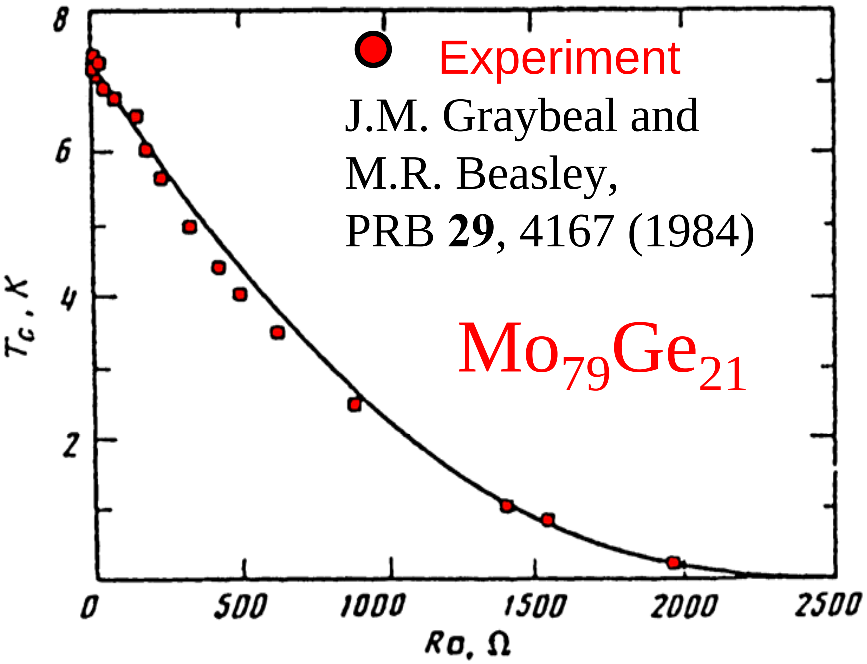
J.M. Graybeal and M.R. Beasley, PRB **29**, 4167 (1984).

$$\ln\left(\frac{T_c}{T_{c0}}\right) = -\frac{1}{2}gr\left[\ln\left(\frac{\hbar}{kT_c\tau}\right)\right]^2 - \frac{1}{3}gr\left[\ln\left(\frac{\hbar}{kT_c\tau}\right)\right]^3$$

$$r = G_{00} \cdot R_\square \qquad G_{00} = e^2/(2\pi^2\hbar)$$

weak disorder

Theory
A.M. Finkel'stein, JETP Lett. 45, 46 (1987).



The physical mechanism:

the decrease of the dynamical screening of the Coulomb repulsion between electrons because of the diffusive character of their motion in dirty systems

=> the decrease of the net attraction between electrons

=> the decrease of the transition temperature

$$\ln\left(\frac{T_c}{T_{c0}}\right) = \frac{1}{|\gamma|} - \frac{1}{\sqrt{2r}} \ln\left(\frac{\gamma - r/4 - \sqrt{r/2}}{\gamma - r/4 + \sqrt{r/2}}\right)$$

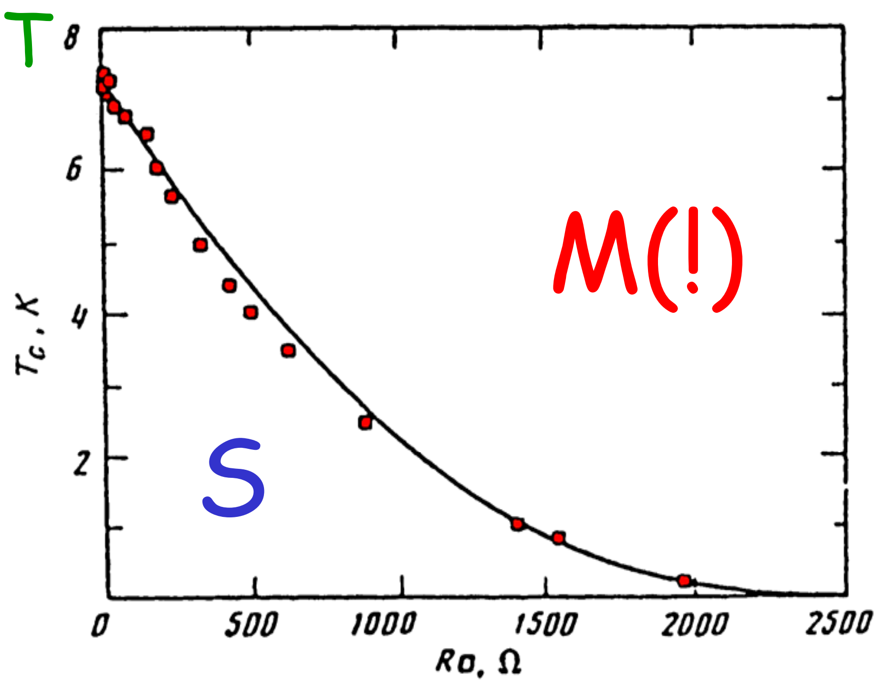
$$m^* \propto \hbar/D$$

$$r = G_{00} \cdot R_\square \qquad G_{00} = e^2/(2\pi^2\hbar) \qquad \gamma = 1/\ln(kT_{c0}\tau/\hbar)$$

Suppression of Superconductivity by Disorder

weak disorder

Theory
A.M. Finkel'stein, JETP Lett. 45, 46 (1987).



Fermionic mechanism

Vanishing of T_c is accompanied by vanishing of the amplitude of the superconductive order parameter Δ (!)

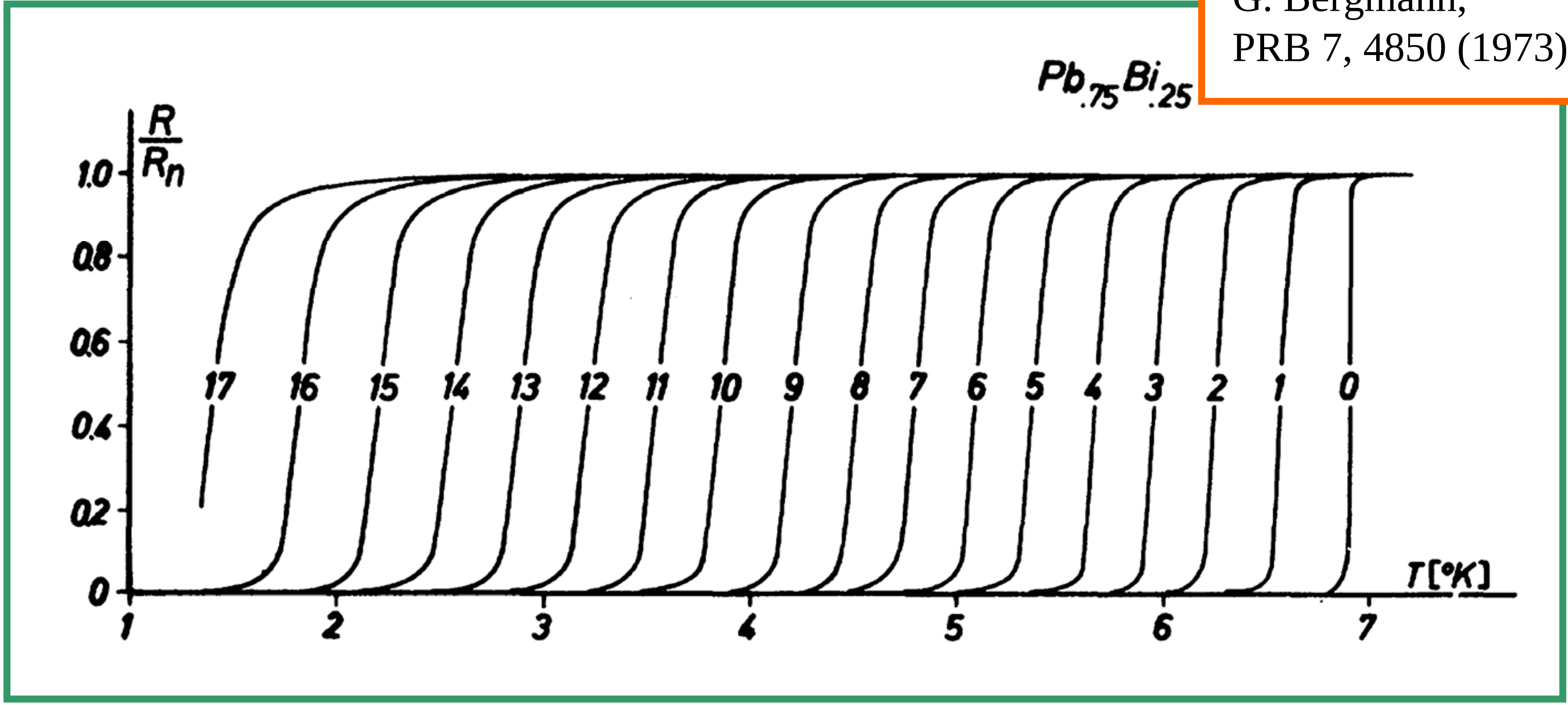
Phase diagram

There is no Cooper pairs at the transition.

Review: A.M. Finkel'stein, Physica B 197, 636 (1994).

Suppression of Superconductivity by Magnetic field

Field-induced ***superconductor – normal metal transition***

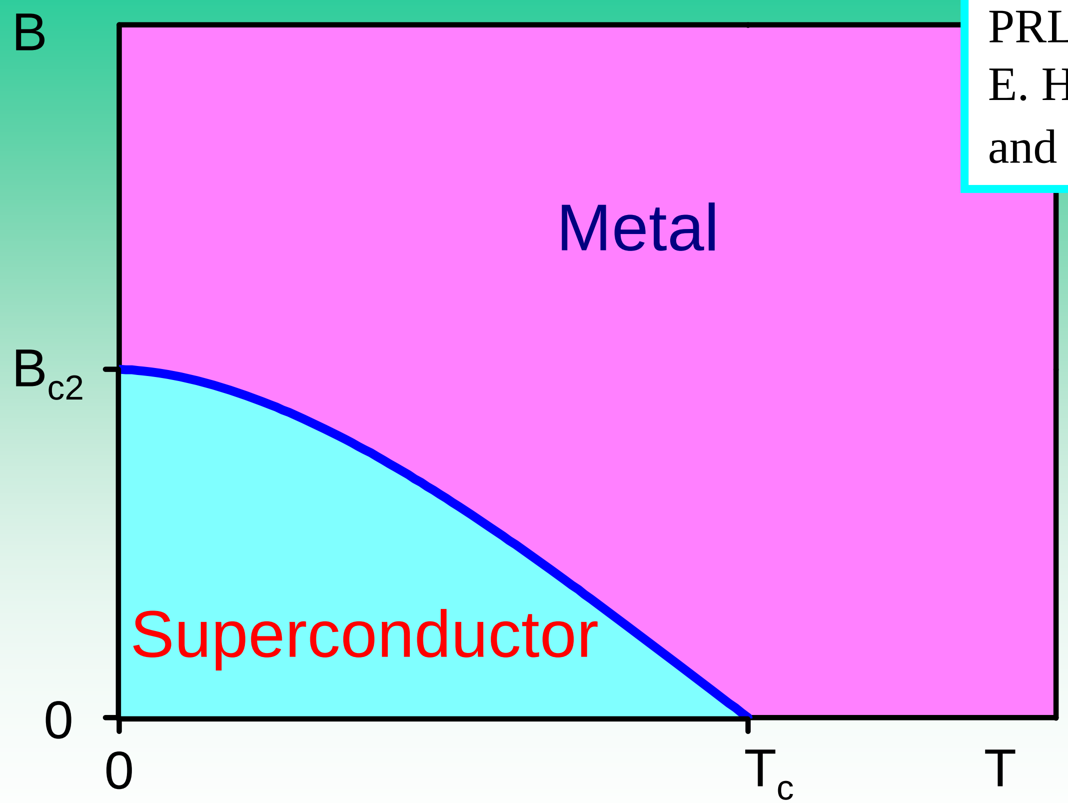


G. Bergmann,
PRB 7, 4850 (1973)

Suppression of Superconductivity by Magnetic field

Field-induced ***superconductor – normal metal transition***

Phase diagram



Temperature dependence of the superconducting critical field, B_{c2}

E. Helfand and N.R. Werthamer,
PRL 13, 686 (1964); PR 147, 288 (1964);
E. Helfand, N.R. Werthamer,
and C. Hohenberg, PR 147, 295 (1964).

$$B_{c2}(0) = \frac{\pi}{2\gamma} \cdot \frac{kT_c}{eD}$$

$$\gamma = 1.781$$

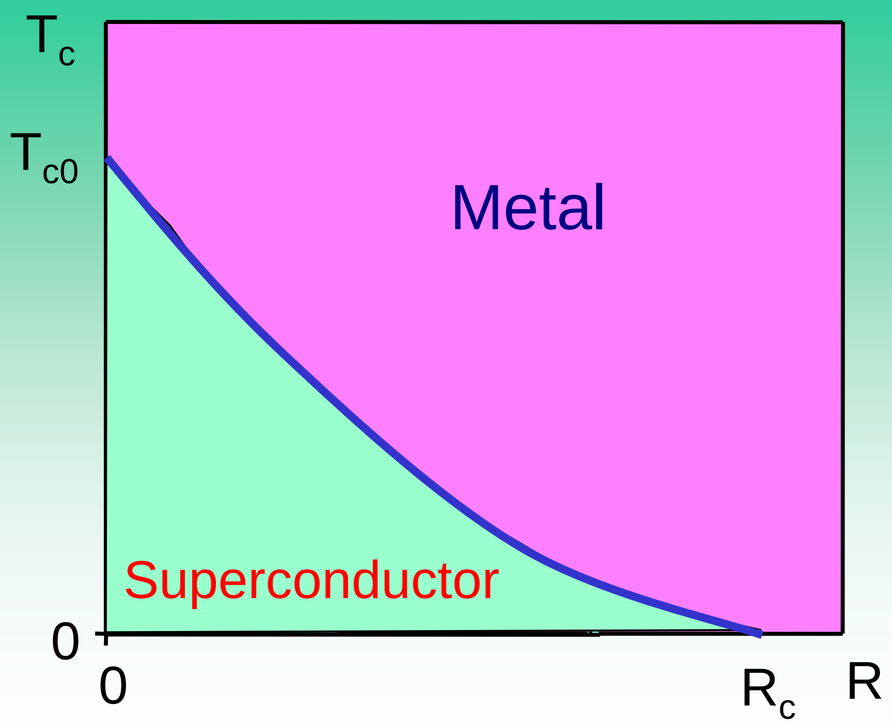
$$-\frac{dB_{c2}}{dT}\bigg|_{T=T_c} = \frac{4k}{\pi eD}$$

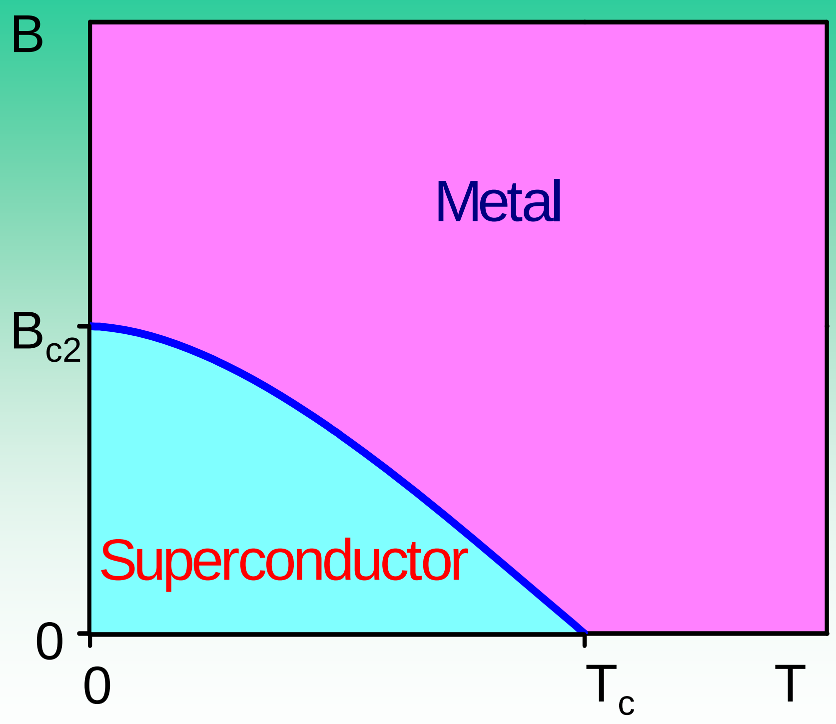
Suppression of Superconductivity by <u>Disorder</u> & <u>Magnetic field</u>

superconductor – normal metal transition

A.M. Finkel'stein,
JETP Lett. 45, 46 (1987).

E. Helfand and N.R. Werthamer,
PRL 13, 686 (1964); PR 147, 288 (1964);
E. Helfand, N.R. Werthamer,
and C. Hohenberg, PR 147, 295 (1964).





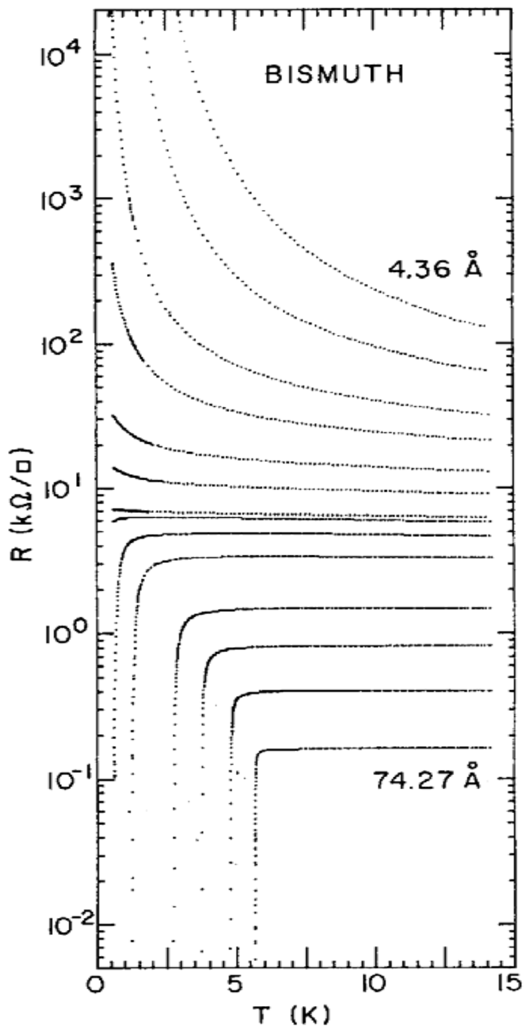
New era!!!

Suppression of Superconductivity by Disorder

strong disorder

D.V. Haviland, Y. Liu, A.M. Goldman,

PRL **62**, 2180 (1989).



Superconductor-insulator transition

Bi films

R_c = 6.45 kΩ

$d < d_c$ Insulator

d_c Metal

$R_c = h/(2e)^2$

$d > d_c$ Superconductor

Fan-shaped curves

Bosonic mechanism

*** Quantum phase transition ***

Theory Matthew P.A. Fisher, G. Grinstein, S.M. Girvin , PRL **64**, 587 (1990).

Continuos zero-temperature phase transition

Quantum ordered phase

Quantum disordered phase

0

K_c

K

$K < K_c$ Superconductor

Condensate of Cooper pairs

$K > K_c$ Insulator

Localized Cooper pairs

$K = K_c$ Metal

$$R_c = \frac{h}{4e^2} = 6.45\ k\Omega/\square$$

The system behaves like a normal metal right at the transition.
The resistance has a finite, nonzero value at T = 0.

This value is *universal* - independent of all microscopic details.

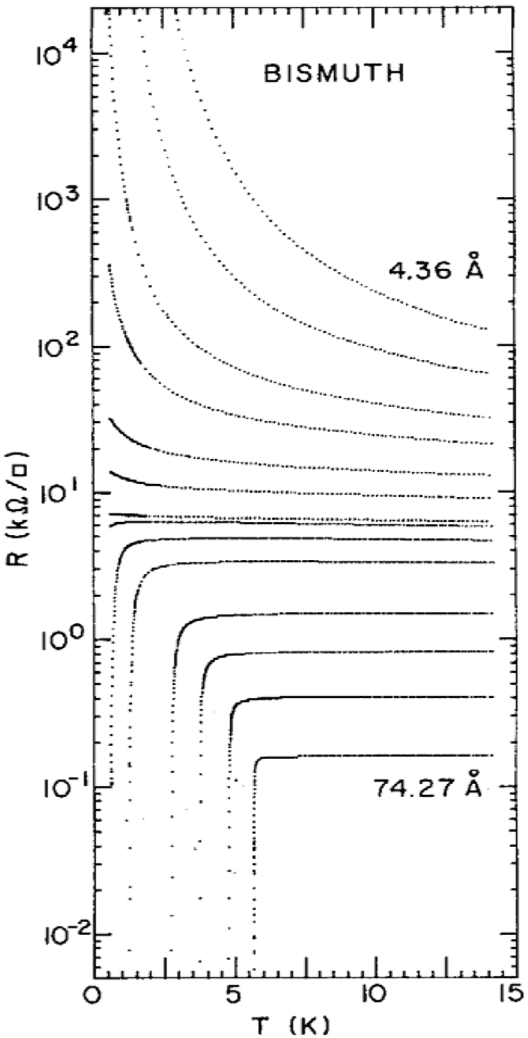
picture-gallery

"In search of disorder-driven superconductor-insulator transition"

***** collection *****

Suppression of Superconductivity by Disorder

D.V. Haviland, Y. Liu, and A.M. Goldman,
PRL **62**, 2180 (1989).



d < d_c Insulator

d_c Metal

d > d_c Superconductor

Bi films

R_c = 6.45 kΩ

$R_c = h/(2e)^2$

Fan-shaped curves

The onset of superconductivity in homogeneous ultrathin films is found to occur when their normal-state sheet resistance falls below a value close to $h/4e^2$, the quantum resistance for pairs. The data fur-

Suppression of Superconductivity by Disorder

Bi films R_c = 6.45 kΩ

Y. Liu, D.V. Haviland, B. Nease, and A.M. Goldman,
PRB **47**, 5931 (1993).

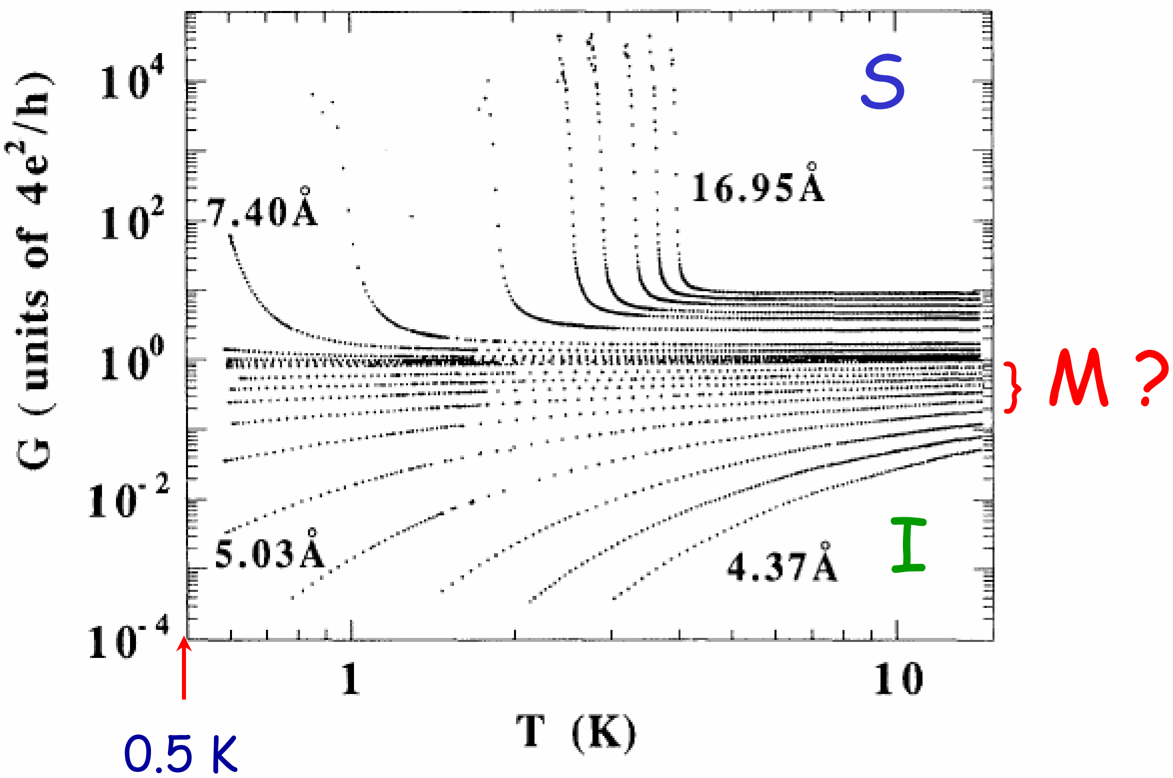
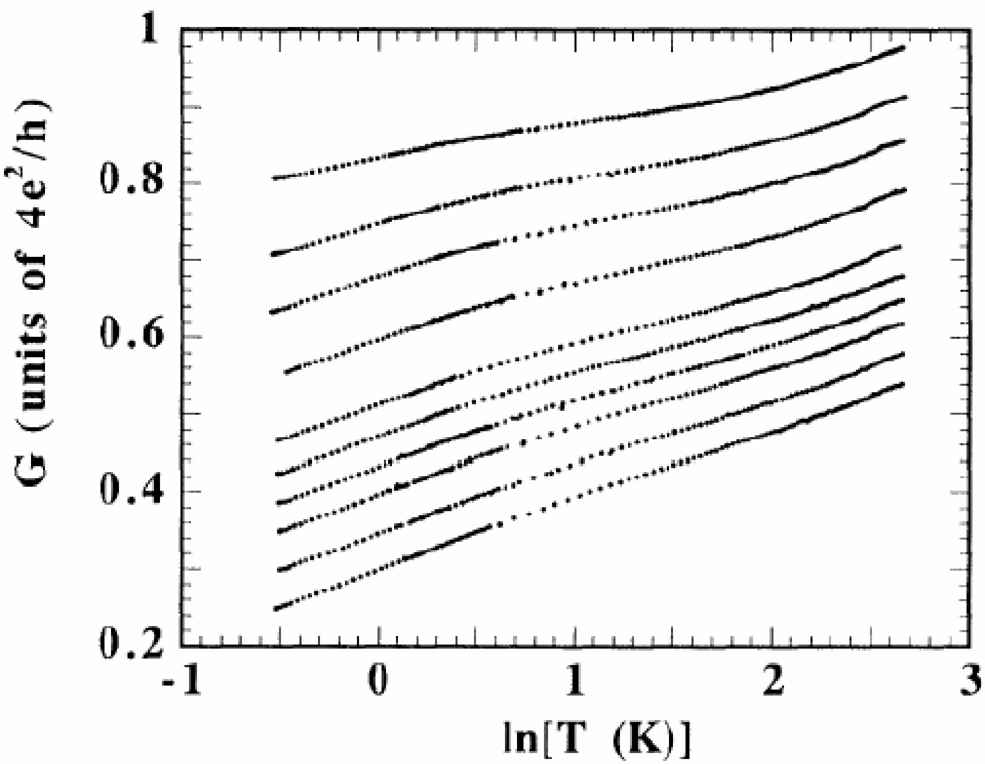


FIG. 2. Evolution for Bi films of the electrical conductance G in units of $4e^2/h$ as a function of temperature T. The thicknesses of a few selected films are indicated. Note that conductance and conductivity are identical in two dimensions. Only some of the data of the sequence of films is shown to avoid too high a density of data points.

Suppression of Superconductivity by Disorder

Bi films

Y. Liu, D.V. Haviland, B. Nease, and A.M. Goldman,
PRB **47**, 5931 (1993).



$G \propto \ln T$

metal

Drude conductivity

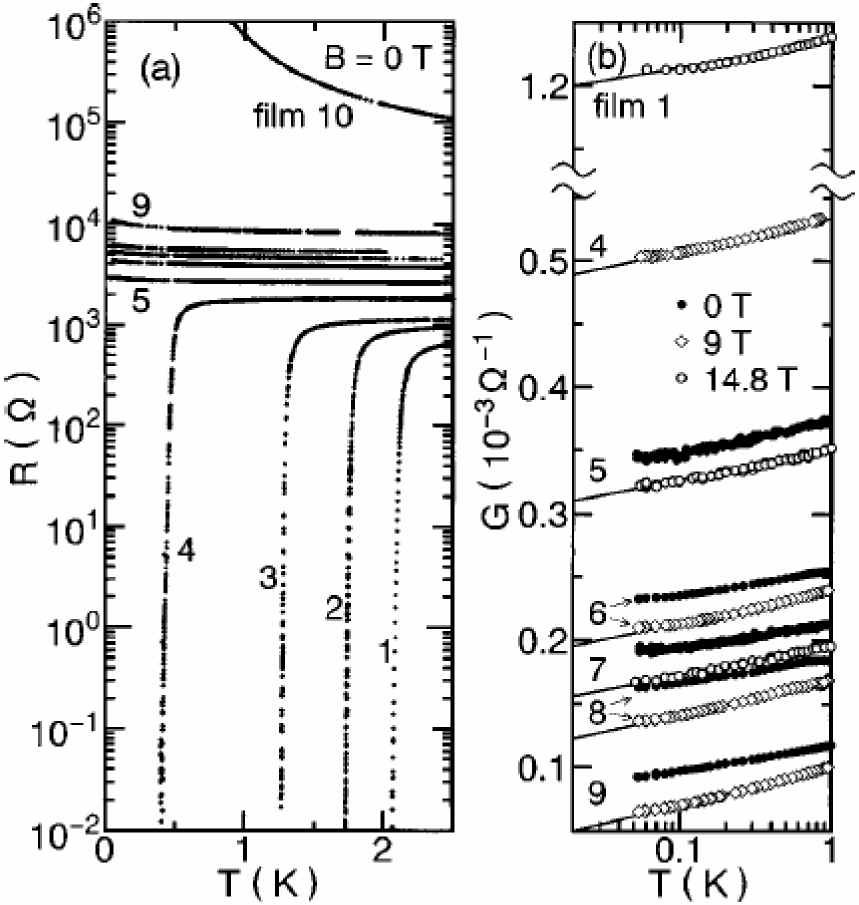
+

quantum corrections

SMIT

FIG. 6. Conductance G vs $\ln T$ of last ten insulating Bi films. (The 22nd to 31st films of the Bi sequence.) The temperature dependences of the conductances are approximately logarithmic. Notice that in the low-temperature limit, the slope of the logarithm decreases as the onset of superconductivity is approached.

Suppression of Superconductivity by Disorder



Mo_xSi_{1-x} films

S. Okuma, T. Terashima, and N. Kokubo, PRB 58, 2816 (1998).

$G \propto \ln T$

metal

Drude conductivity

+

quantum corrections

Figure 1(a) illustrates the temperature dependence of the sheet resistance $R(T)$ in $B=0$ for ten selected films. Films with $R_n(10\text{ K})$ smaller than 1.8 kΩ (films 1–4) achieve global superconductivity, while those with $R_n(10\text{ K})$ larger than 2.5 kΩ (films 5–10) behave like an insulator, showing an increase in R at low temperatures.

SMIT

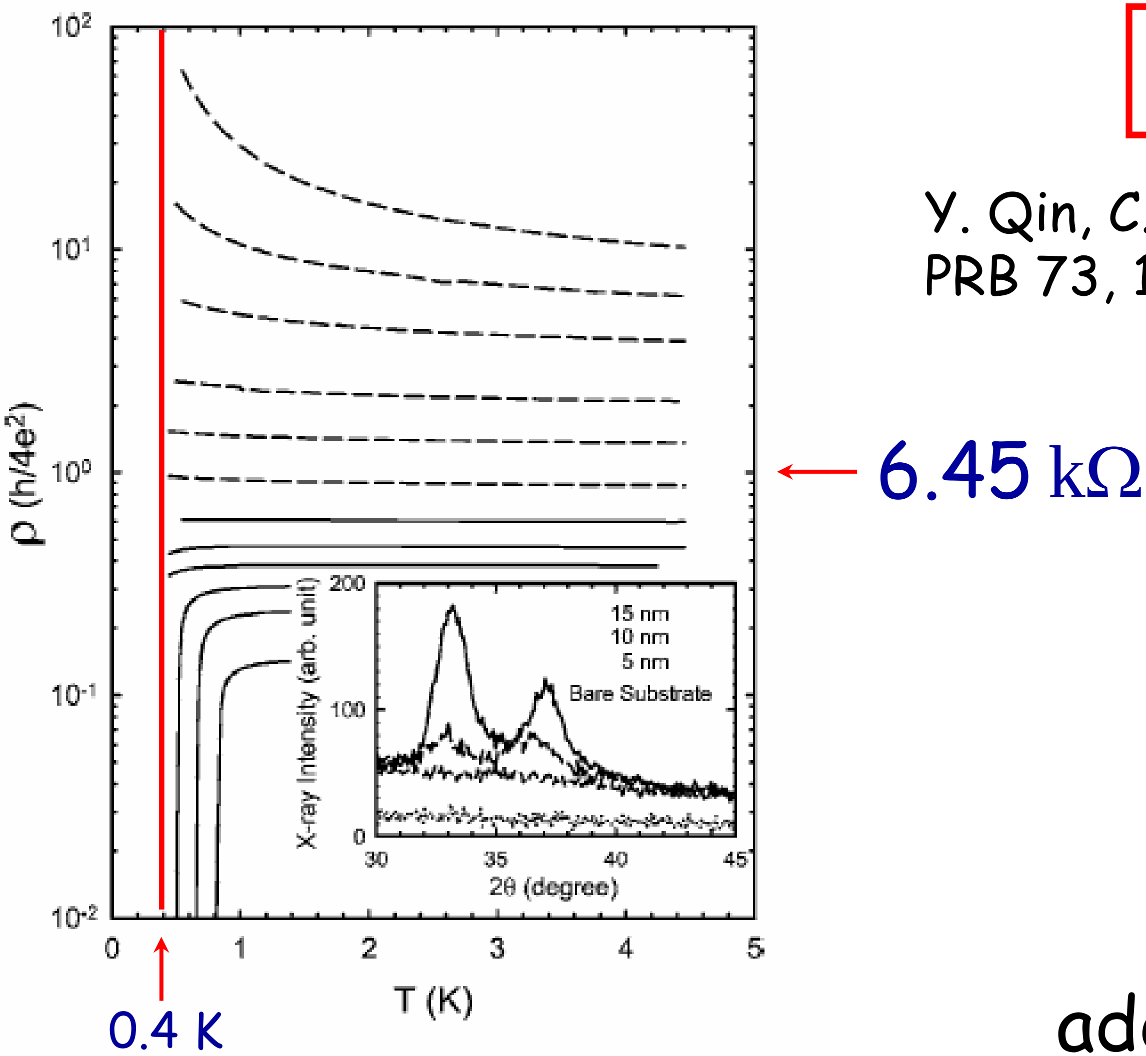


FIG. 1. The resistance is measured at $B=0$ with a dc current in the range 1–10 nA that is within the linear response regime. The thicknesses of the films are, from the top, 1.9, 2.0, 2.1, 2.3, 2.5, 2.8, 3.1, 3.4, 3.7, 4.0, 4.5, and 5.5 nm. The dashed lines are for the insulating phase and the solid lines are for the superconducting phase. Inset: x-ray diffraction patterns of 15, 10, 5 nm thick Ta films, and a bare Si substrate.

Ta films

Y. Qin, C.L. Vicente, J. Yoon, PRB 73, 100505(R) (2006).

SMIT ?

or
additional study
at lower temperature
is needed

InO$_x$ films

V.F. Gantmakher *et al.*, JETP 82, 951 (1996).

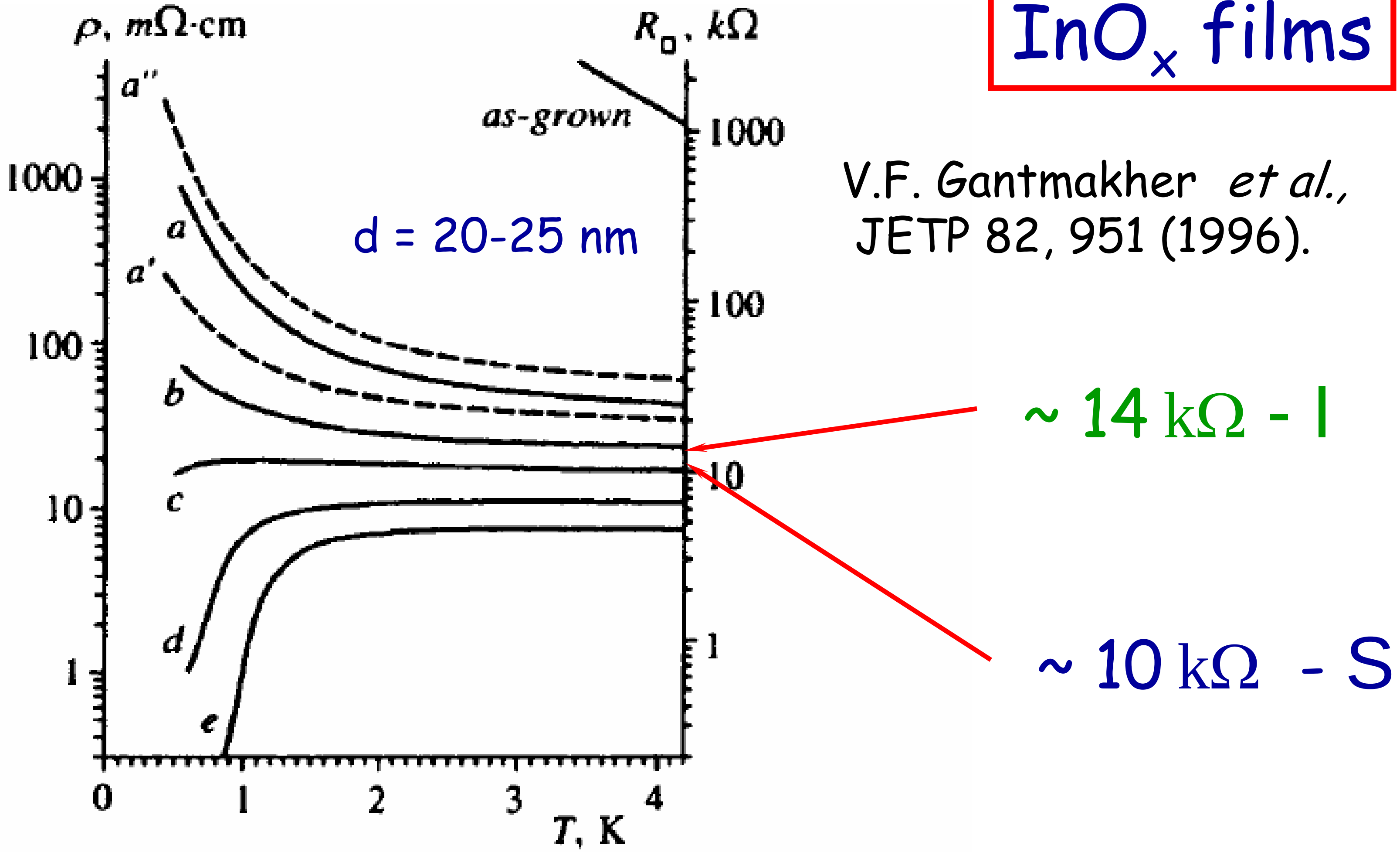


FIG. 2. Evolution of the temperature dependence of the resistance of a-In_2O_x films in zero magnetic field after different treatments. Film No. 1: states a (initial)–e, film No. 2: states a' (initial) and a''. A part of the dependence $R(T)$ for the as-grown film from the inset of Fig. 1 is also plotted.

Be films

E. Bielejec, J. Ruan, and W. Wu
PRL 87, 36801 (2001).

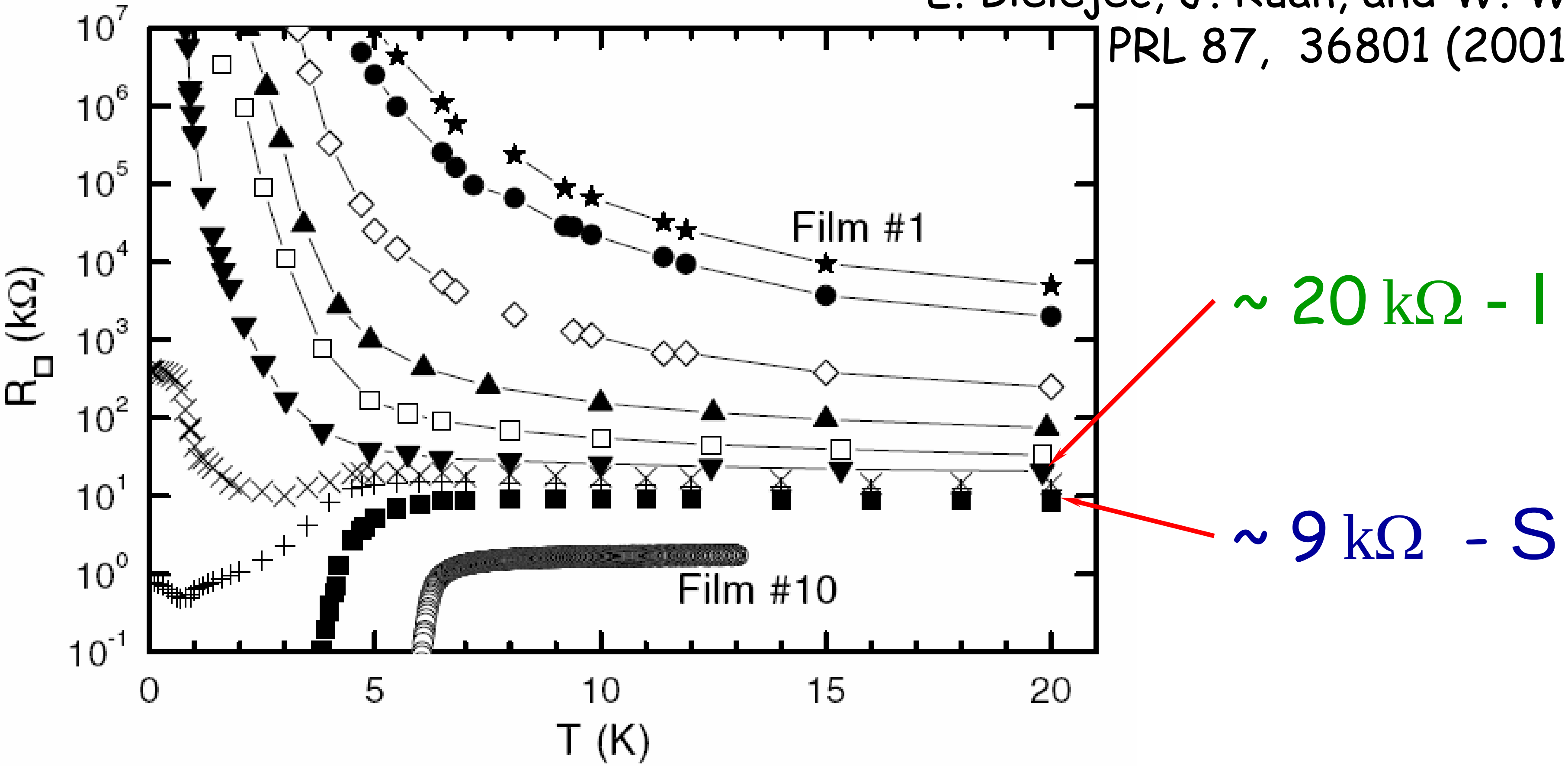
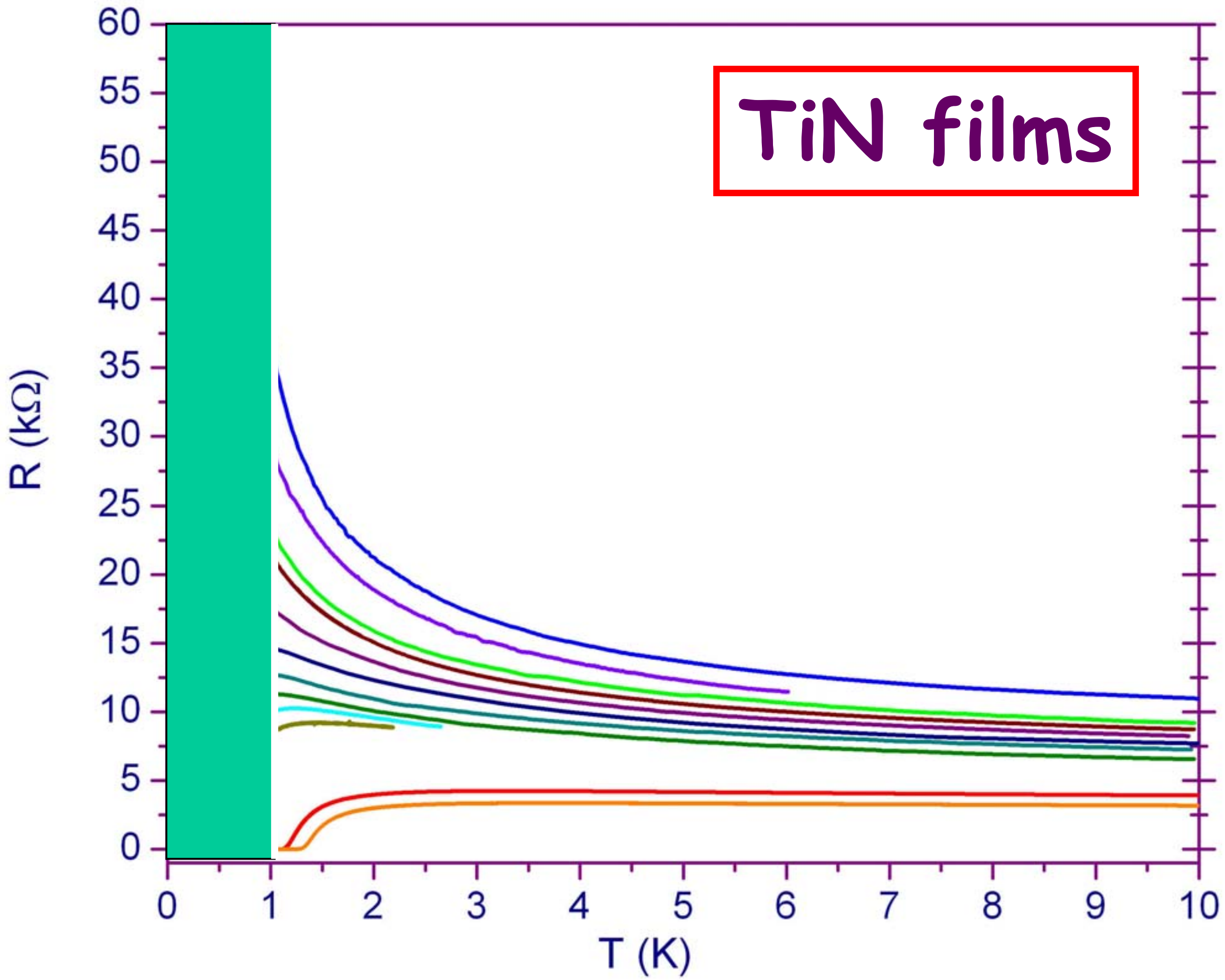
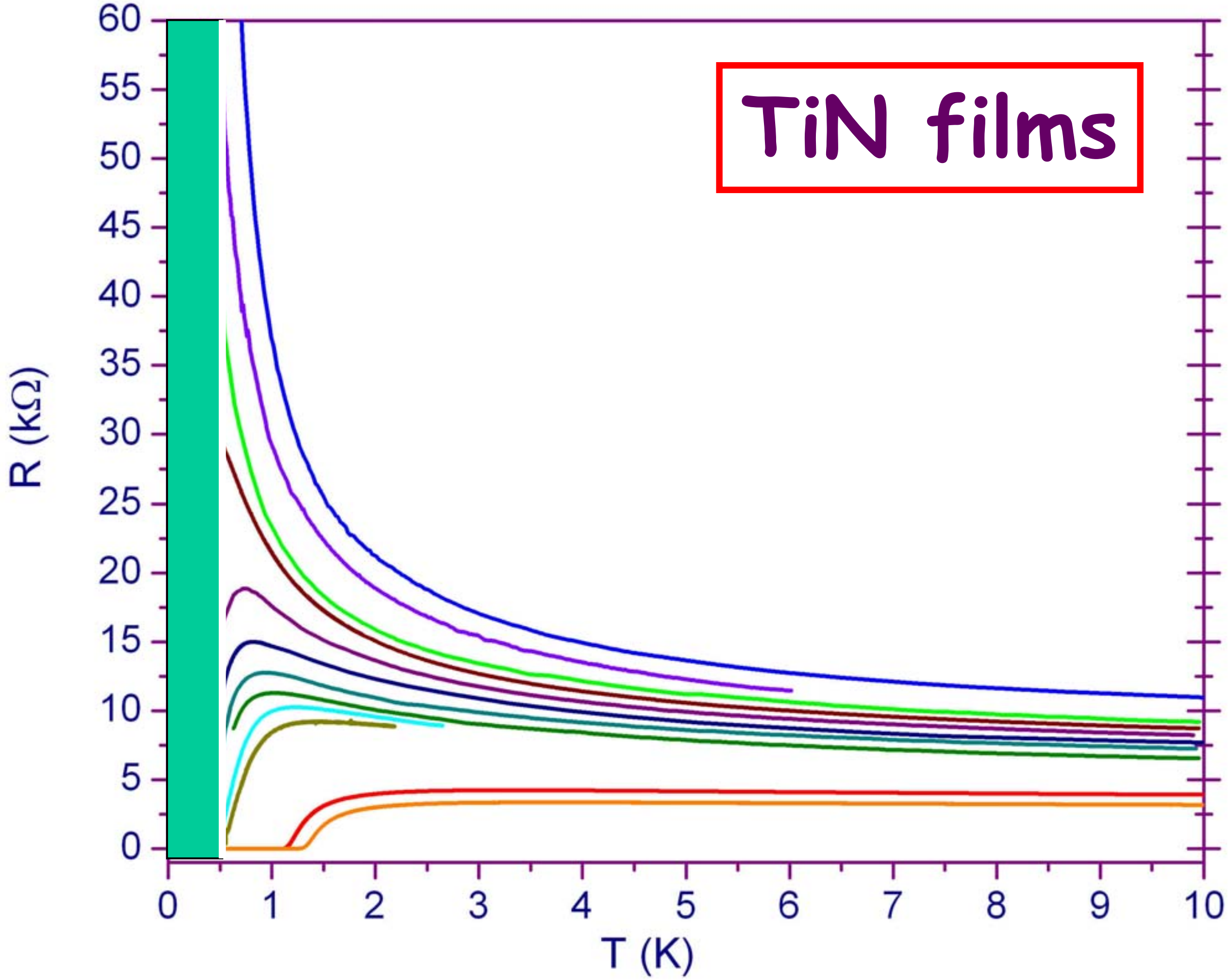


FIG. 1. Curves of film sheet resistance as a function of temperature measured on one film section following a series of deposition steps to increase film thickness. For curves from top to bottom, we label them as Film #1 to Film #10, respectively. The thickness for these films changed from 4.6 to 15.5 Å.

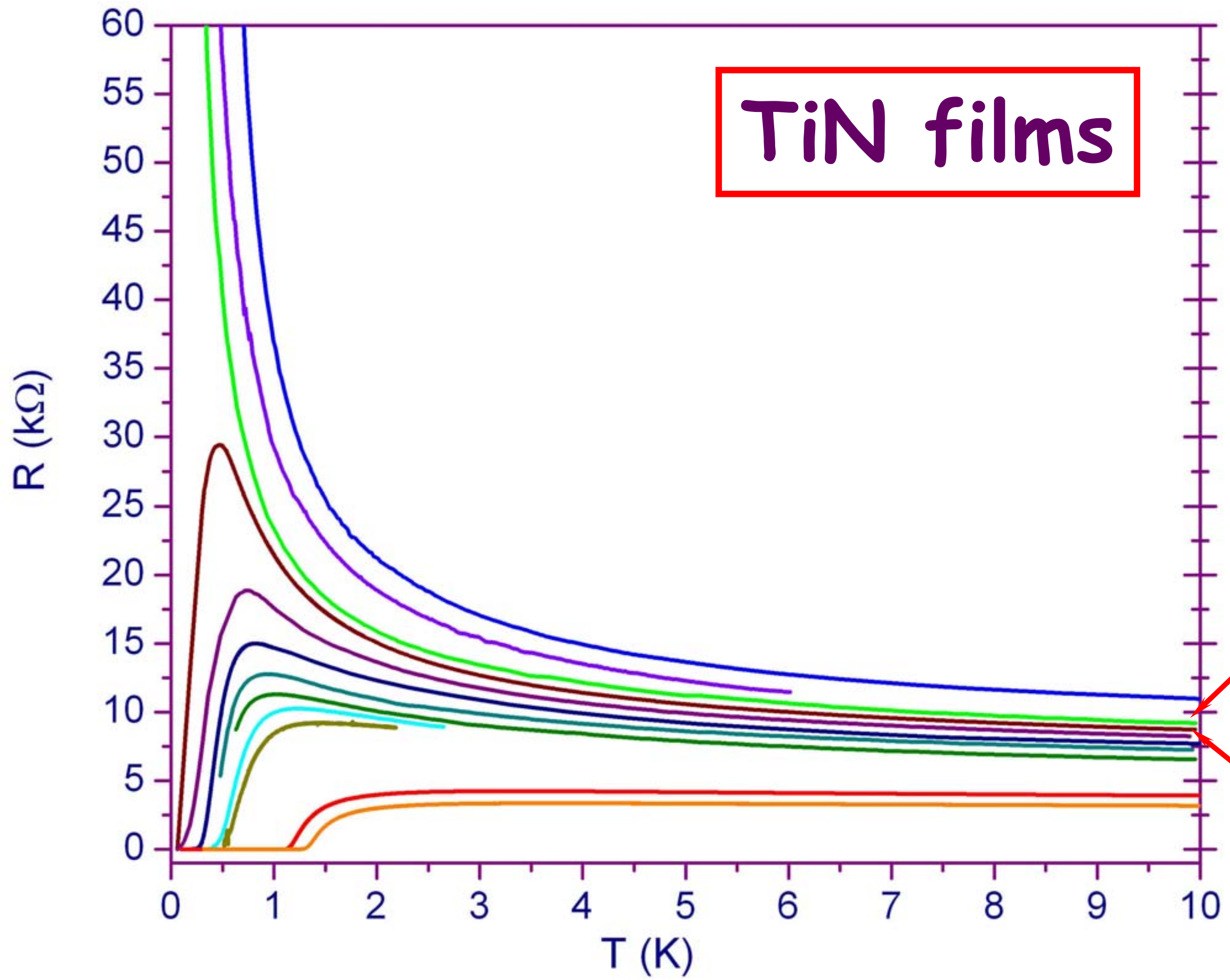
T.I. Baturina, D.R. Islamov, J. Bentner, C. Strunk, M.R. Baklanov, and A. Satta, JETP Lett. 79, 337 (2004).
T.I. Baturina, C. Strunk, M.R. Baklanov, A. Satta, PRL 98, 127003 (2007).
T.I. Baturina, A.Yu. Mironov, V.M. Vinokur, M.R. Baklanov, and C. Strunk, cond-mat/0705.1602



T.I. Baturina, D.R. Islamov, J. Bentner, C. Strunk, M.R. Baklanov, and A. Satta, JETP Lett. 79, 337 (2004).
T.I. Baturina, C. Strunk, M.R. Baklanov, A. Satta, PRL 98, 127003 (2007).
T.I. Baturina, A.Yu. Mironov, V.M. Vinokur, M.R. Baklanov, and C. Strunk, cond-mat/0705.1602



T.I. Baturina, D.R. Islamov, J. Bentner, C. Strunk, M.R. Baklanov, and A. Satta, JETP Lett. 79, 337 (2004).
T.I. Baturina, C. Strunk, M.R. Baklanov, A. Satta, PRL 98, 127003 (2007).
T.I. Baturina, A.Yu. Mironov, V.M. Vinokur, M.R. Baklanov, and C. Strunk, cond-mat/0705.1602



T = 10 K

9.16 kΩ - I

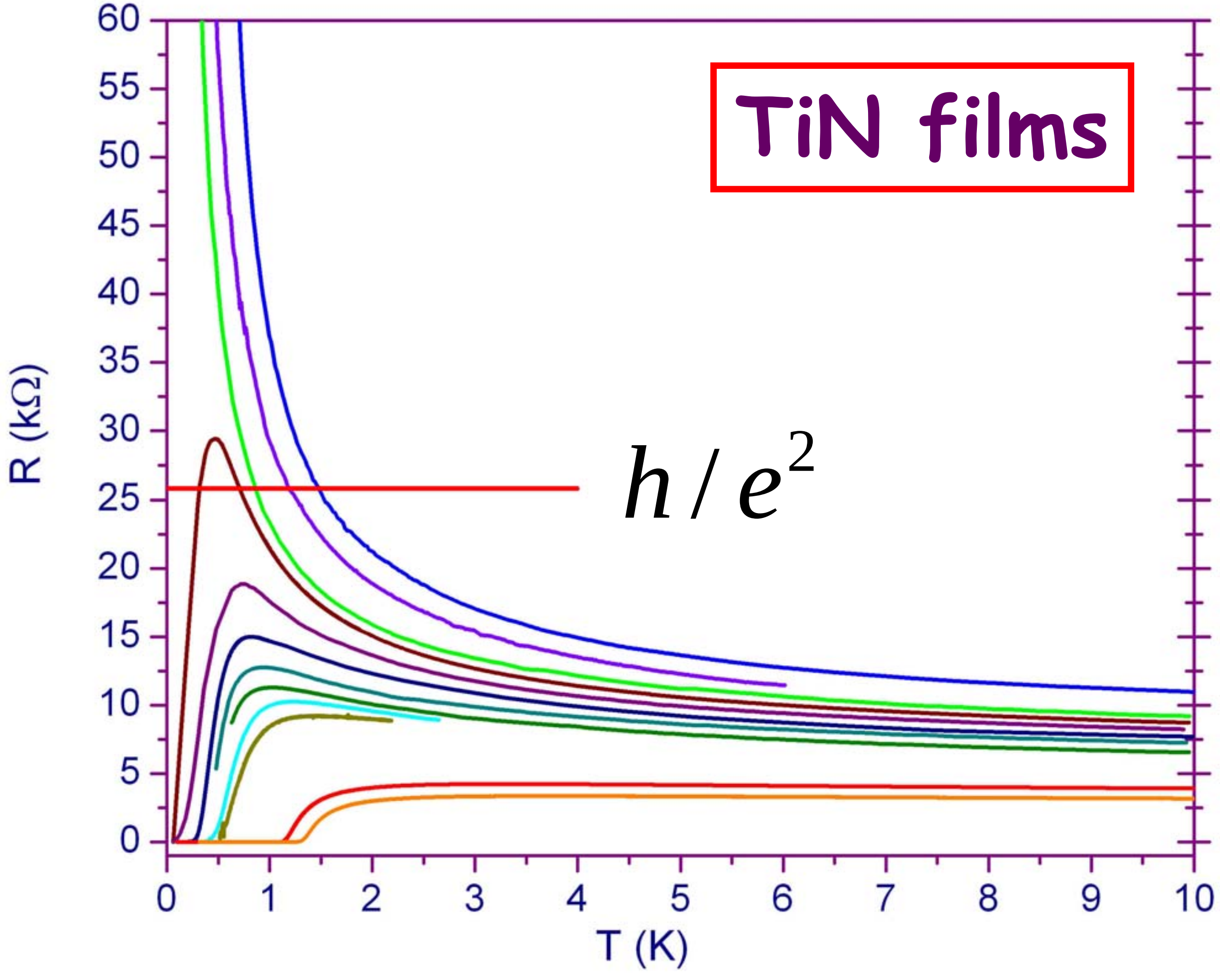
8.74 kΩ - S

< 5% (!)

T.I. Baturina, D.R. Islamov, J. Bentner, C. Strunk, M.R. Baklanov, and A. Satta, JETP Lett. 79, 337 (2004).

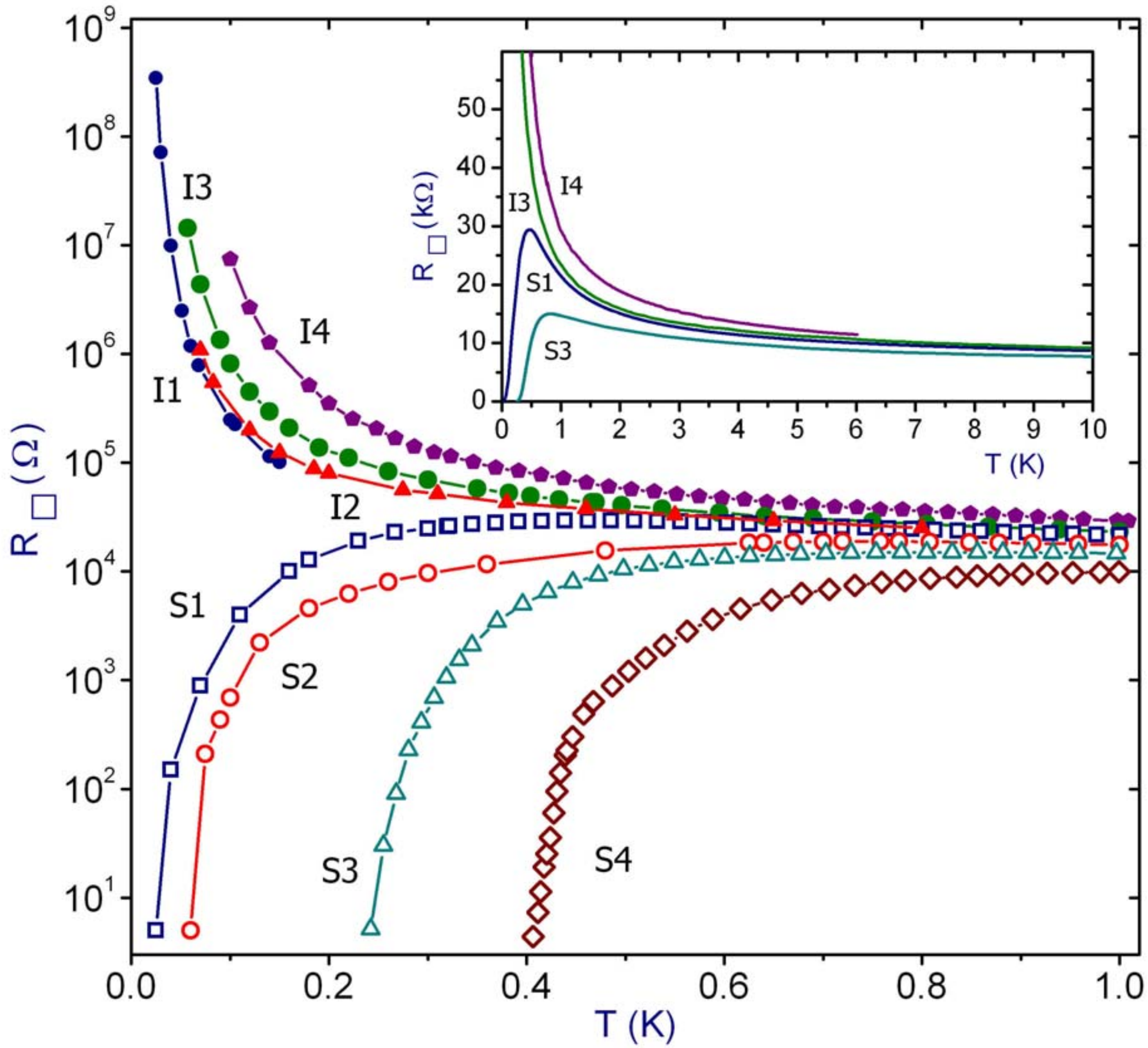
T.I. Baturina, C. Strunk, M.R. Baklanov, A. Satta, PRL 98, 127003 (2007).

T.I. Baturina, A.Yu. Mironov, V.M. Vinokur, M.R. Baklanov, and C. Strunk, cond-mat/0705.1602



TiN films

T.I. Baturina, A.Yu. Mironov, V.M. Vinokur,
M.R. Baklanov, and C. Strunk,
cond-mat/0705.1602



SMIT or SIT

The search for a disorder-driven superconductor-insulator transition has included many materials, e.g.,

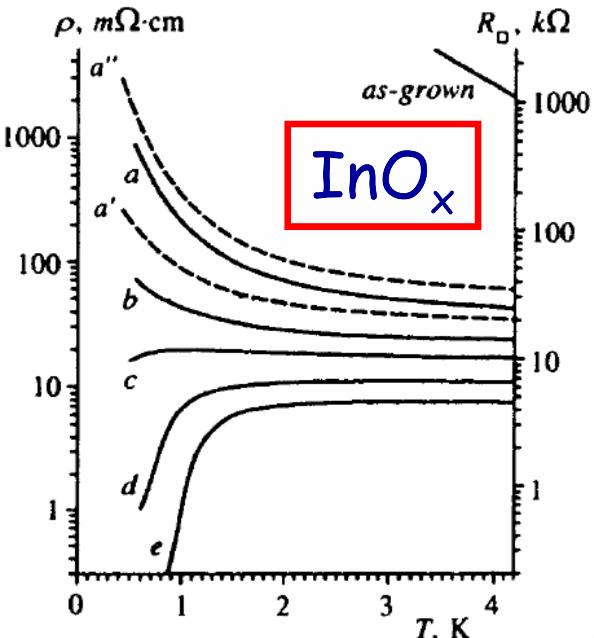
Bi, MoSi, Ta, InO_x, Be, TiN.

The immediate onset of exponential temperature dependence of the resistance, which conclusively evidences **the direct transition into an insulator,** was found so far only in **InO_x**, **Be**, and **TiN** films.

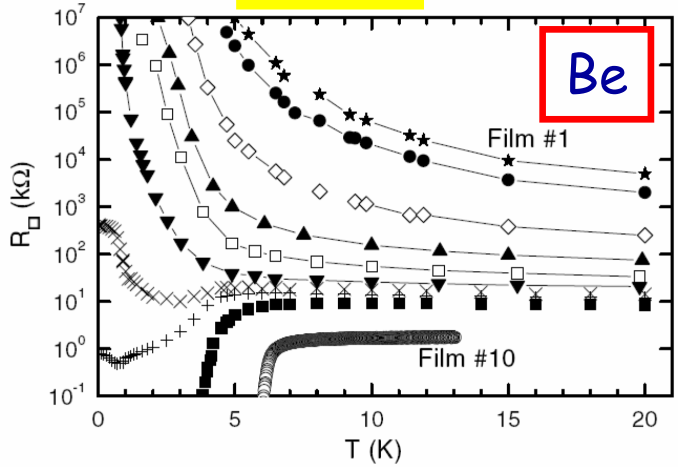
For **Bi**, **MoSi**, and **Ta**-compounds a weak logarithmic temperature dependence of the resistance was observed on the nonsuperconducting side in the vicinity of the transition.

- ✓ This possibly indicates an intermediate metallic phase
- ✓ More studies at even lower temperatures are needed to obtaine conclusive evidences on which films fall into a superconducting state and which become insulating state

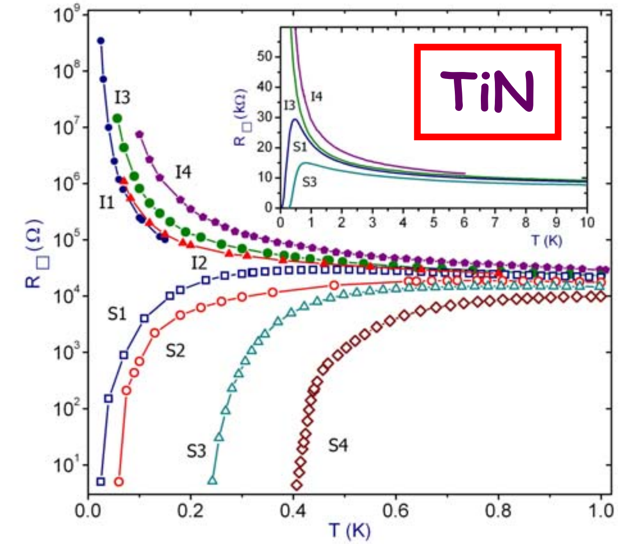
SIT



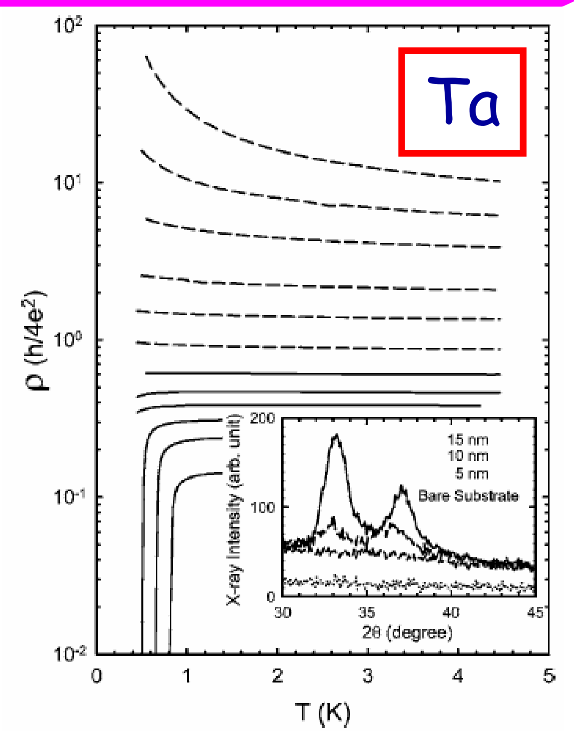
ρ, mΩ·cm
R□, kΩ
as-grown
InOx
a''
a
a'
b
c
d
e
T, K



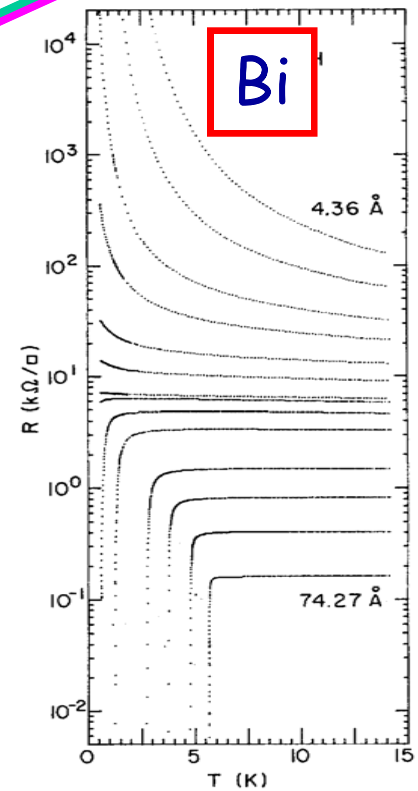
Be
Film #1
Film #10
R□ (kΩ)
T (K)



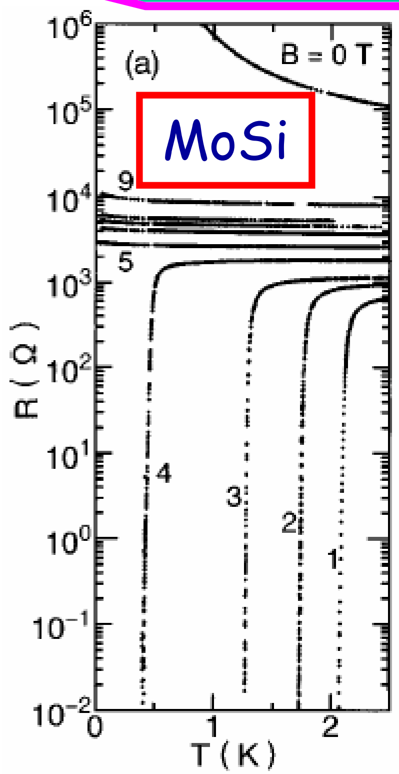
TiN
I1
I2
I3
I4
S1
S2
S3
S4
R□ (Ω)
T (K)



Ta
ρ (h/4e²)
T (K)
X-ray Intensity (arb. unit)
2θ (degree)
15 nm
10 nm
5 nm
Bare Substrate



Bi
4.36 Å
74.27 Å
R (kΩ/□)
T (K)



MoSi
(a)
B = 0 T
R (Ω)
T (K)

SMIT

SIT

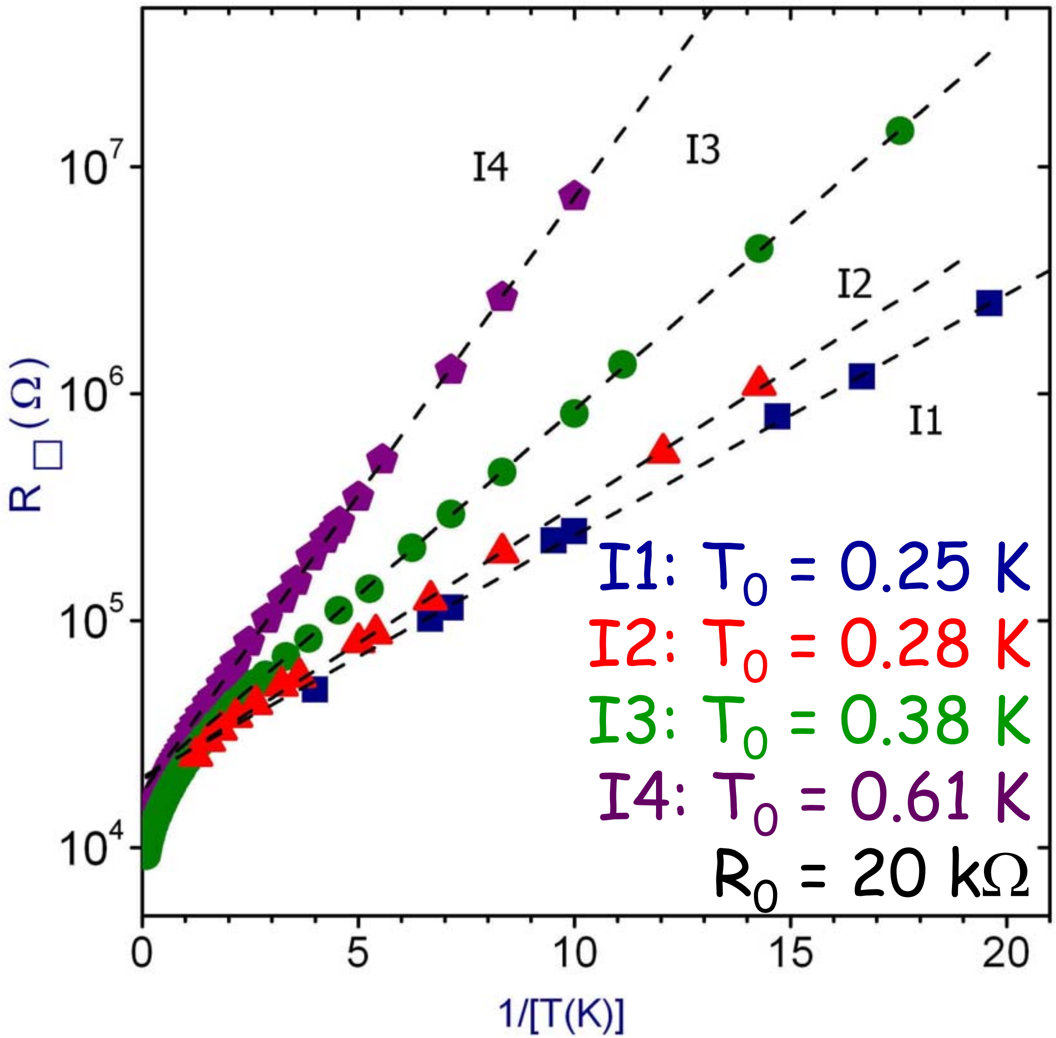
The immediate onset of exponential temperature dependence of the resistance, which conclusively evidences **the direct transition into an insulator,** was found so far only in **InO_x** , **Be**, and **TiN** films.

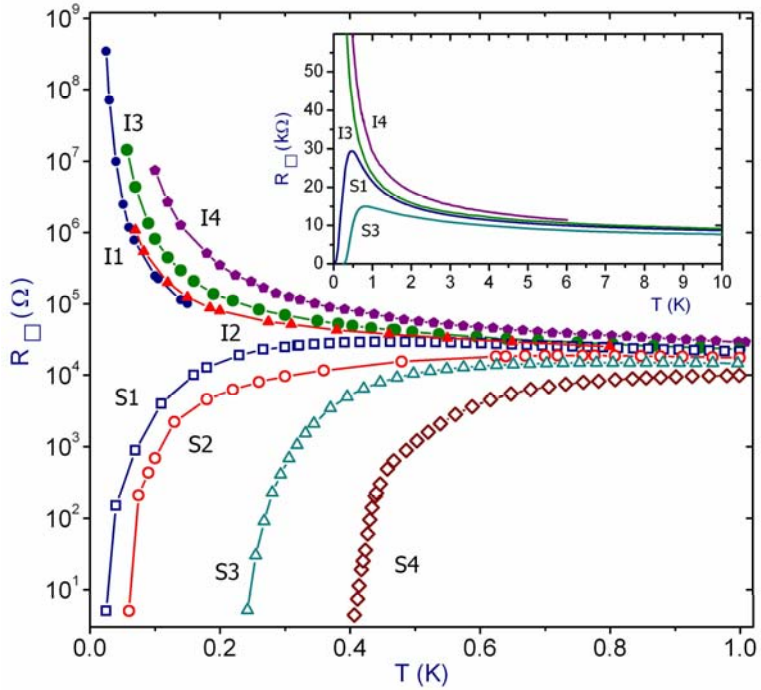
Insulating side of the transition

InO_x, **Be**, and **TiN** films

TiN films

T.I. Baturina, A.Yu. Mironov, V.M. Vinokur,
M.R. Baklanov, and C. Strunk,
cond-mat/0705.1602



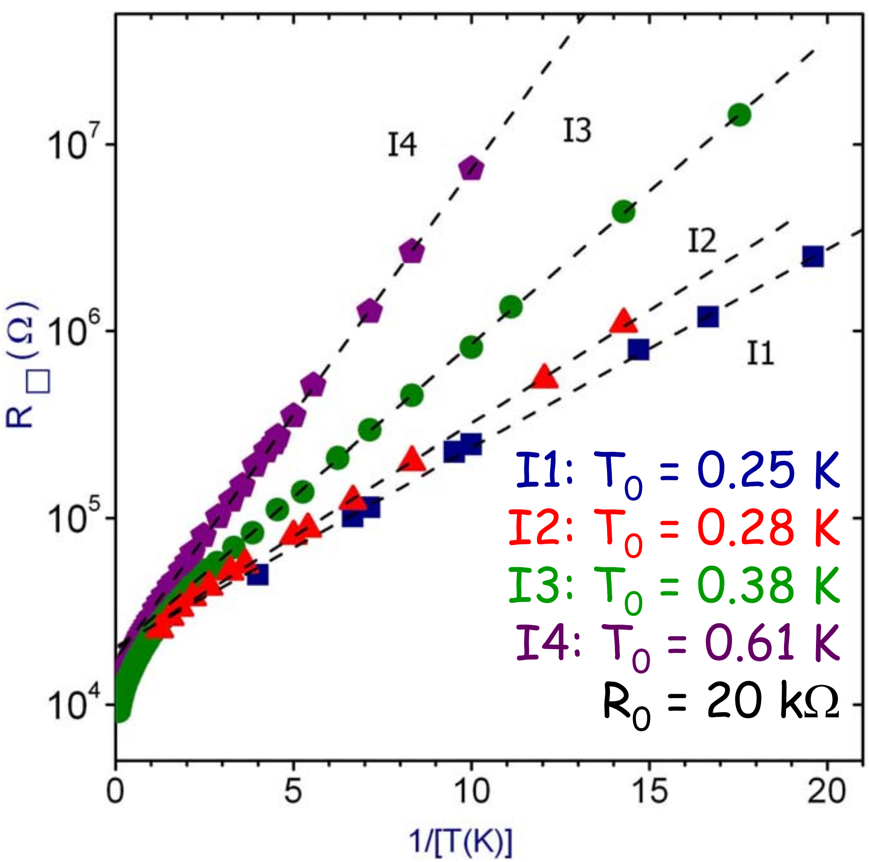


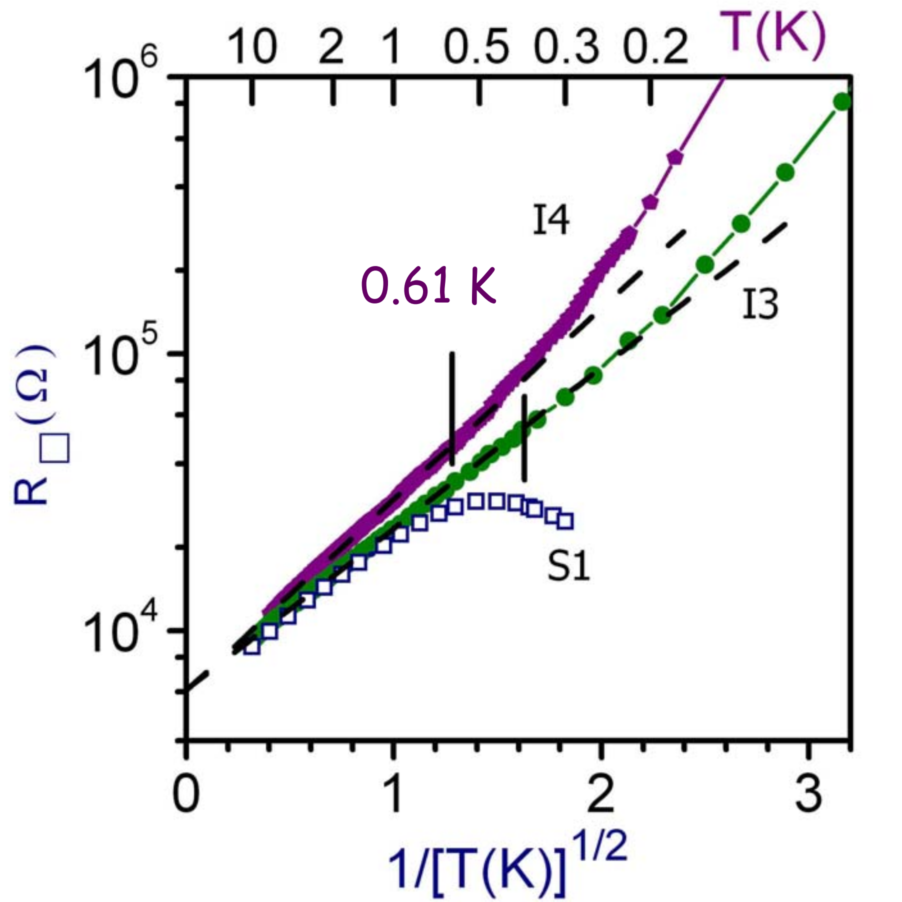
$$R = R_0 \exp(T_0/T)$$

At low temperatures we observe an Arrhenius behavior of the resistance

TiN films

T. B., A.Yu. Mironov, V.M. Vinokur,
M.R. Baklanov, and C. Strunk,
cond-mat/0705.1602



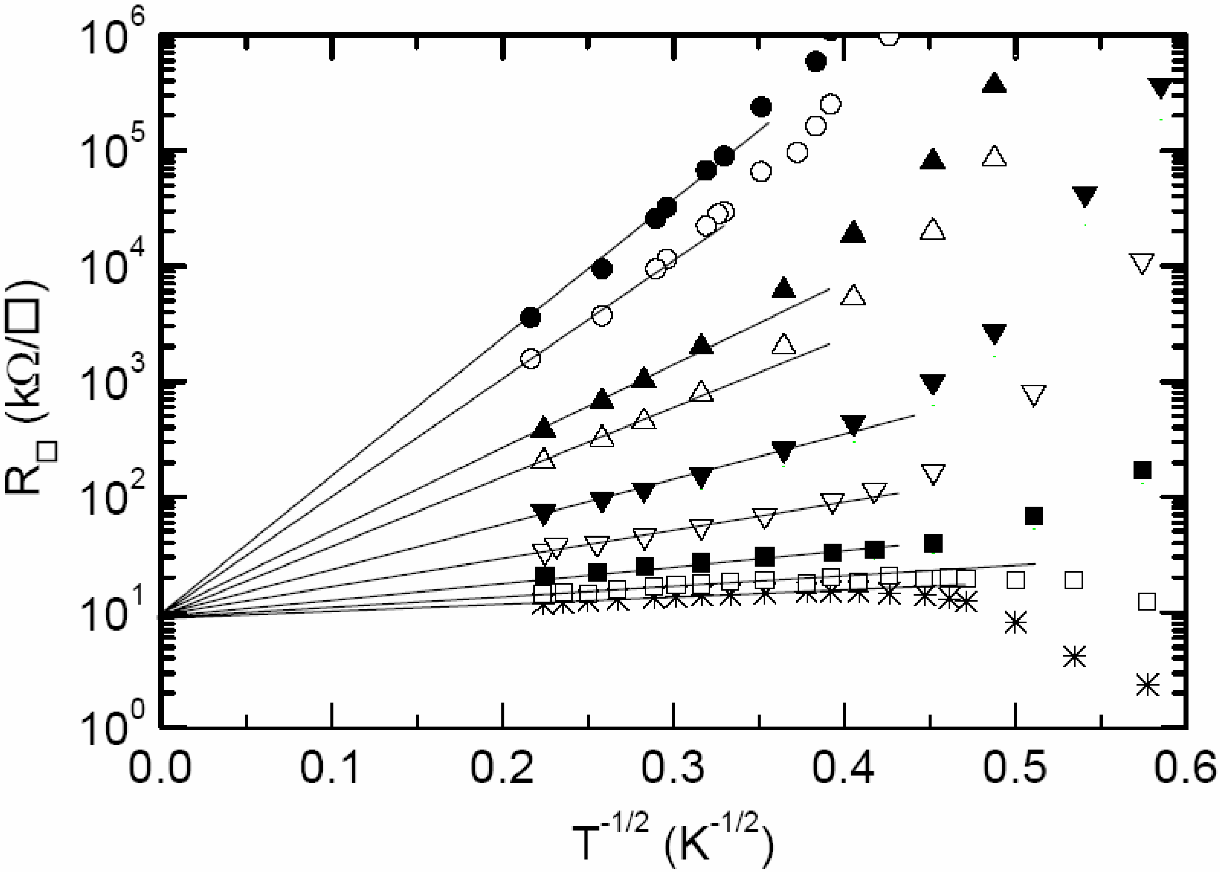


$$R = R_0 \exp(T_0/T)$$

At low temperatures we observe
an Arrhenius behavior
of the resistance

$$R = R_1 \exp(T_1/T)^{1/2}$$

Be films



W. Wu and E. Bielejec, cond-mat/051121.

Fig. 1 Selected curves of $R_\square$ versus $1/T^{1/2}$ for one Be film section following deposition steps to increase film thickness (from top to bottom). The thickness for these films changed from 4.6 Å to about 10 Å. The straight lines are draw as a guide for eye, showing that in the high-T regime all the curves follow straight lines that converge to about 10 kΩ/□ in the T→ ∞ limit. The films for bottom curve is superconducting at low temperatures.

InO_x films

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

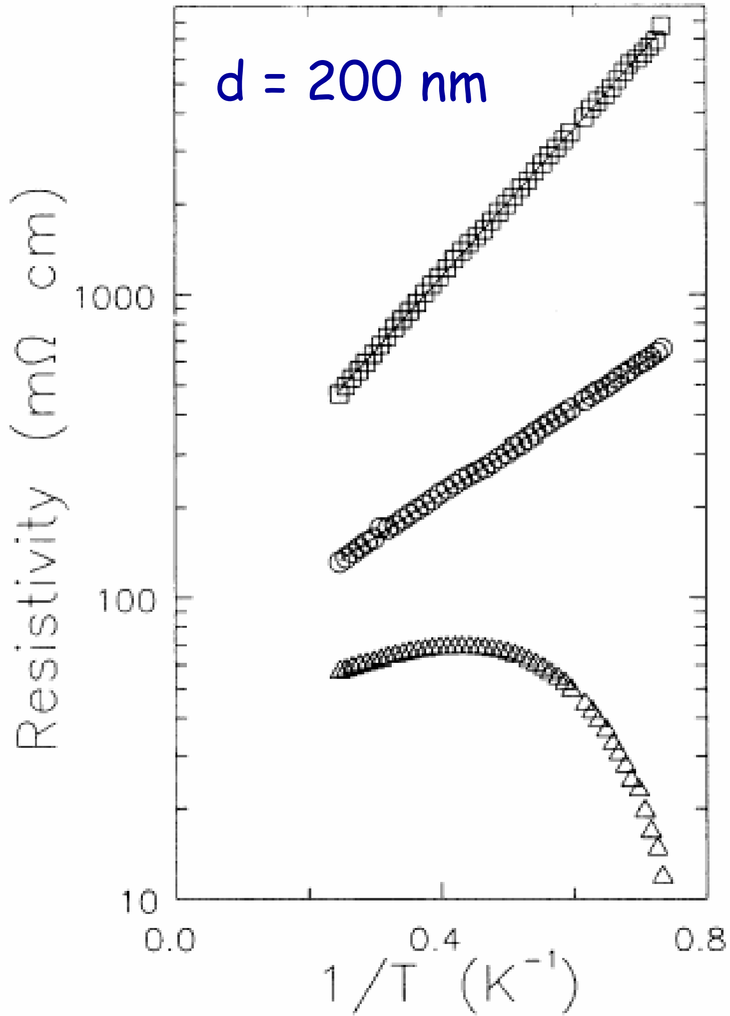


FIG. 2. Resistivity vs temperature of a typical batch of indium-oxide samples measured between 1.3 and 4.11 K. The upper curve is for the as-deposited film. The lower curves depict the $R(T)$ of the same sample after thermal annealing. The solid lines for the top two curves are fits to an Arrhenius behavior from which the various T_0 values were extracted. $k_F l$ values of these samples are 0.177 (□), 0.21 (○), and 0.272 (△). The sample thickness is 2000 Å and $n = 4\times10^{21}$.

InO_x film

D. Kowal and Z. Ovadyahu
Solid State Comm. 90, 783 (1994).

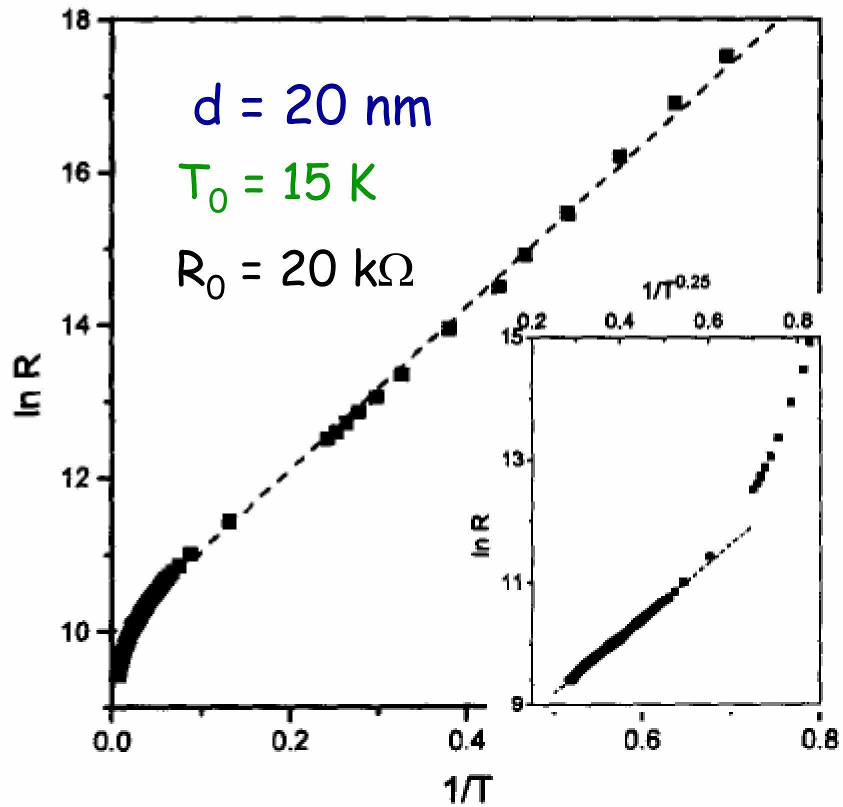
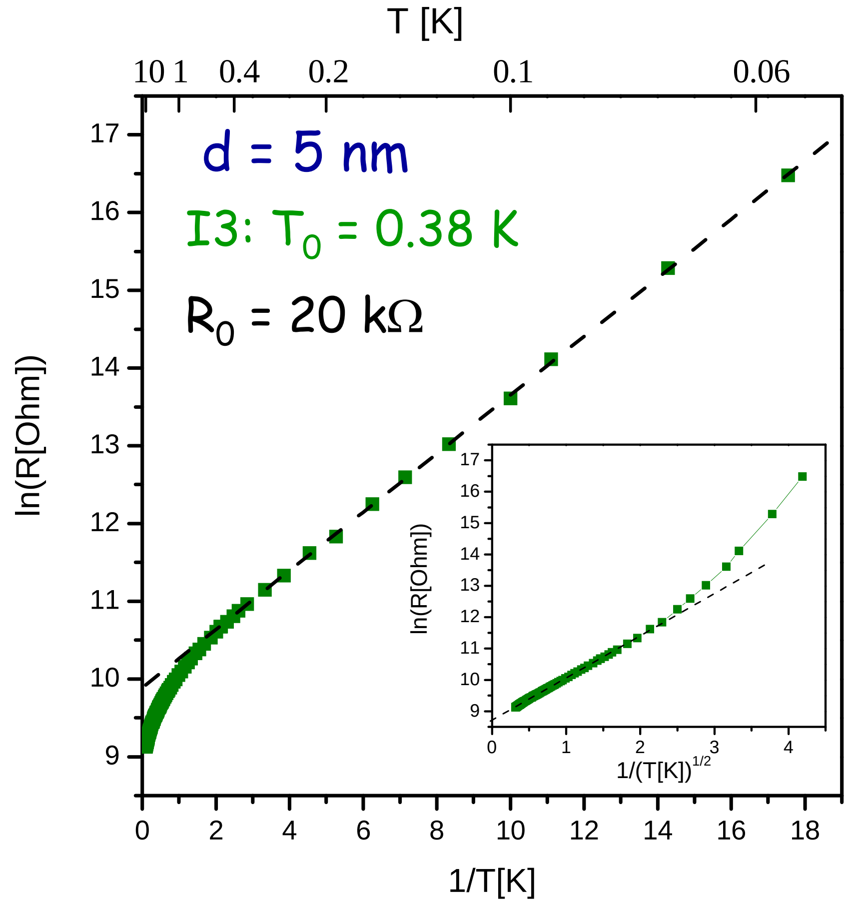


Fig. 1. The temperature dependence of the resistance for a 200Å thick sample in the range 1.4K-200K. Below 4.1K simple activation is observed with T_0=15K. Inset: The same data plotted against $T^{1/4}$ exhibits 3D VRH above 10K. The localization length determined from the slope and the known density of electrons is 12Å.

TiN film



Insulating side of the transition
InO_x, Be, and TiN films

- at low temperatures
- activation law

$$R = R_0 \exp(T_0/T)$$

- at temperatures higher than T_0

InO_x films

- 3D Mott's VRH

$$R = R_1 \exp(T_1/T)^{1/4}$$

Be and TiN films

- the ES hopping

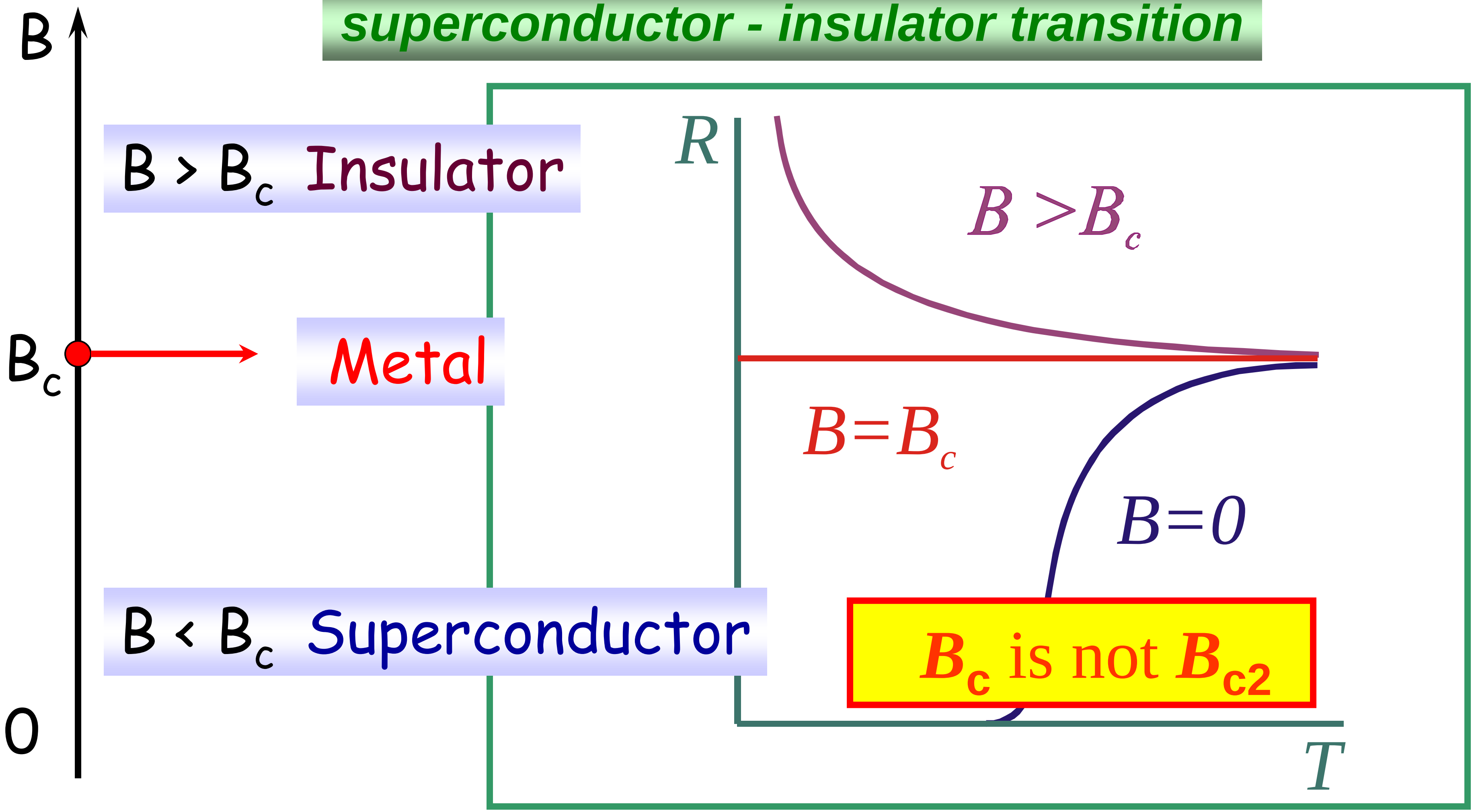
$$R = R_1 \exp(T_1/T)^{1/2}$$

Suppression of Superconductivity by Magnetic field

T = 0

Field-induced

superconductor - insulator transition



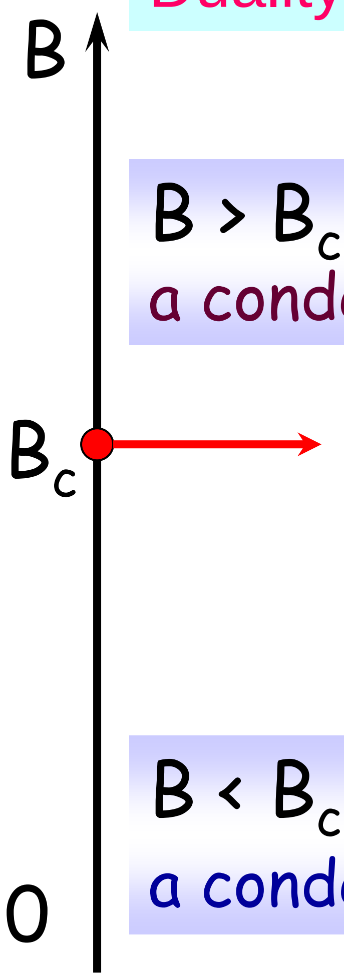
Field-induced superconductor – insulator transition

$T = 0$

***** Quantum phase transition *****

Duality between the dynamics of Cooper pairs and vortices

Matthew P.A. Fisher, PRL **65**, 923 (1990)



$B > B_c$ **Insulator:**

a condensate of vortices; Cooper pairs are localized

Metal:

The resistance has a finite, nonzero value at $T = 0$.

This value *is universal* – $R_c = h/(2e)^2$

$= 6.45\ k\Omega$

$B < B_c$ **Superconductor:**

a condensate of Cooper pairs; vortices are localized

Field-induced superconductor – insulator transition

$T = 0$

*** Quantum phase transition ***

Continuos zero-temperature phase transition

Matthew P.A. Fisher, PRL **65**, 923 (1990)

B

$B > B_c$ quantum disordered phase

B_c

$B = B_c$ quantum critical point

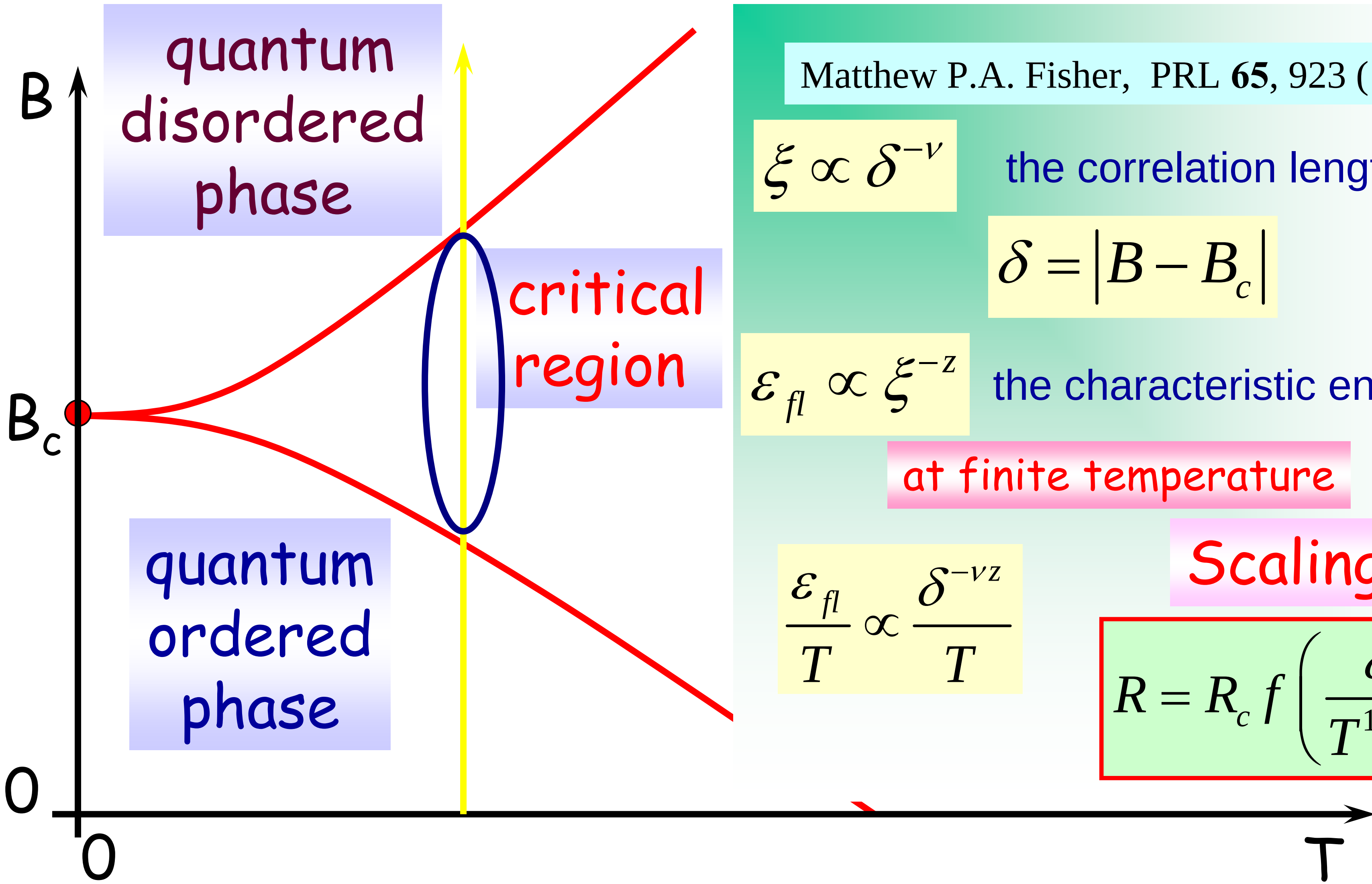
$B < B_c$ quantum ordered phase

0

Field-induced superconductor – insulator transition

T > 0

*** Quantum phase transition ***



Matthew P.A. Fisher, PRL **65**, 923 (1990)

$\xi \propto \delta^{-\nu}$ the correlation length

$\delta = |B - B_c|$

$\varepsilon_{fl} \propto \xi^{-z}$ the characteristic energy

at finite temperature

$$\frac{\varepsilon_{fl}}{T} \propto \frac{\delta^{-\nu z}}{T}$$

Scaling

$$R = R_c f\left(\frac{\delta}{T^{1/\nu z}}\right)$$

Field-induced superconductor – insulator transition

*** Quantum phase transition ***

EXPERIMENT

✓ Fan-shaped curves

$dR/dT > 0$ at $B < B_c$

$dR/dT < 0$ at $B > B_c$

✓ Scaling

$$R = R_c f(|B - B_c|/T^{1/\nu z})$$

✓ Negative magnetoresistance at high magnetic fields

(as result of the break up of the localized Cooper pairs)

V.F. Gantmakher, et. al. JETP Lett. 68, 363 (1998)

picture-gallery

"In search of Magnetic-field-driven superconductor-insulator transition"

***** collection *****

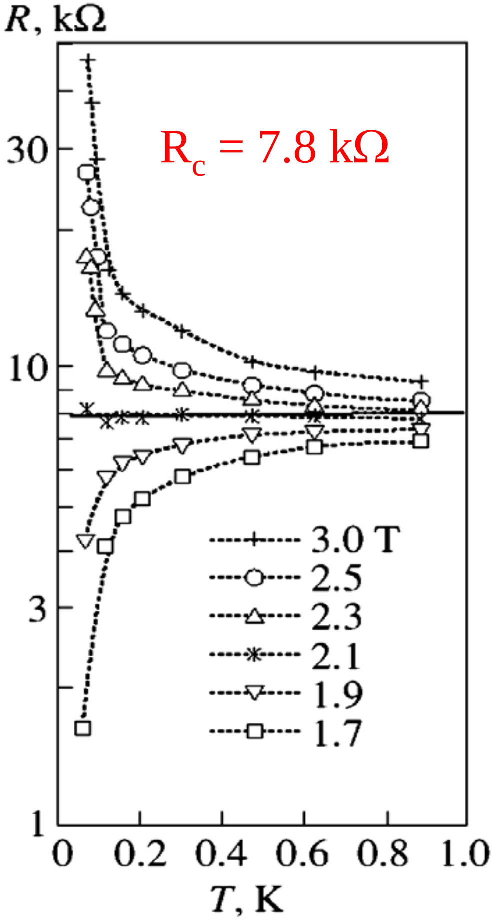
Bi, MoSi, MoGe, Ta, InO_x, Be, TiN

Field-induced superconductor – insulator transition

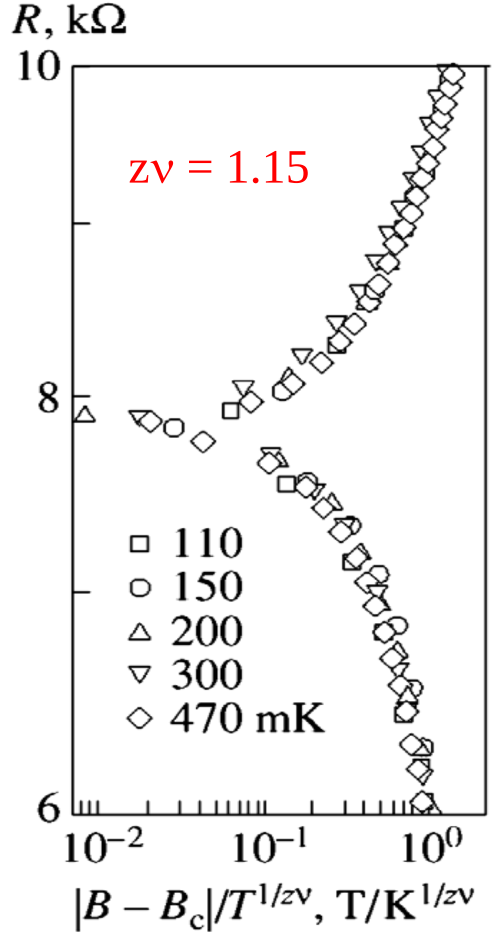
V. F. Gantmakher, M. V. Golubkov, V. T. Dolgopolov, A. A. Shashkin, G. E. Tsydynzhapov, JETP Lett. **71**, 160 (2000); **71**, 473 (2000)

InO_x films

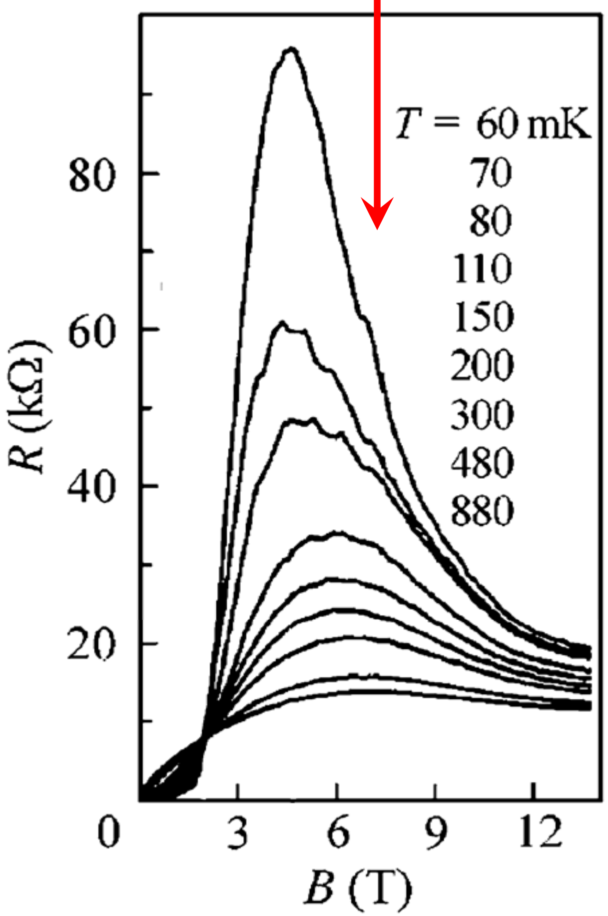
Fan-shaped curves



Scaling



Negative magnetoresistance

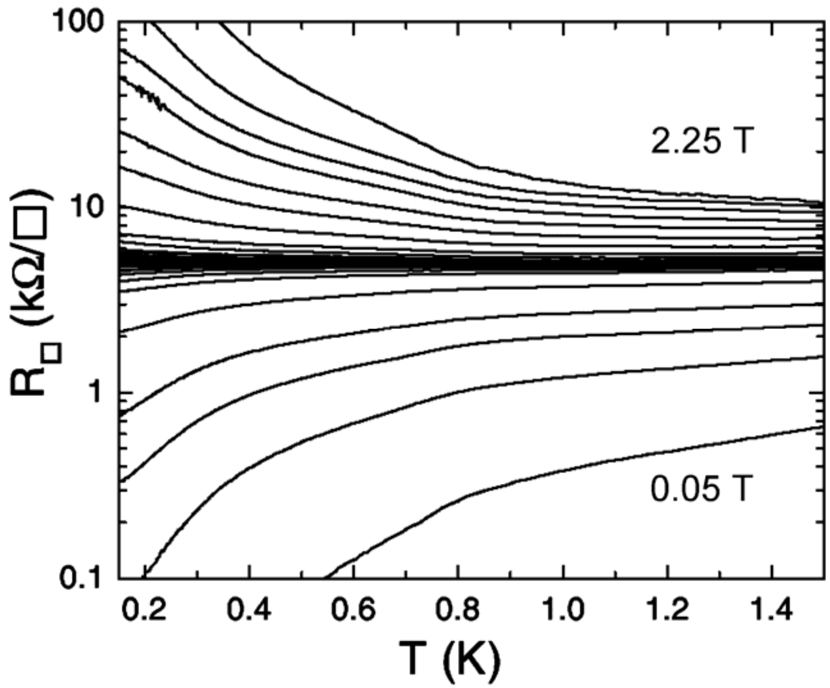


Field-induced superconductor – insulator transition

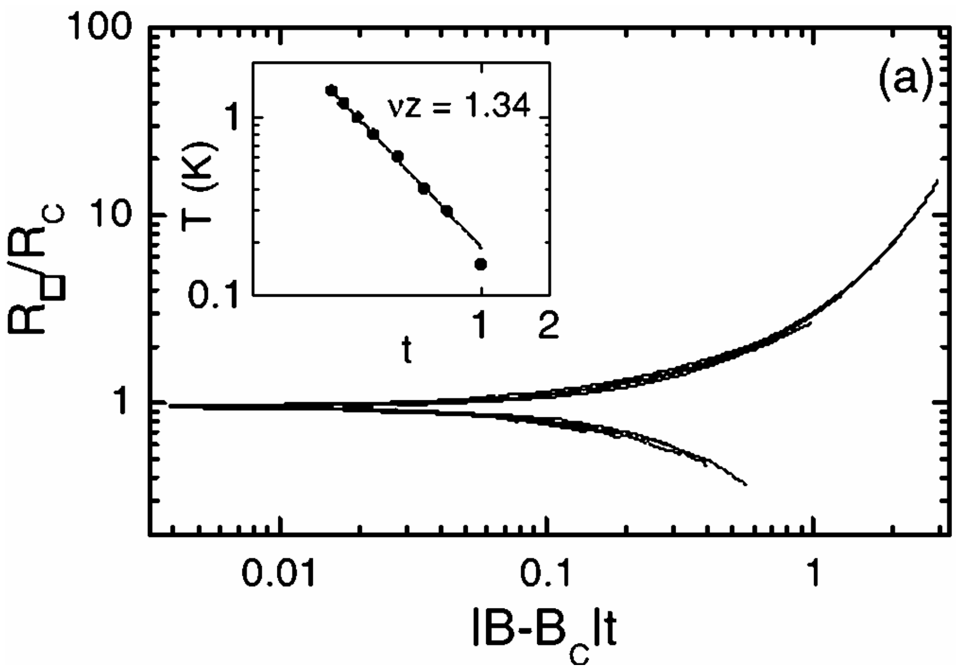
E. Bielejec and Wenhao Wu, PRL **88**, 206802 (2002).

Be films

Fan-shaped curves



Scaling



Field-induced superconductor – insulator transition

VOLUME 74, NUMBER 15 PHYSICAL REVIEW LETTERS 10 APRIL 1995

Superconducting-Insulating Transition in Two-Dimensional *a*-MoGe Thin Films

Ali Yazdani* and Aharon Kapitulnik
Department of Applied Physics, Stanford University, Stanford, California 94305

MoGe

$d = 8$ nm, $R_c = 1750\ \Omega$

Fan-shaped curves

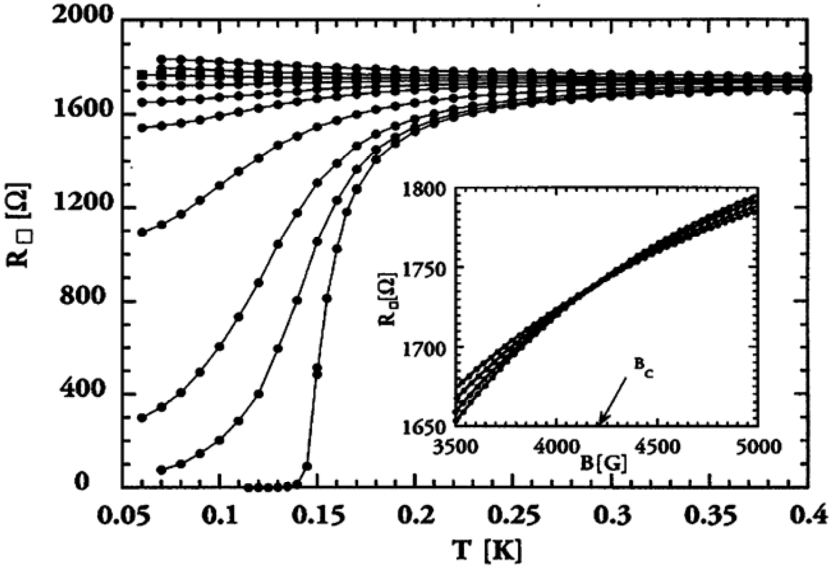


FIG. 1. Zero bias resistance of sample 2 plotted versus temperature at $B = 0, 0.5, 1.0, 2.0, 3.0, 4.0, 4.4, 4.5, 5.5, 6$ kG. In the inset, $R_{\square}(B, T, E = 0)$ for the same sample measured versus field, at $T = 80, 90, 100, 110$ mK.

Scaling

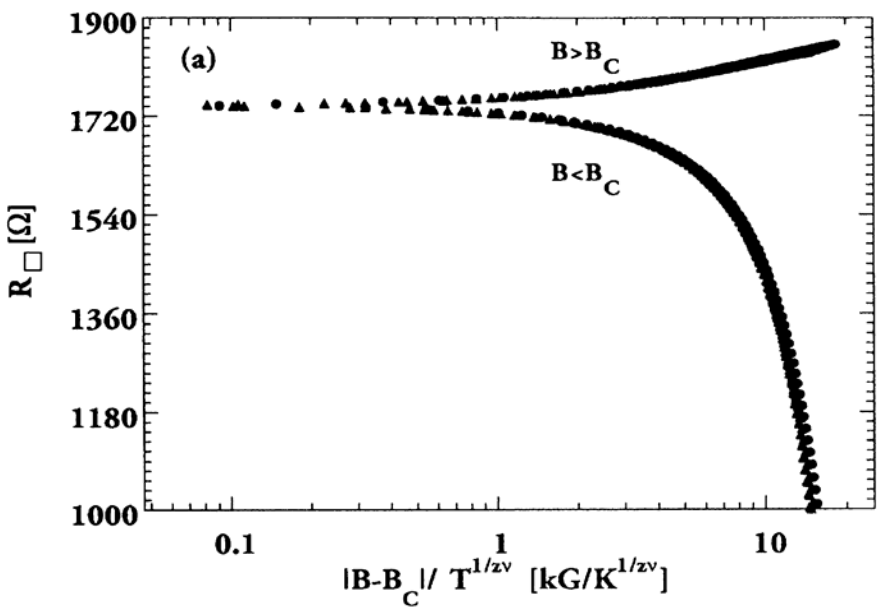


FIG. 3. Top: Scaling of $R_{\square}(B, T, E = 0)$ for sample 2 measured at $T = 80, 90, 100, 110$ mK ($B_c = 4.19$ kG, $\nu z = 1.36$).

Field-induced superconductor – insulator transition

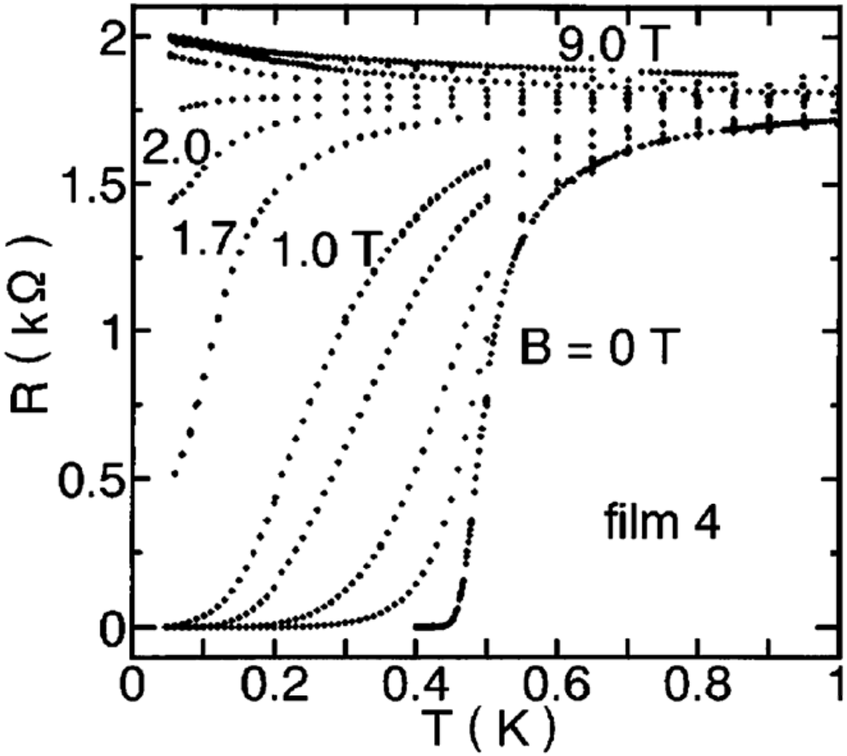
PHYSICAL REVIEW B VOLUME 58, NUMBER 5 1 AUGUST 1998-I

Anomalous magnetoresistance near the superconductor-insulator transition in ultrathin films of *a*-Mo_xSi_{1-x}

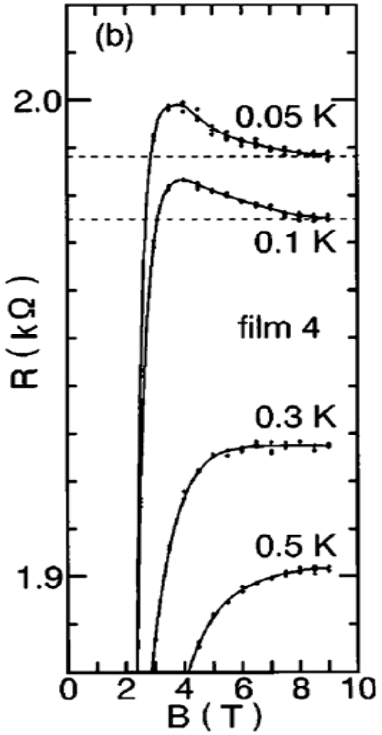
MoSi

S. Okuma, T. Terashima, and N. Kokubo
Research Center for Very Low Temperature System, Tokyo Institute of Technology, 2-12-1, Ohokayama, Meguro-ku, Tokyo 152-8551, Japan

Fan-shaped curves



Negative magnetoresistance

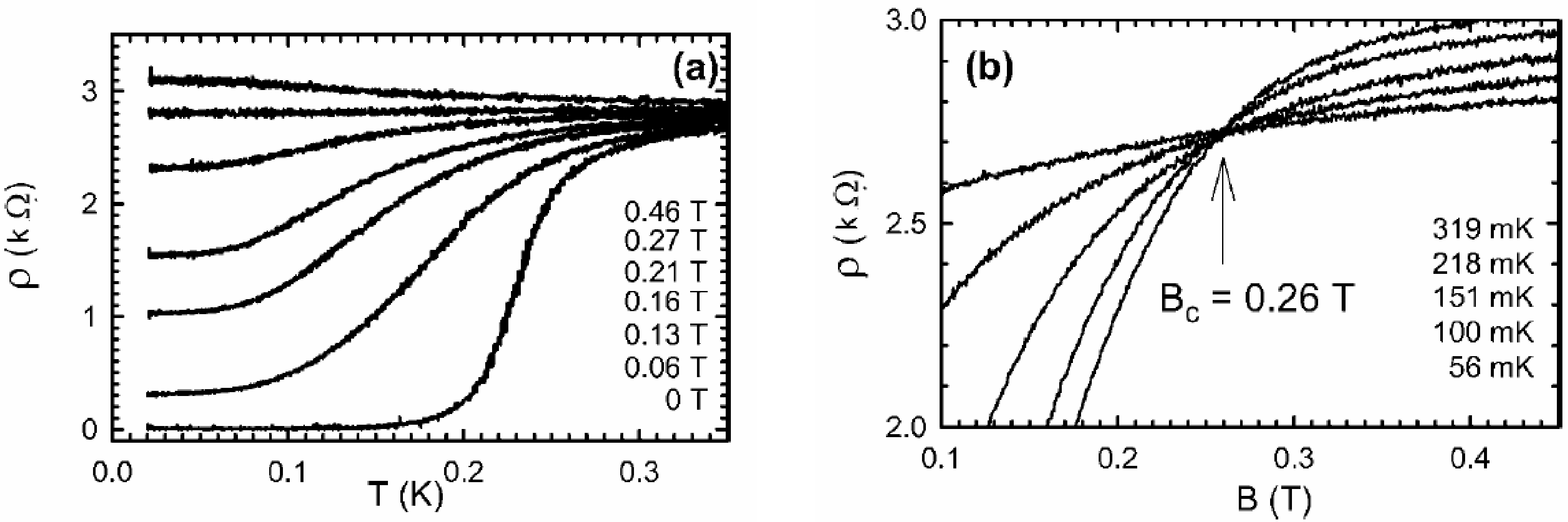


Field-induced superconductor – insulator transition

Y. Qin, C.L. Vicente, J. Yoon,
PRB 73, 100505(R) (2006).

Ta films

The resistance in the low T limit increases toward ρ_n with increasing B, and at B=0.27 T it becomes almost T independent over the entire T range. At higher fields [the top trace in Fig. 2(a)] $d\rho/dT$ becomes negative, which we take as an indication for an insulator.



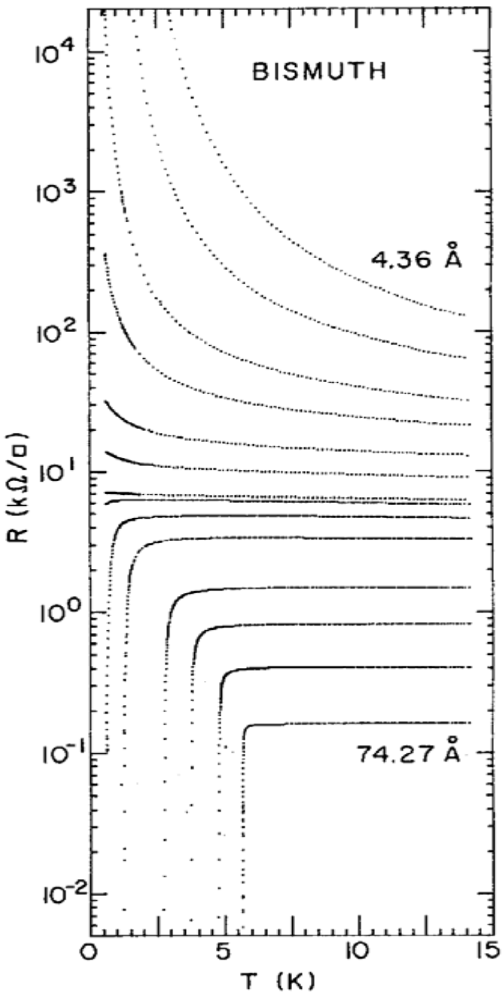
Field-induced superconductor – insulator transition ?

PHYSICAL REVIEW B VOLUME 60, NUMBER 6 1 AUGUST 1999-II

Superconductor-insulator transition in two dimensions

Bi films

N. Marković,* C. Christiansen, A. M. Mack, W. H. Huber, and A. M. Goldman



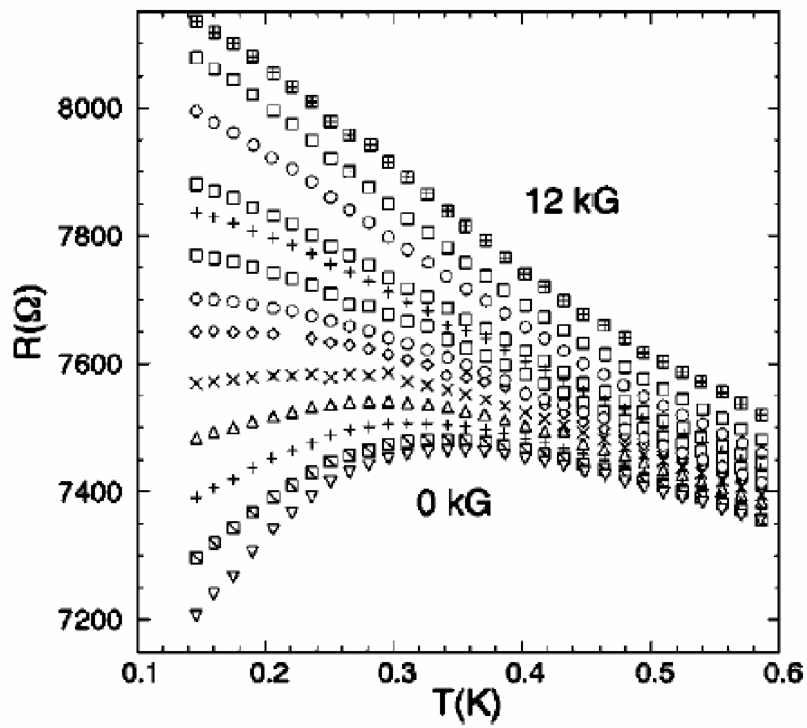


FIG. 1. Resistance per square as a function of temperature in different magnetic fields, ranging from 0 kG (bottom) to 12 kG (top), in 1 kG increments.

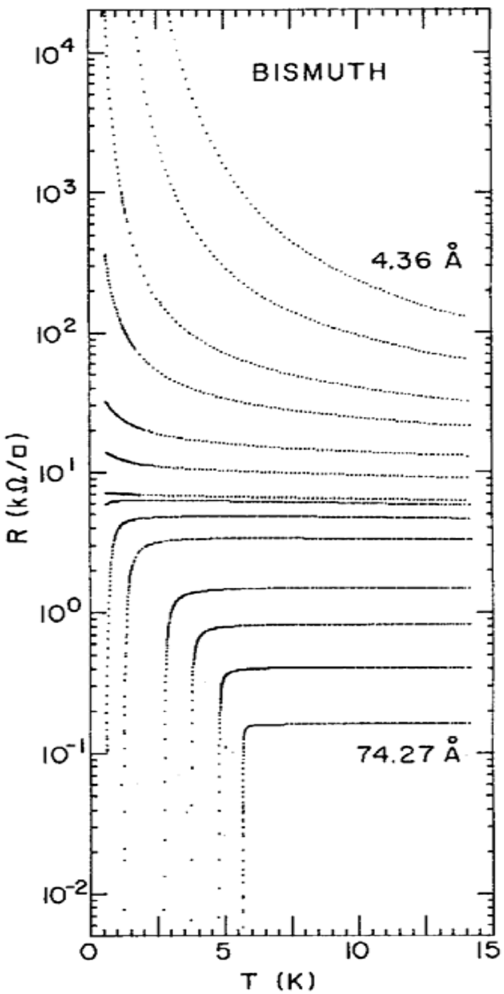
Field-induced superconductor – insulator transition

PHYSICAL REVIEW B VOLUME 60, NUMBER 6 1 AUGUST 1999-II

Superconductor-insulator transition in two dimensions

Bi films

N. Marković,* C. Christiansen, A. M. Mack, W. H. Huber, and A. M. Goldman



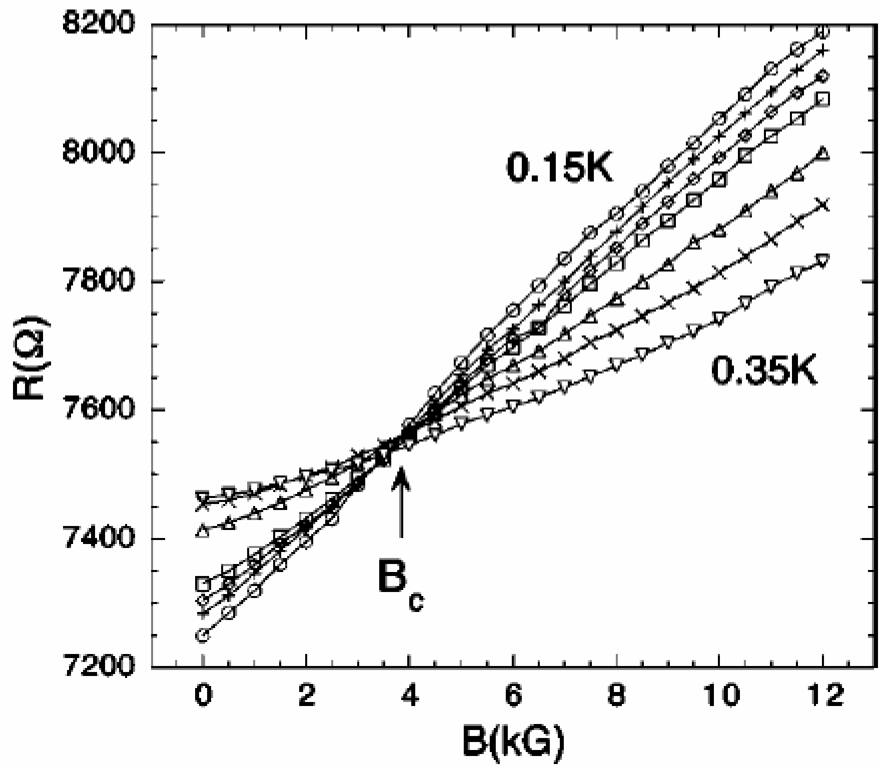


FIG. 2. Resistance per square as a function of magnetic field for a bismuth film close to the transition. Different curves represent different temperatures: 0.15, 0.17, 0.19, 0.2, 0.25, 0.3, and 0.35 K.

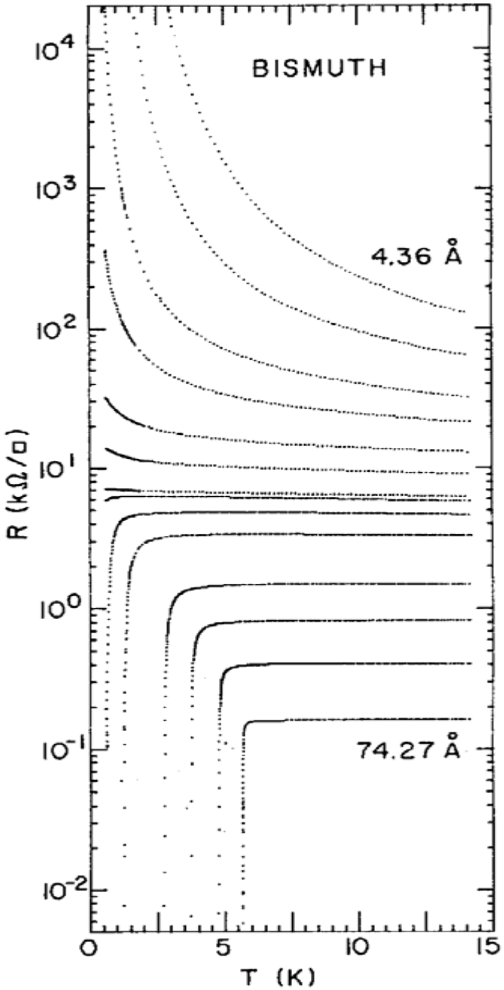
Field-induced superconductor – insulator transition

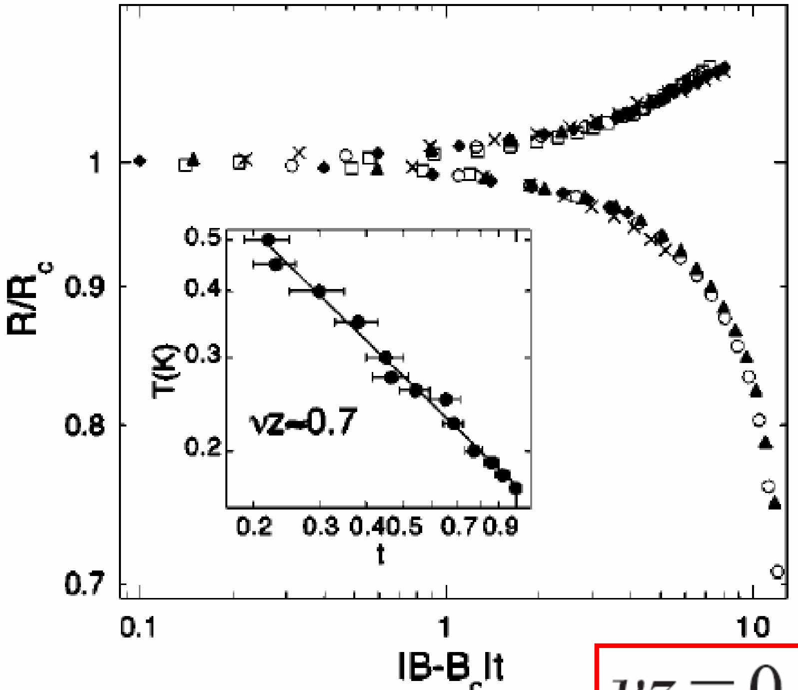
PHYSICAL REVIEW B VOLUME 60, NUMBER 6 1 AUGUST 1999-II

Superconductor-insulator transition in two dimensions

Bi films

N. Marković,* C. Christiansen, A. M. Mack, W. H. Huber, and A. M. Goldman





$\nu z = 0.7 \pm 0.2$

FIG. 3. Normalized resistance per square as a function of the scaling variable $T^{-1/\nu z}|B-B_c|$. Each symbol represents one film at different temperatures (only a small portion of the data is shown for clarity). Inset: The fitting a power law to the temperature dependence of the parameter t determines the value of νz.

Field-induced superconductor – insulator transition

InO_x films

M. Steiner and A. Kapitulnik, Physica C **422**, 16 (2005)

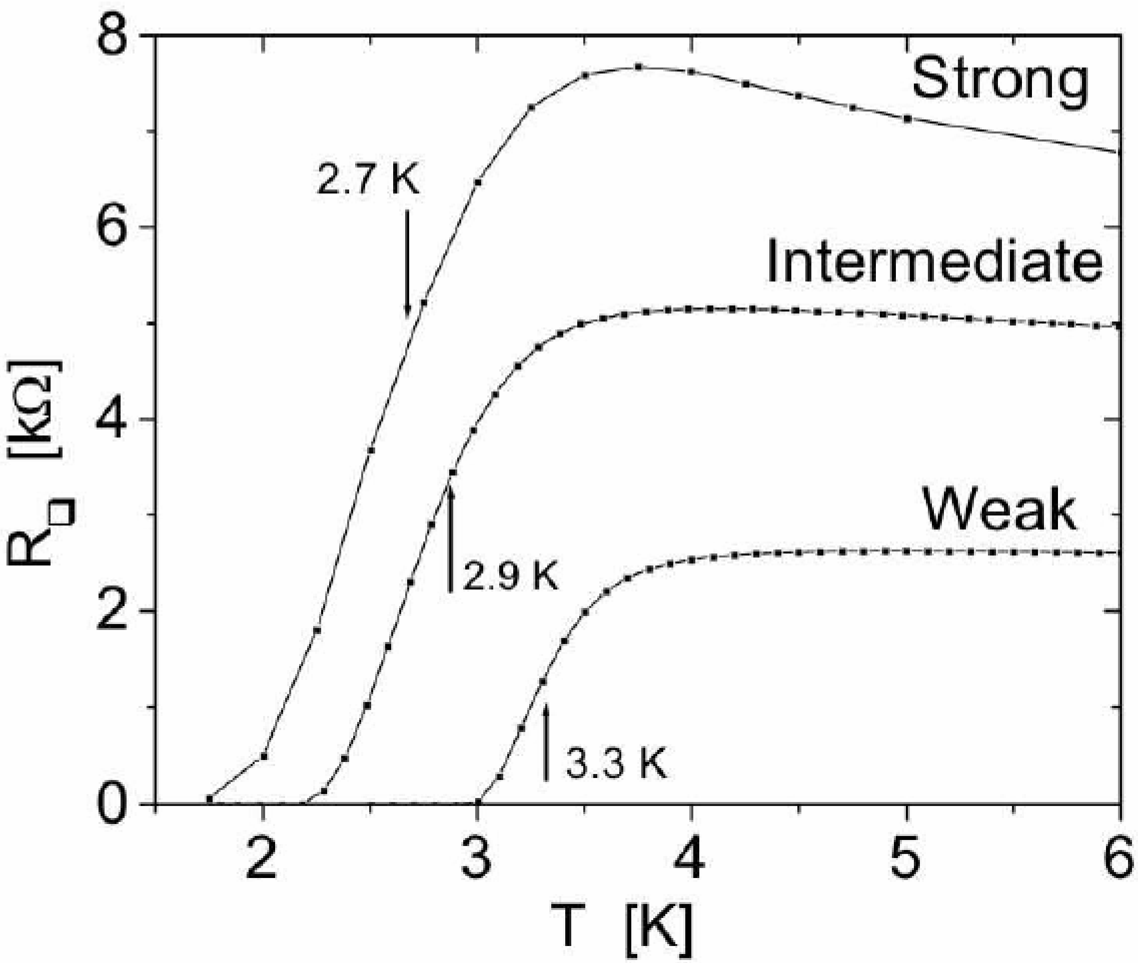
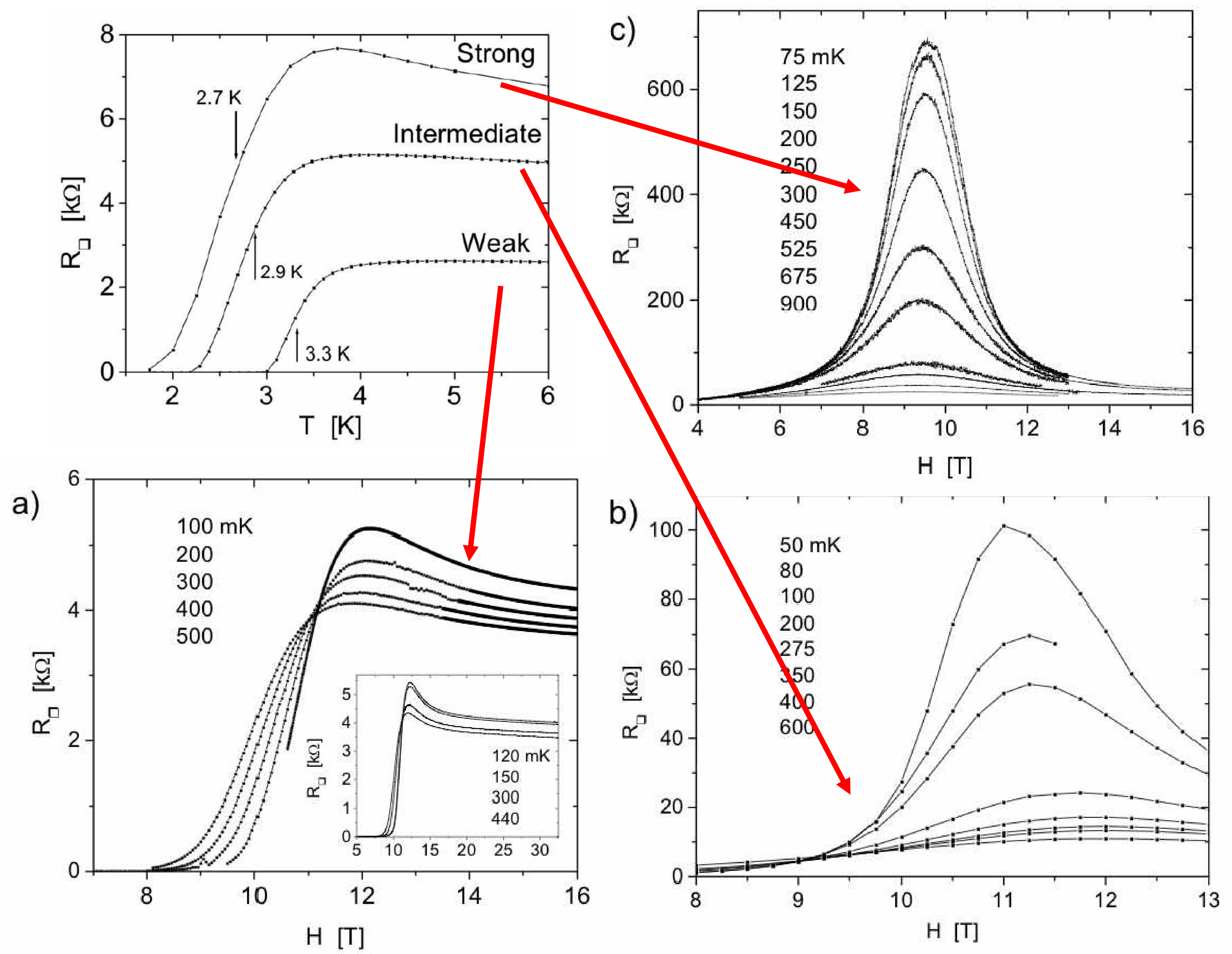


FIG. 1: Zero-field superconducting transitions for three samples. The labels denote the strength of the insulating phase, discussed later in the text. The mean field transition temperatures T_{c0} are indicated by the vertical arrows.



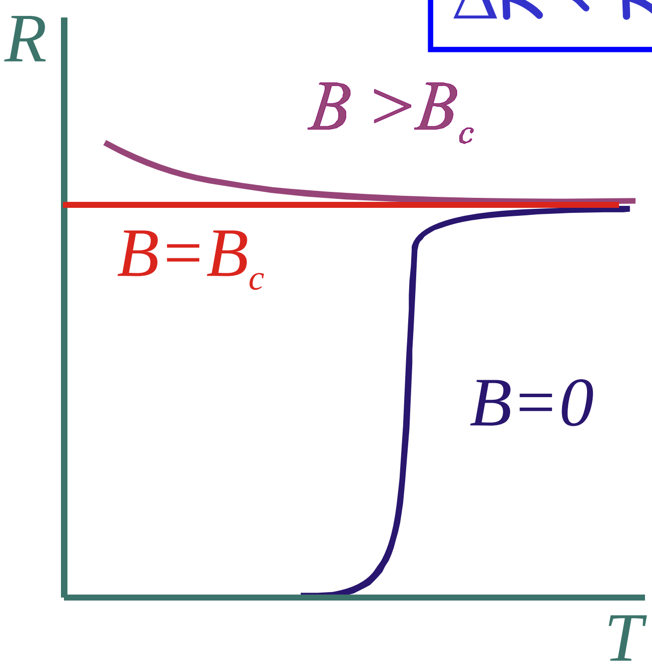
Strong
Intermediate
Weak
2.7 K
2.9 K
3.3 K
R□ [kΩ]
T [K]
c)
75 mK
125
150
200
250
300
450
525
675
900
H [T]
a)
100 mK
200
300
400
500
120 mK
150
300
440
b)
50 mK
80
100
200
275
350
400
600

Suppression of Superconductivity by **Magnetic Field**

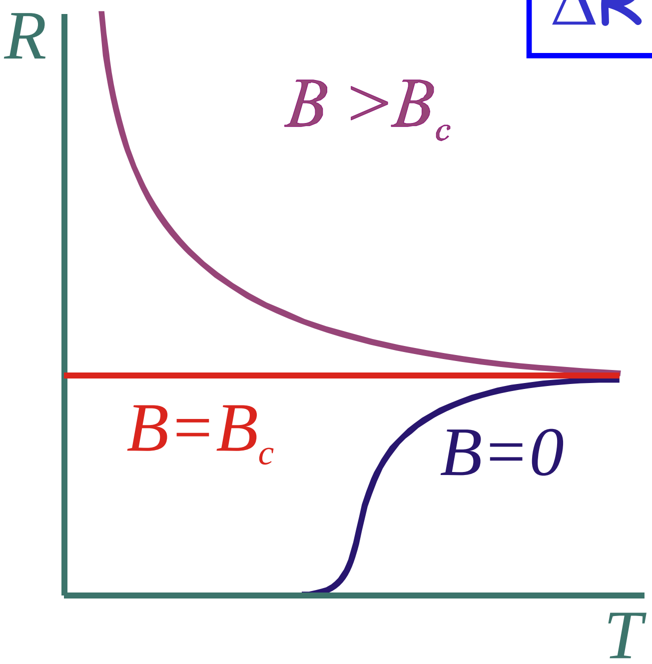
Field-induced...

superconductor – insulator transition

$\Delta R < R$



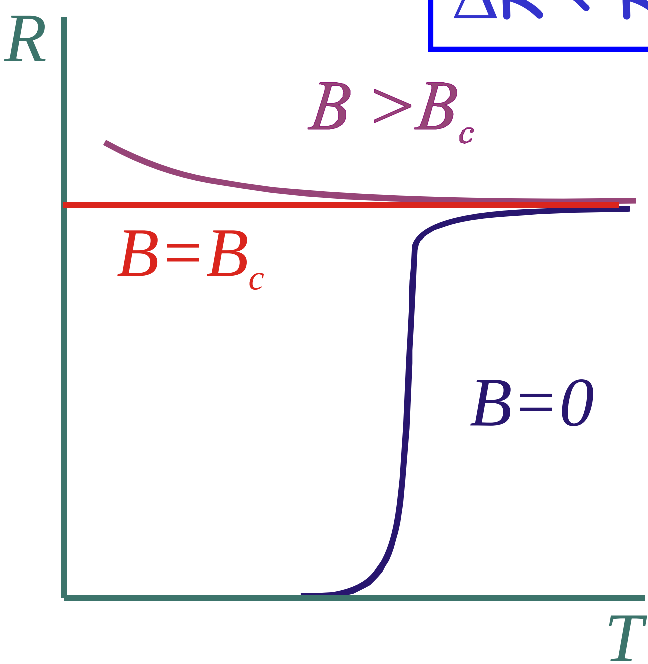
$\Delta R > R$



Suppression of Superconductivity by **Magnetic Field**

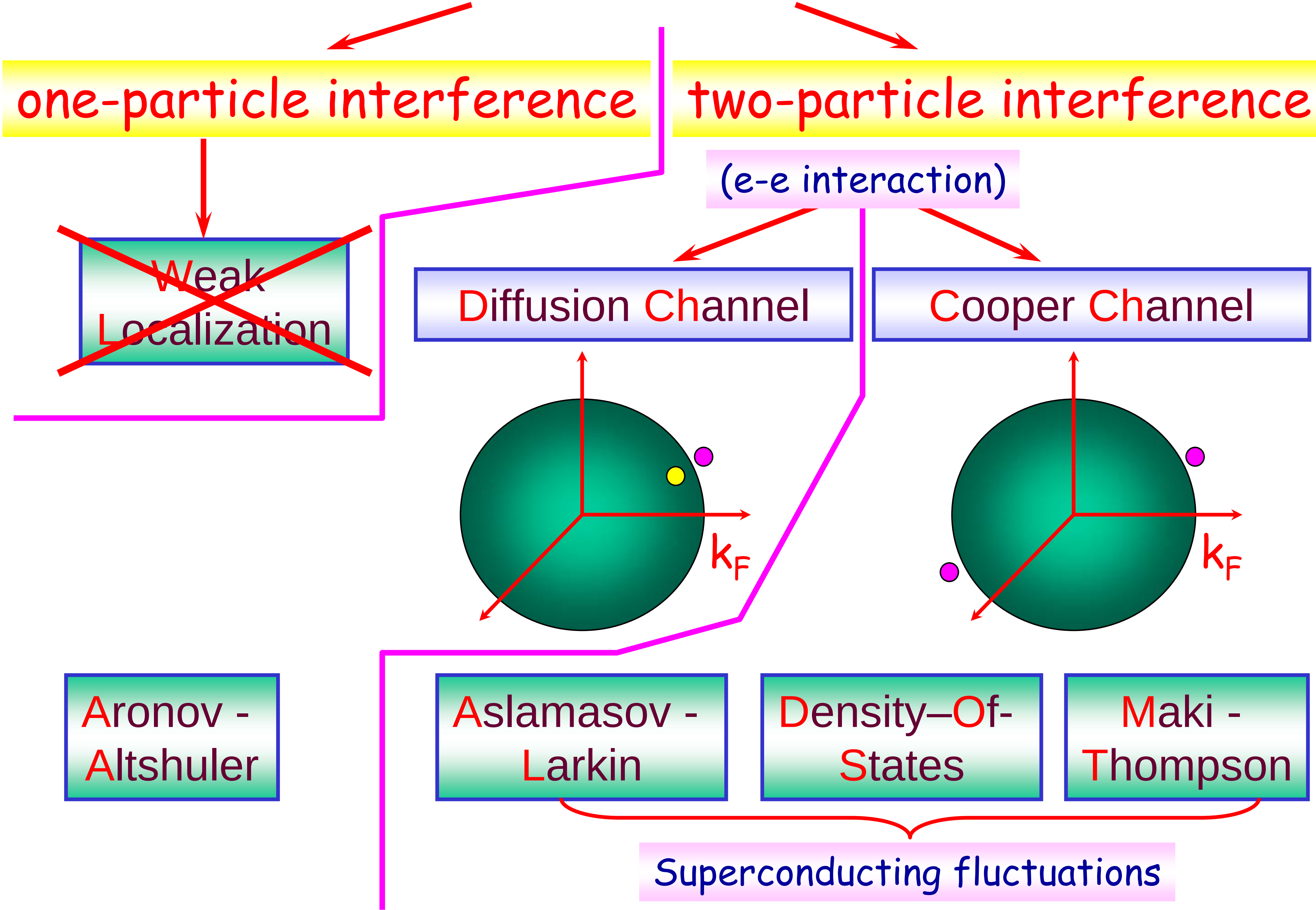
Field-induced...

$\Delta R < R$



This reminds us of the behavior of a disordered metal with quantum corrections to the conductivity rather than that of an insulator.

Quantum corrections to conductivity



Quantum corrections to conductivity

Aronov - Altshuler

$$\delta_{AA}\sigma(T) \propto \ln(T)$$

Aslamasov - Larkin | Density–Of-States | Maki - Thompson

Superconducting fluctuations

at $T << T_{c0}$ in magnetic field ???

V.M. Galitski and A.I. Larkin, PRB **63**, 174506 (2001)

An analytical expression for the fluctuation conductivity in the region close to the transition line at low temperatures

$$T_{c0}\tau << 1,$$

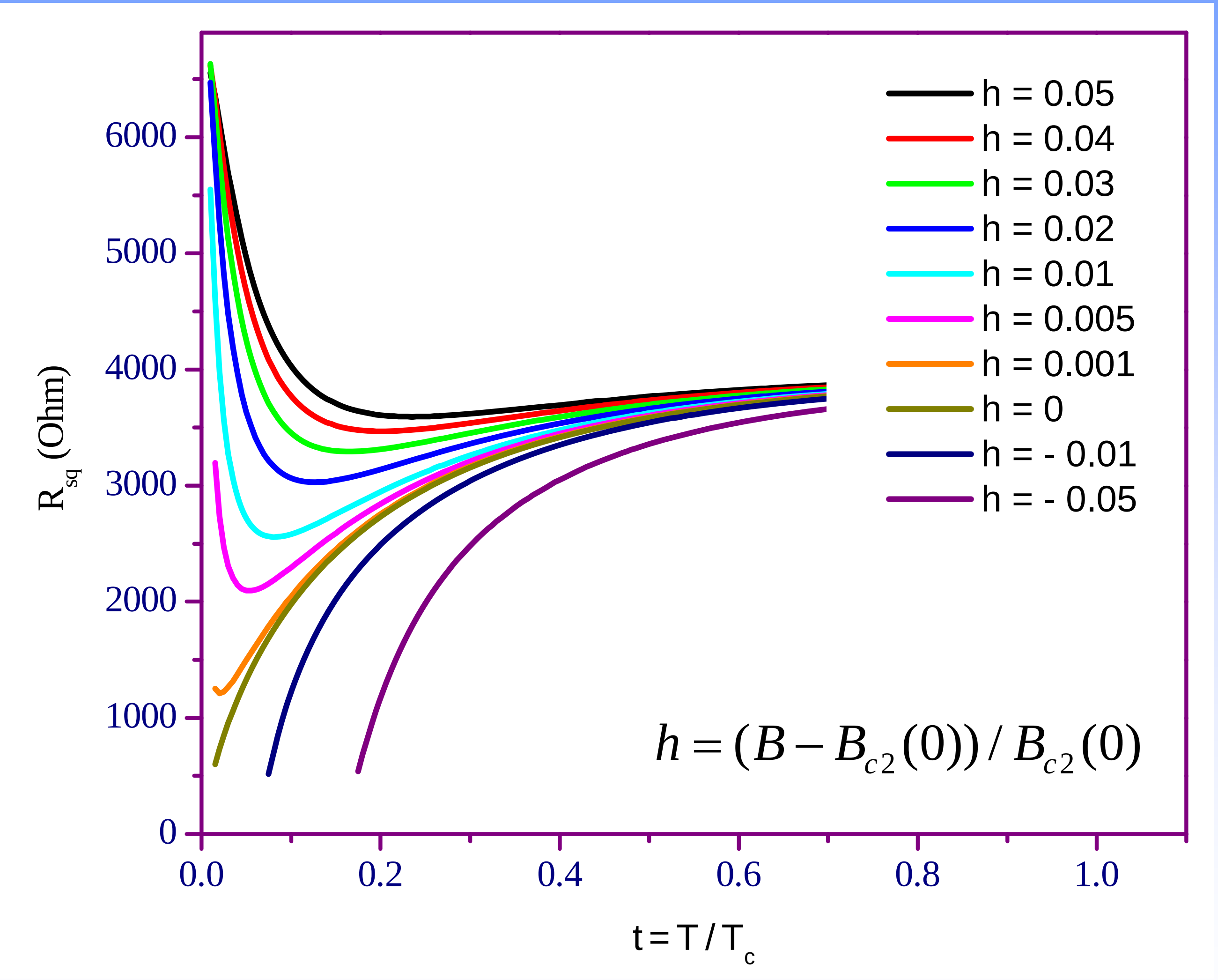
$$\delta\sigma = \frac{2e^2}{3\pi^2\hbar}\left[-\ln\frac{r}{h} - \frac{3}{2r} + \psi(r) + 4[r\psi'(r) - 1]\right]$$

$$t = T/T_{c0} << 1, \qquad h = (B - B_{c2}(T))/B_{c2}(0) << 1$$

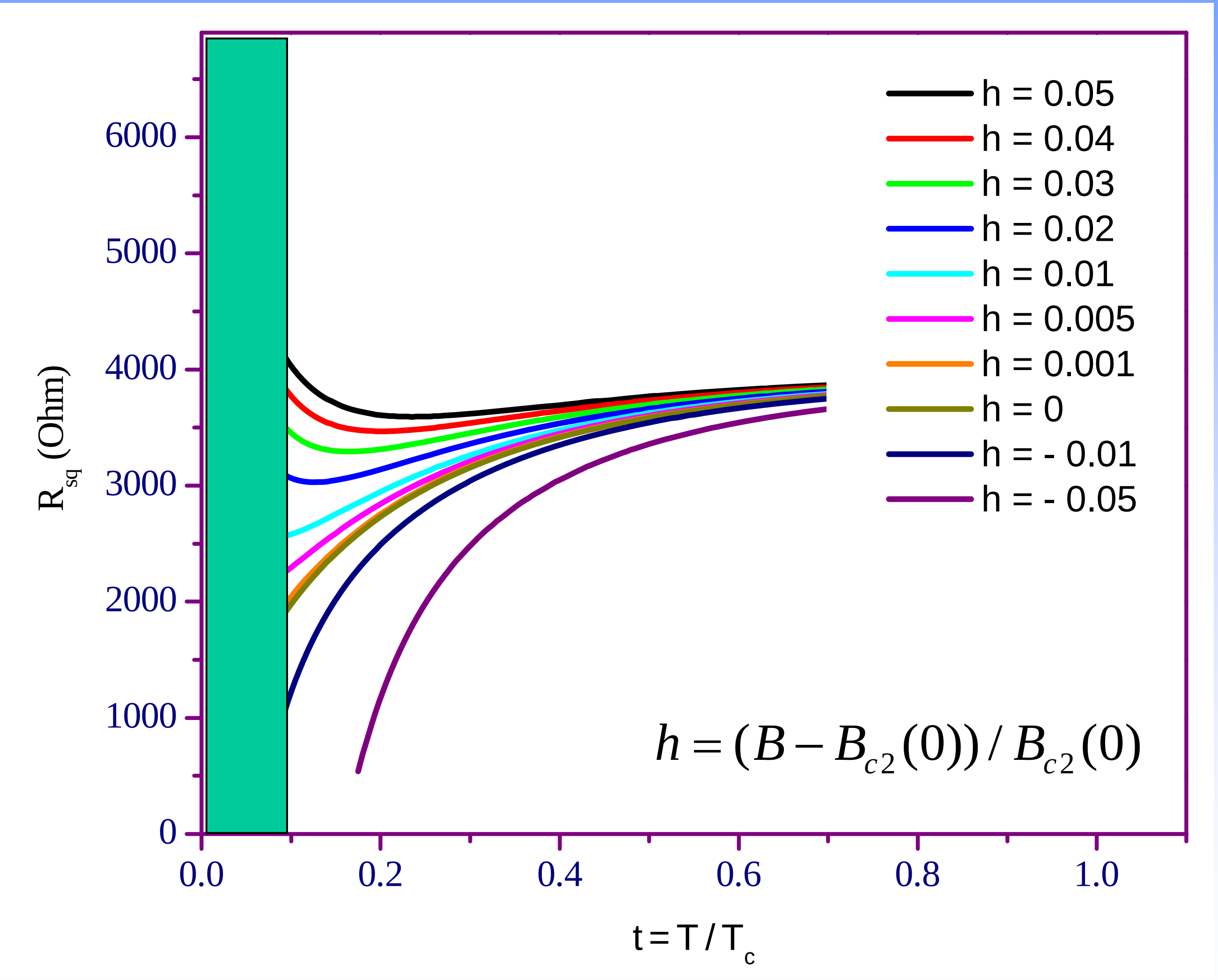
$$r = (1/2\gamma)h/t$$

$$\gamma = 1.781$$

Superconducting fluctuations at low temperature



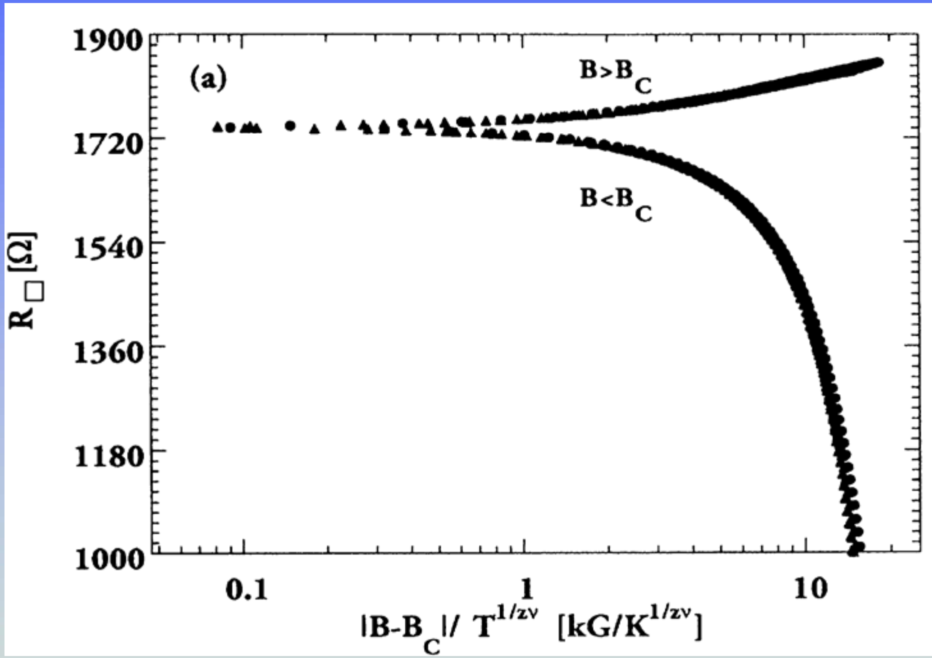
Superconducting fluctuations at low temperature

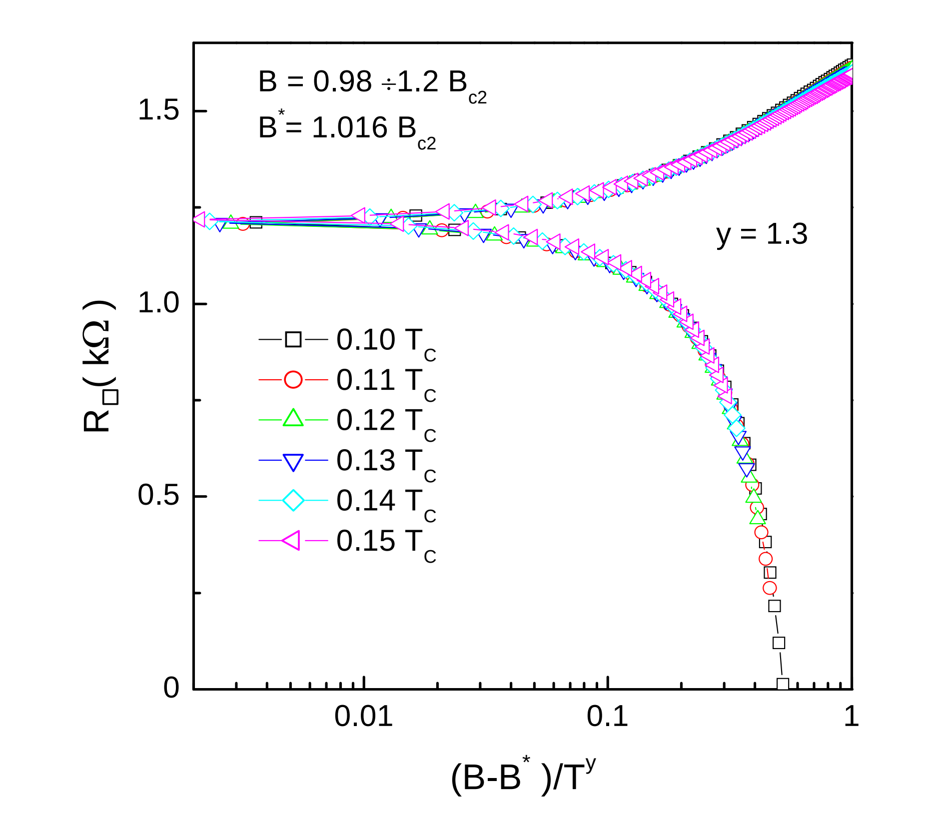


Superconducting fluctuations at low temperature

Scaling

A.Yazdani and A.Kapitulnik (1995)





$T_C = 0.15$ K $\quad B_C = 4.19$ kG

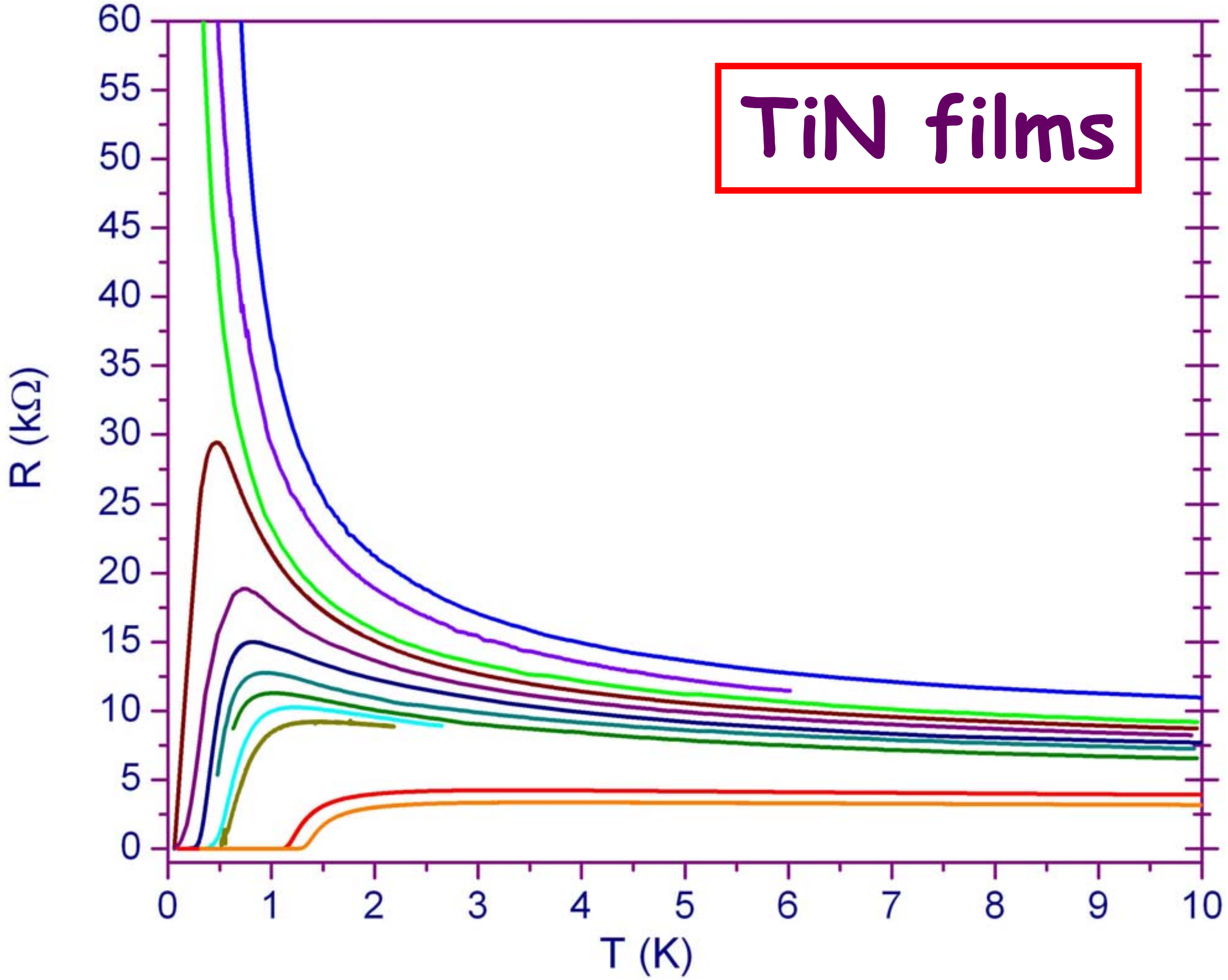
$T = 0.08 \div 0.11$ K $\quad B - B_C < 1$ kG

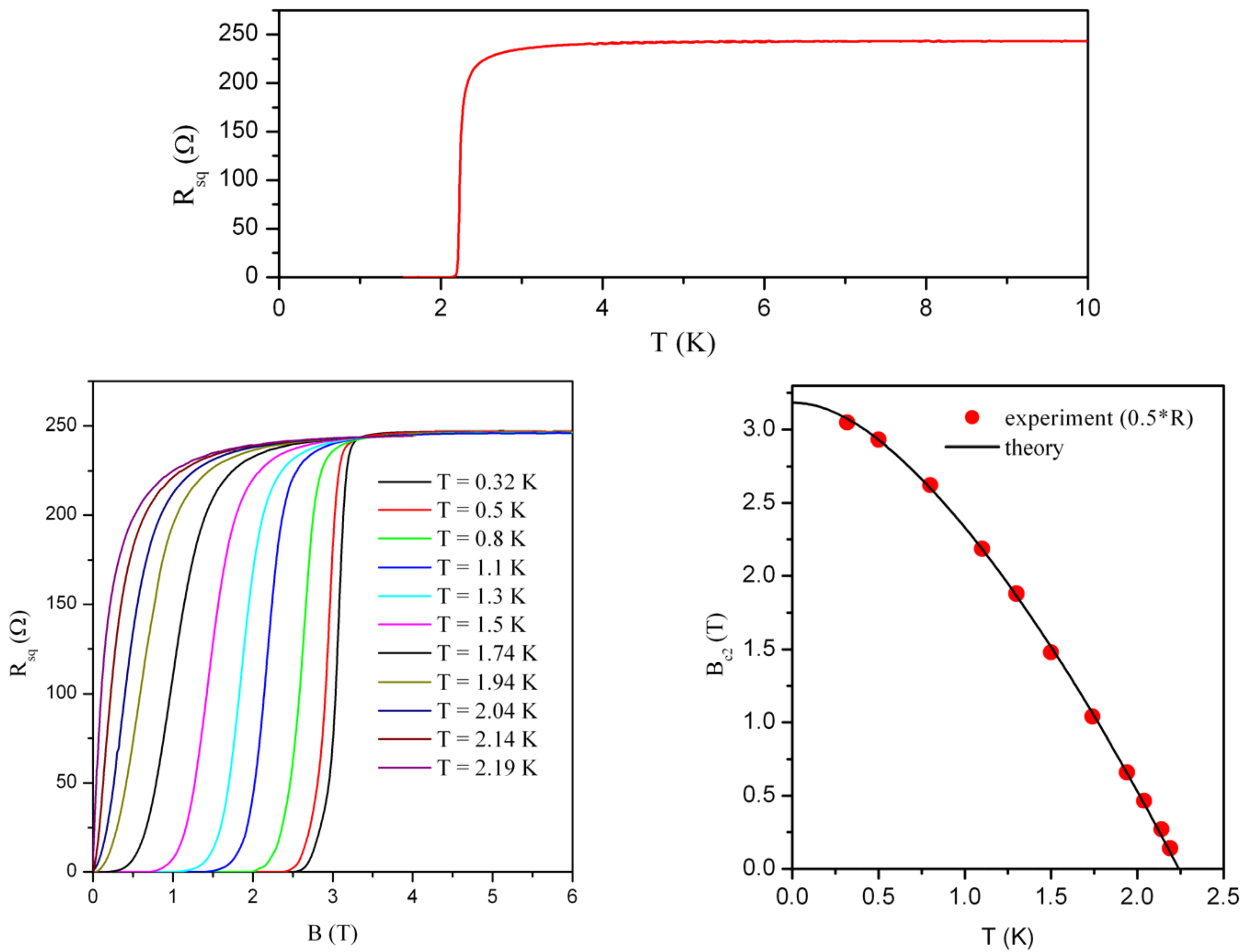
$z\,\nu = 1.36$

Theoretical expression does not contain scaling properties, but in restricted region of values T and B scaling presentation can be done

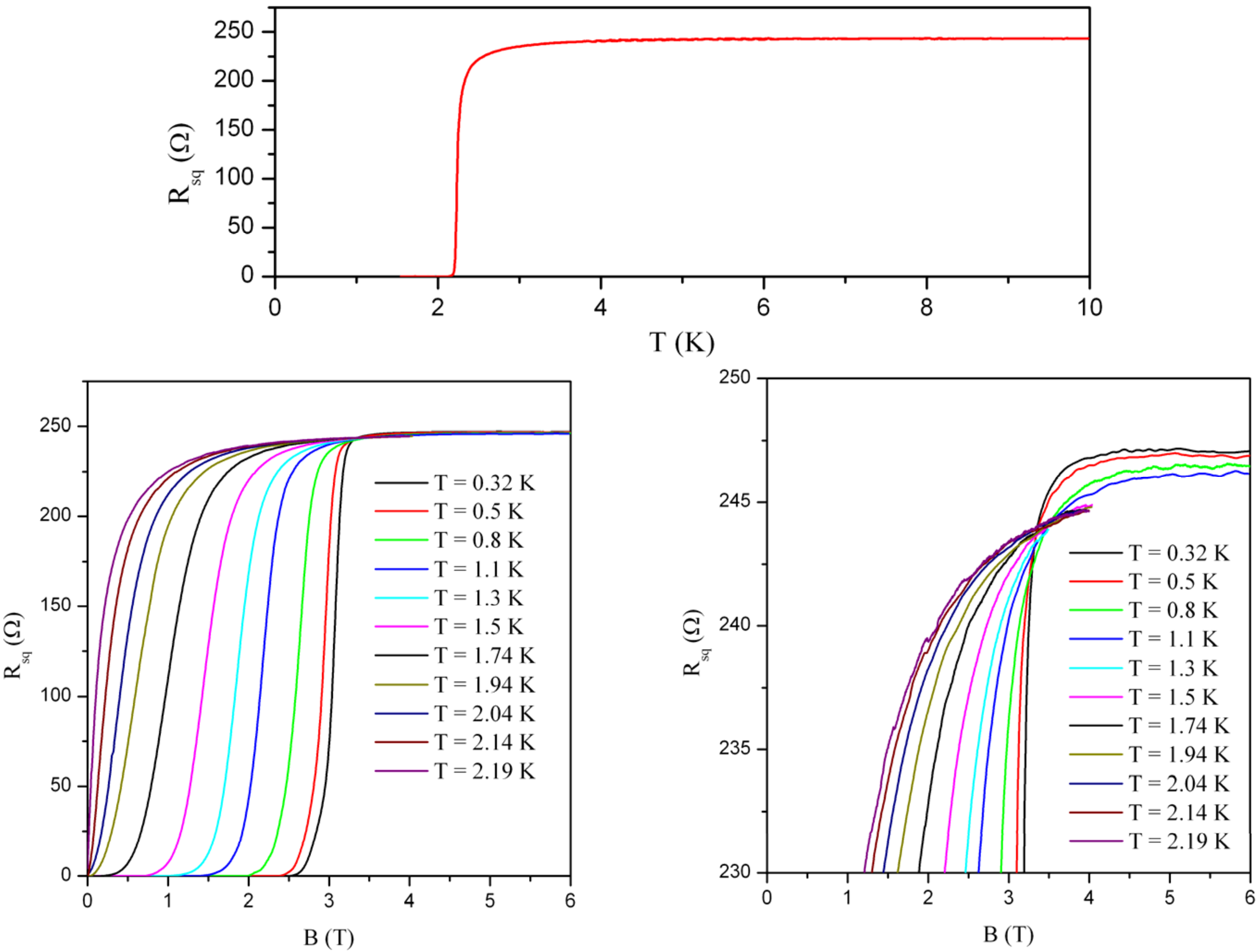
[V.F. Gantmakher, S.N. Ermolov, G.E. Tsydynzhapov, A.F. Zhukov, T.I. Baturina, JETP Lett. 77, 424 (2003)]

T.I. Baturina, D.R. Islamov, J. Bentner, C. Strunk, M.R. Baklanov, and A. Satta, JETP Lett. 79, 337 (2004).
T.I. Baturina, C. Strunk, M.R. Baklanov, A. Satta, PRL 98, 127003 (2007).
T.I. Baturina, A.Yu. Mironov, V.M. Vinokur, M.R. Baklanov, and C. Strunk, cond-mat/0705.1602





R_sq (Ω)
T (K)
R_sq (Ω)
B (T)
T = 0.32 K
T = 0.5 K
T = 0.8 K
T = 1.1 K
T = 1.3 K
T = 1.5 K
T = 1.74 K
T = 1.94 K
T = 2.04 K
T = 2.14 K
T = 2.19 K
B_c2 (T)
T (K)
experiment (0.5*R)
theory


R_sq (Ω)
T (K)
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T = 0.32 K
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T = 1.1 K
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T = 2.19 K
R_sq (Ω)
B (T)
T = 0.32 K
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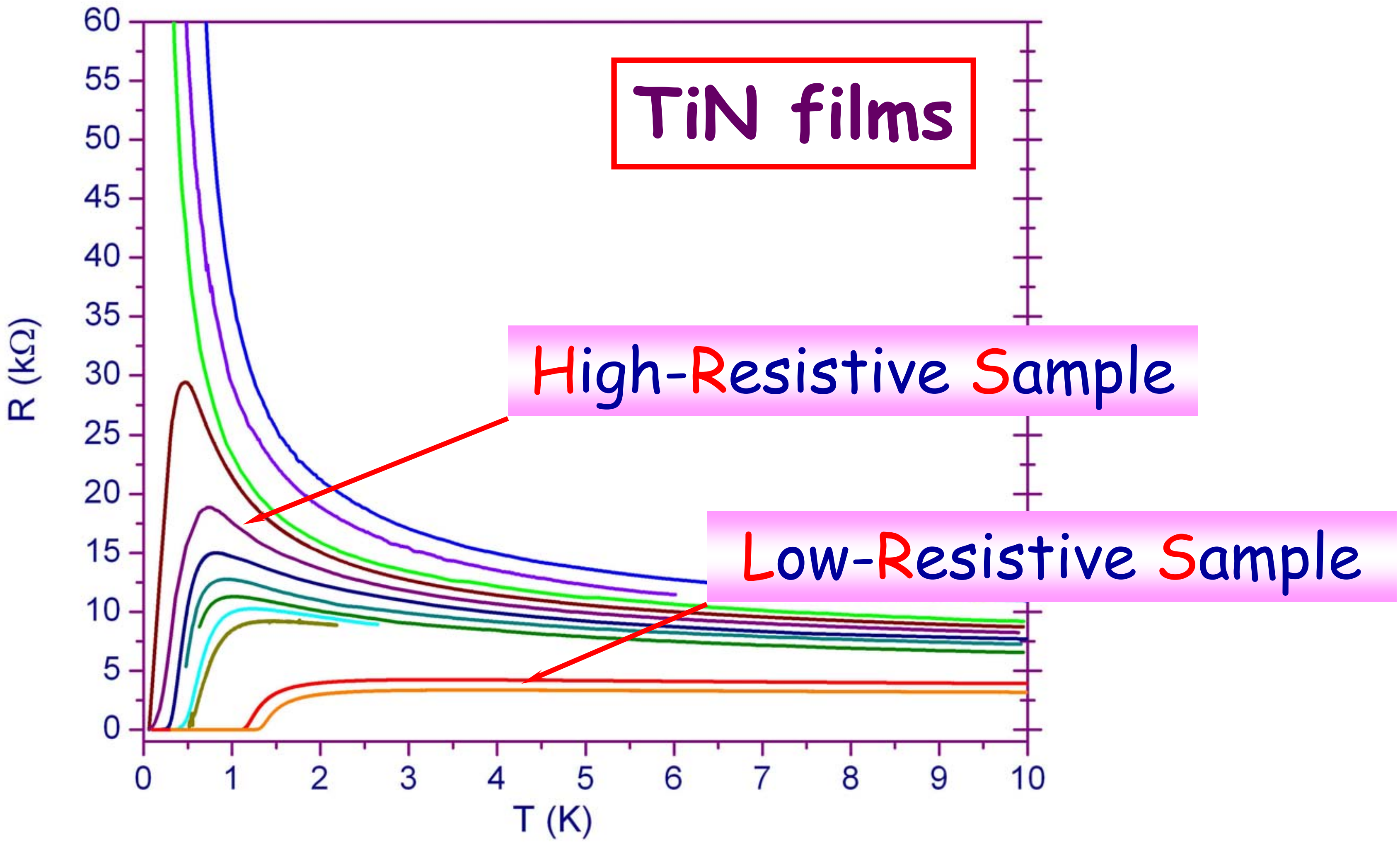
T.I. Baturina, D.R. Islamov, J. Bentner, C. Strunk, M.R. Baklanov, and A. Satta, JETP Lett. 79, 337 (2004).
T.I. Baturina, C. Strunk, M.R. Baklanov, A. Satta, PRL 98, 127003 (2007).
T.I. Baturina, A.Yu. Mironov, V.M. Vinokur, M.R. Baklanov, and C. Strunk, cond-mat/0705.1602

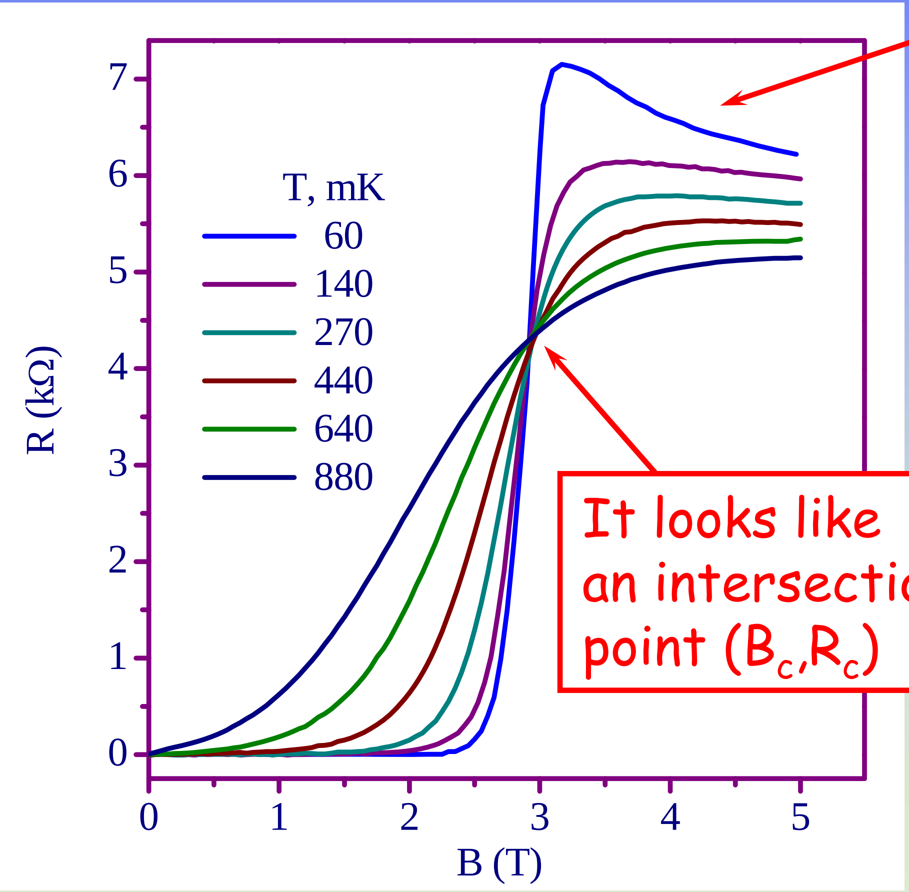


Experiment

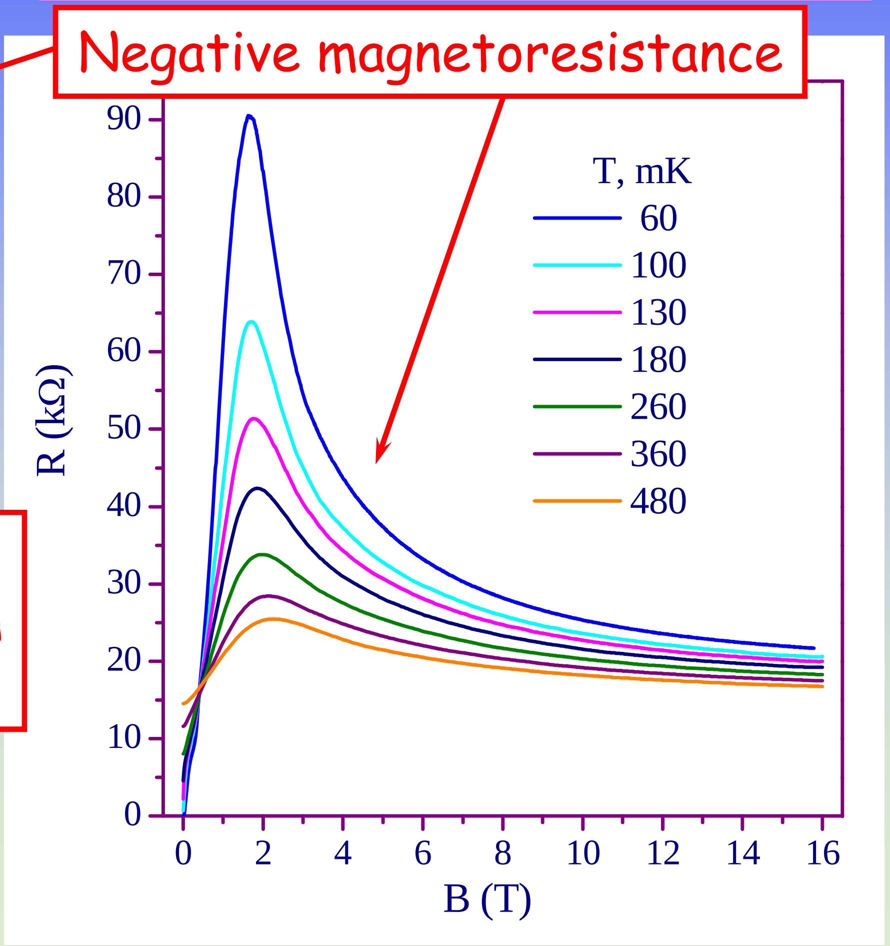
TiN films

Magnetic-field dependence

Low-Resistive Sample



High-Resistive Sample

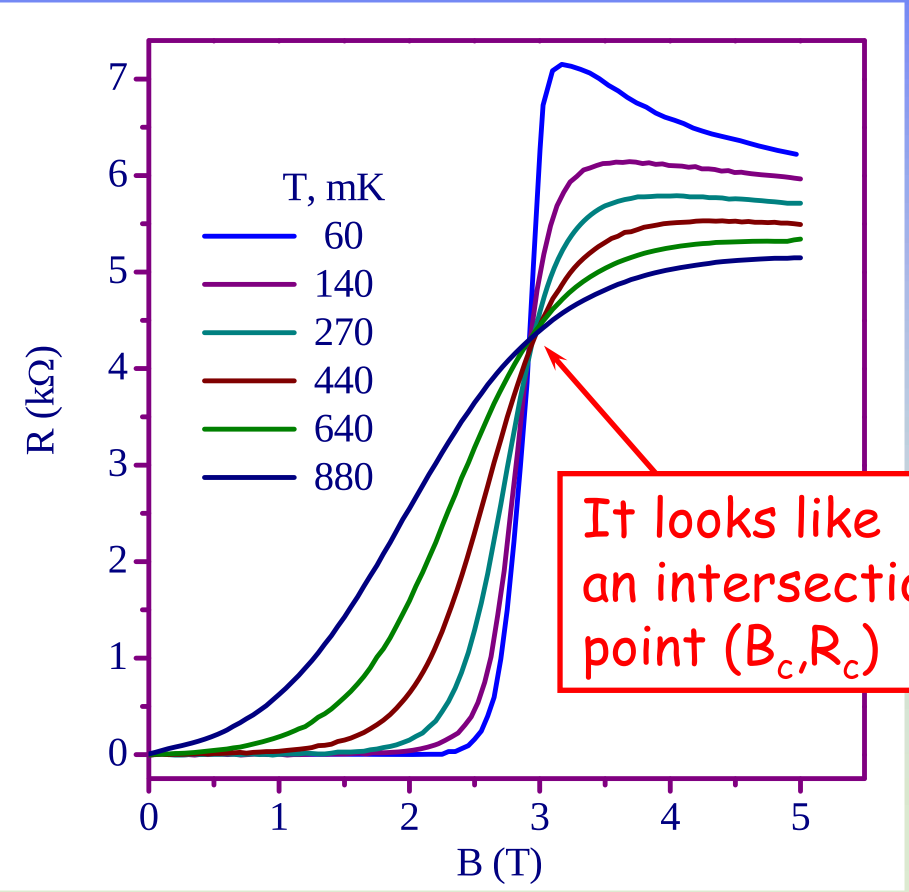


Experiment

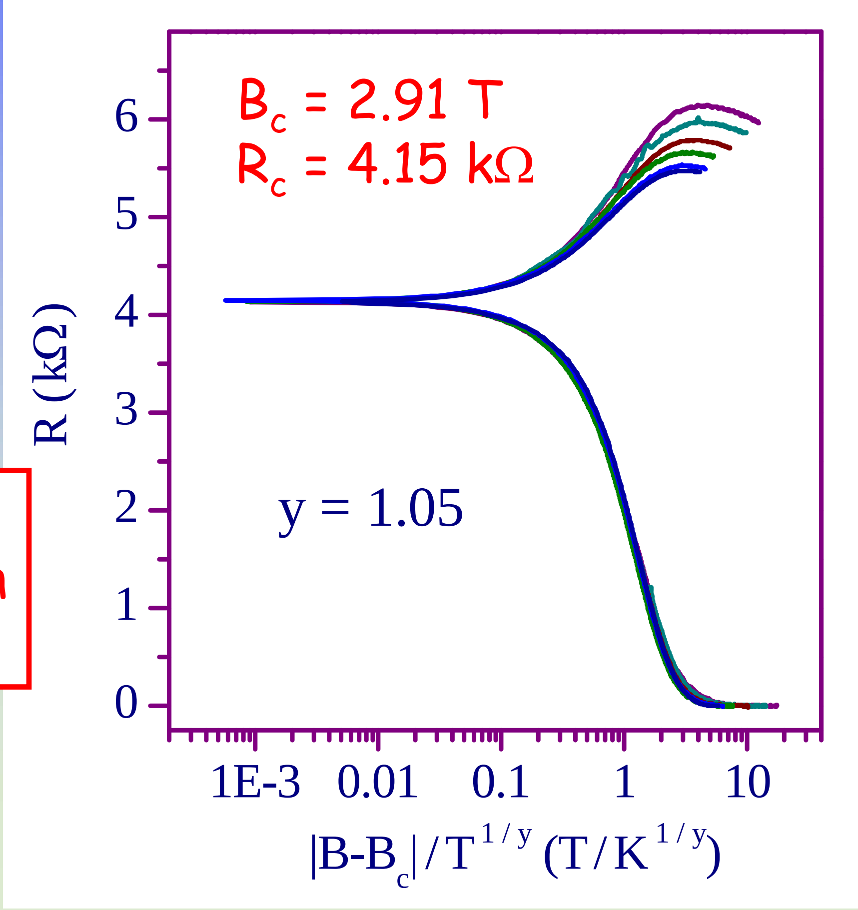
TiN films

Magnetic-field dependence

Low-Resistive Sample



Scaling

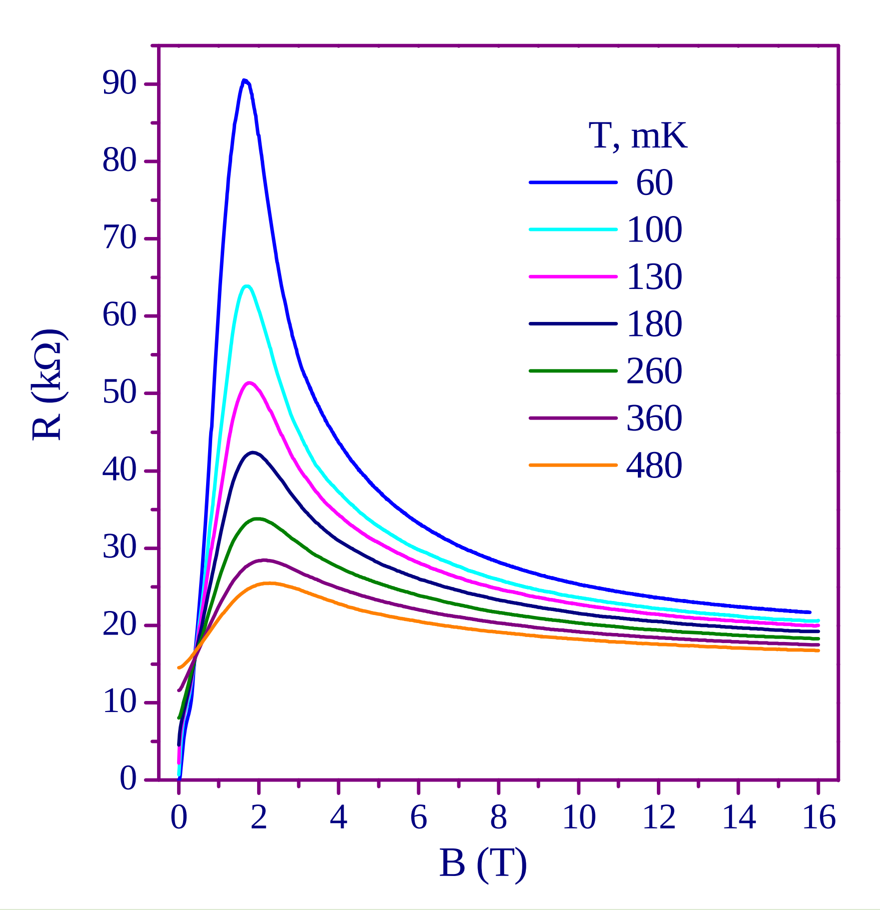


Experiment

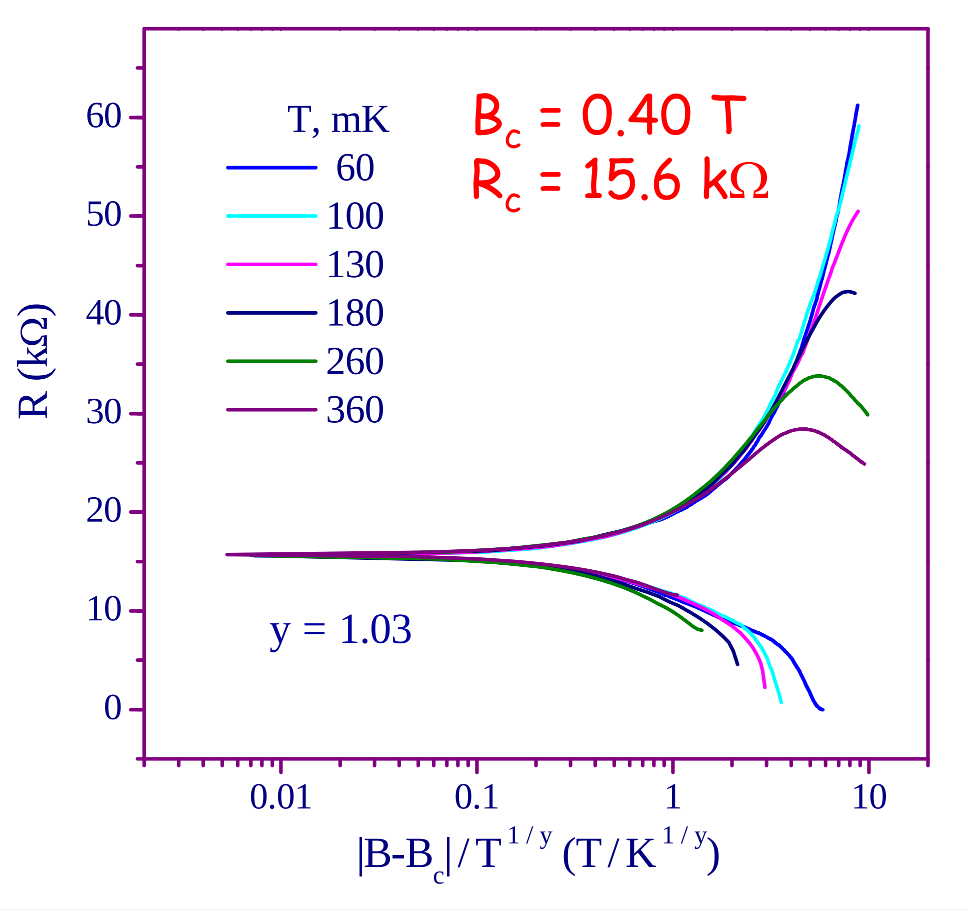
TiN films

Magnetic-field dependence

High-Resistive Sample



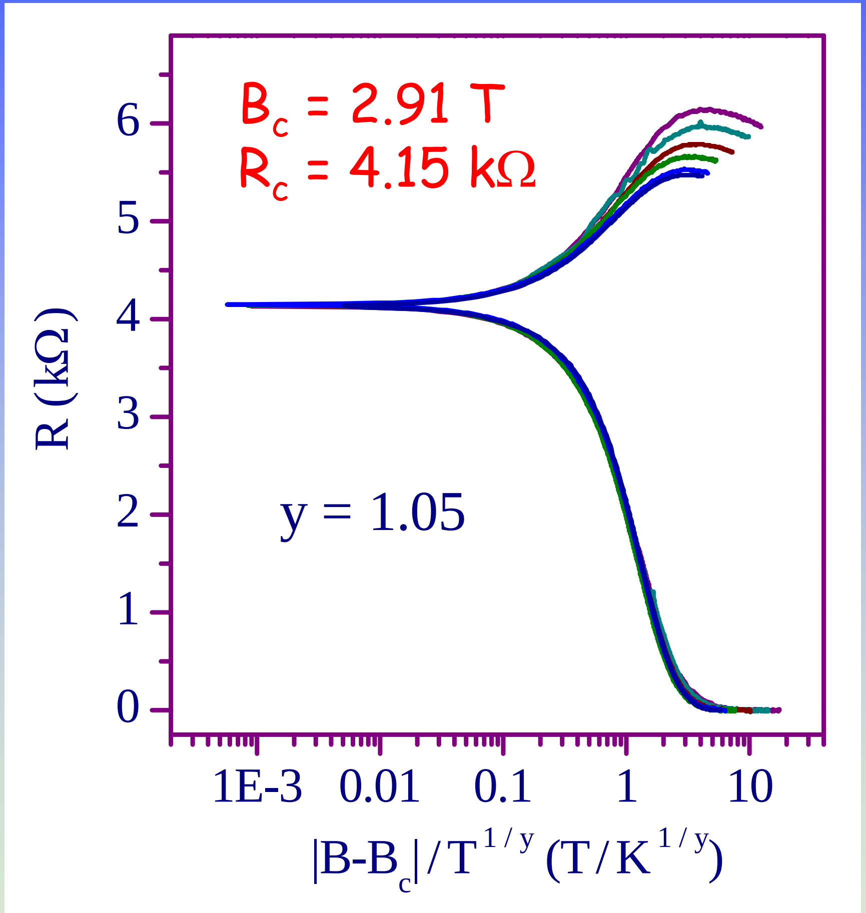
Scaling



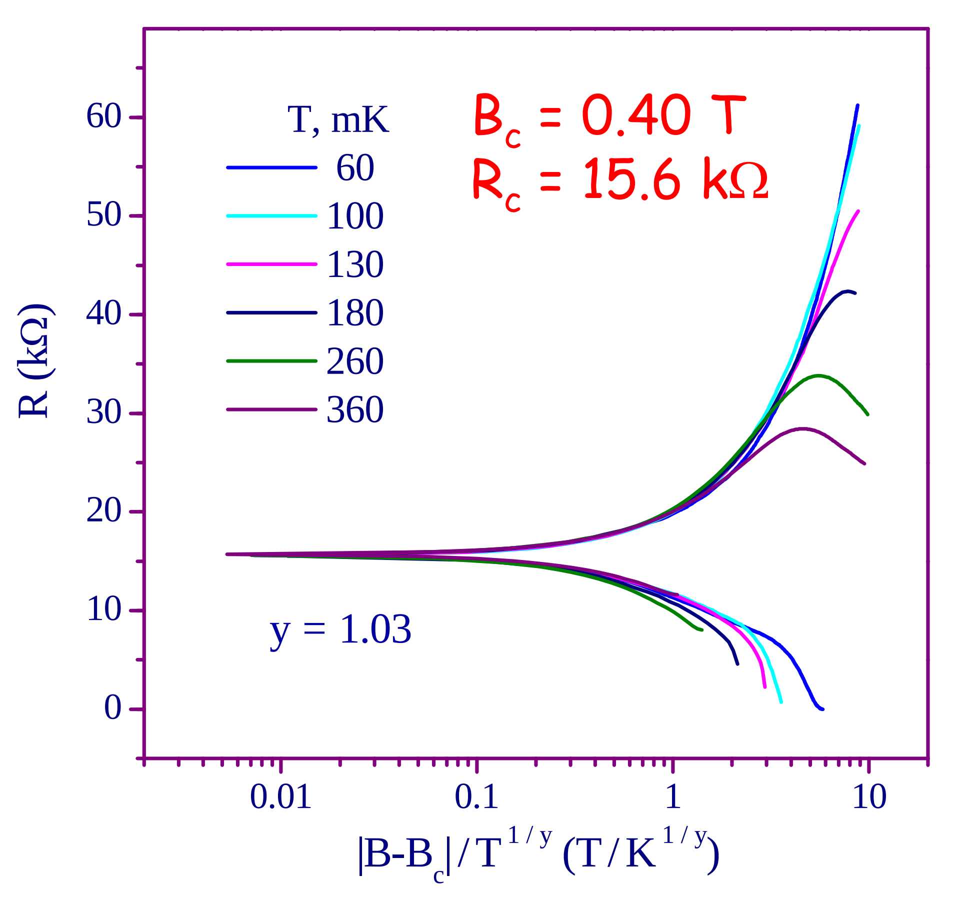
Scaling

Magnetic-field dependence

Low-Resistive Sample



High-Resistive Sample



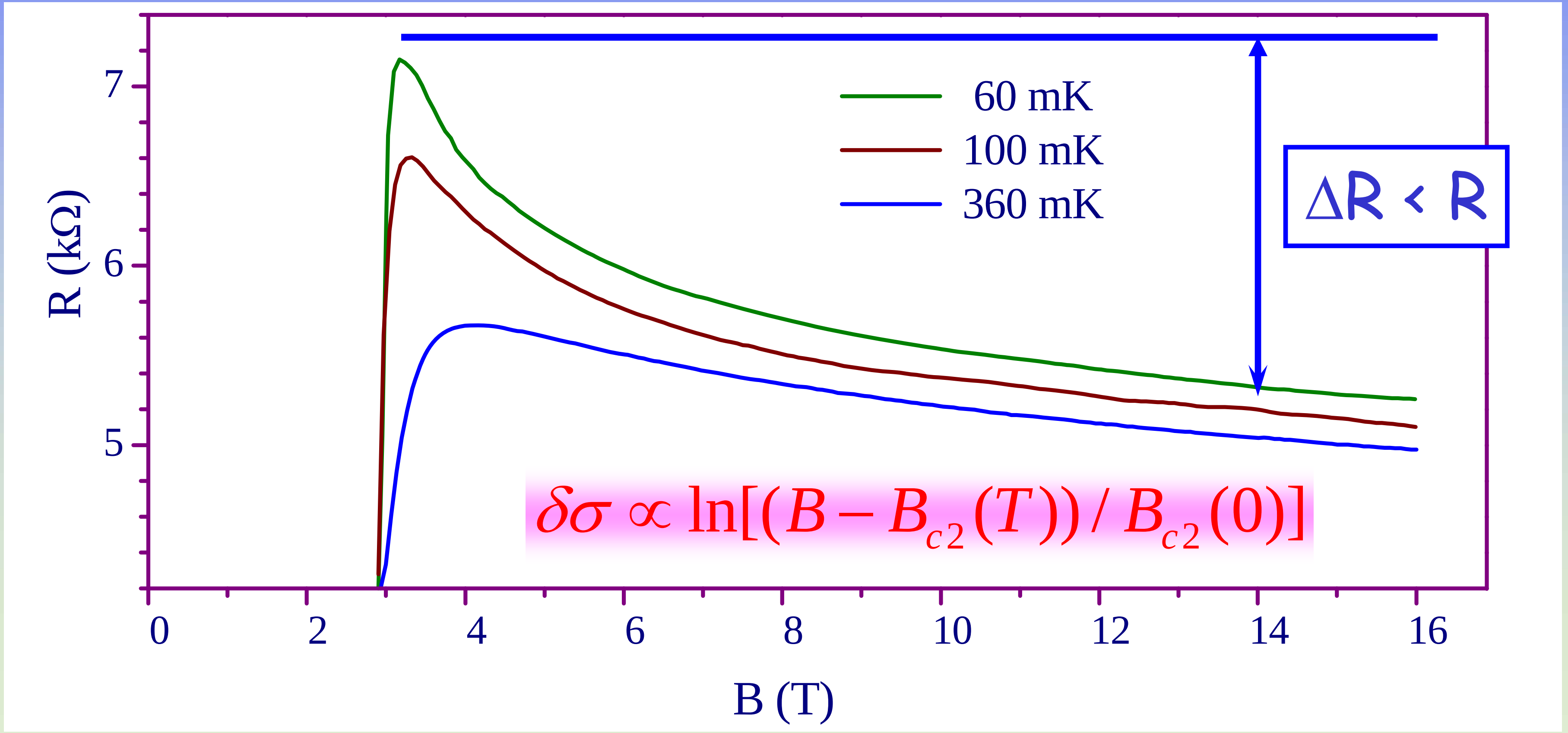
$y\ (= \nu z) \approx 1$ for both samples !

Magnetic-field dependence

Low-Resistive Sample

Negative magnetoresistance

comparison with Galitski – Larkin calculations of the quantum corrections



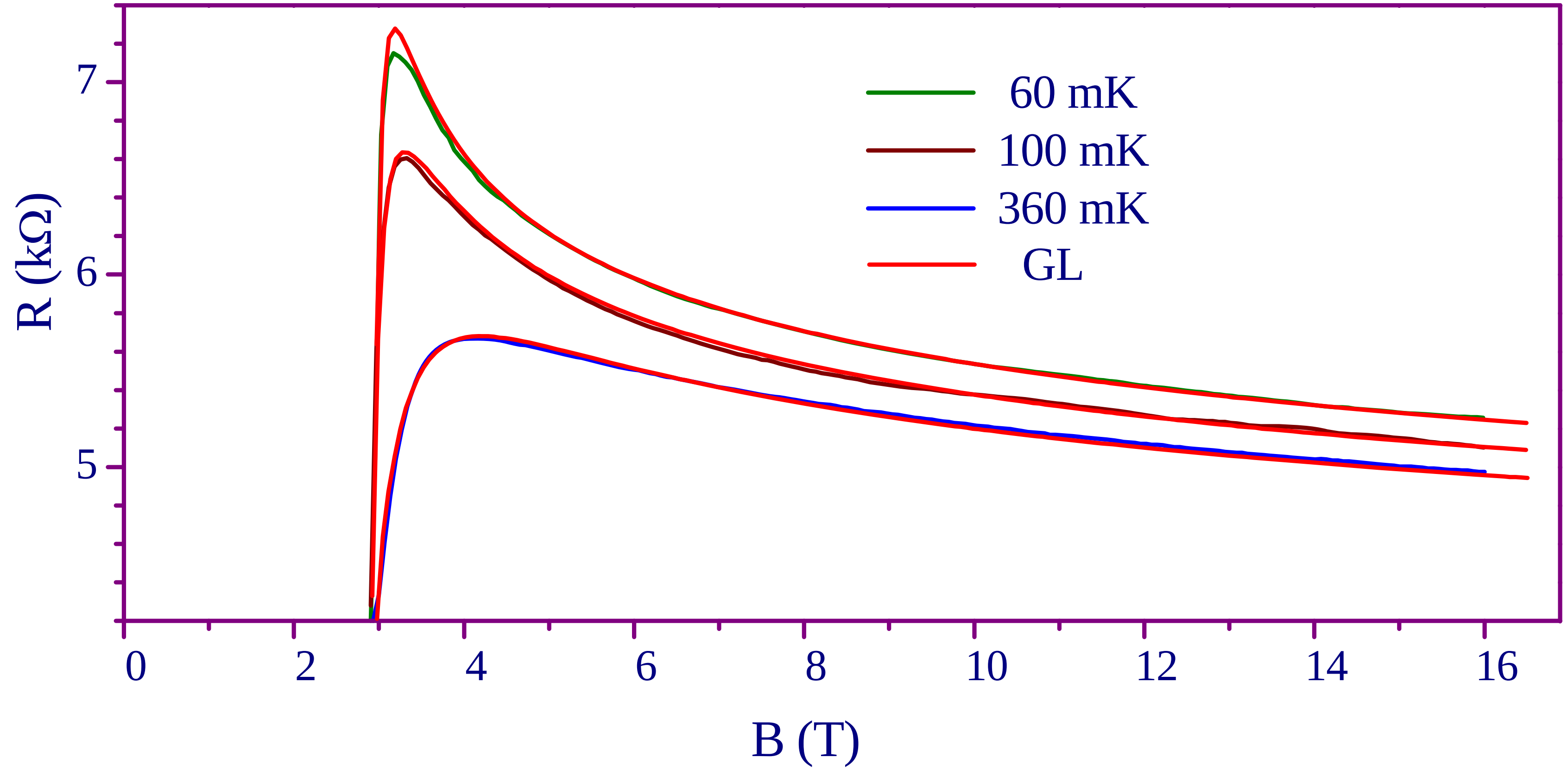
LRS

Negative magnetoresistance

comparison with Galitski - Larkin calculations of the quantum corrections

T_c = 2 K, $B_{c2}(0)$ = 2.8 T

$$\delta\sigma = \frac{2e^2}{3\pi^2\hbar}\left[-\ln\frac{r}{h} - \frac{3}{2r} + \psi(r) + 4[r\psi'(r) - 1]\right]$$



LRS

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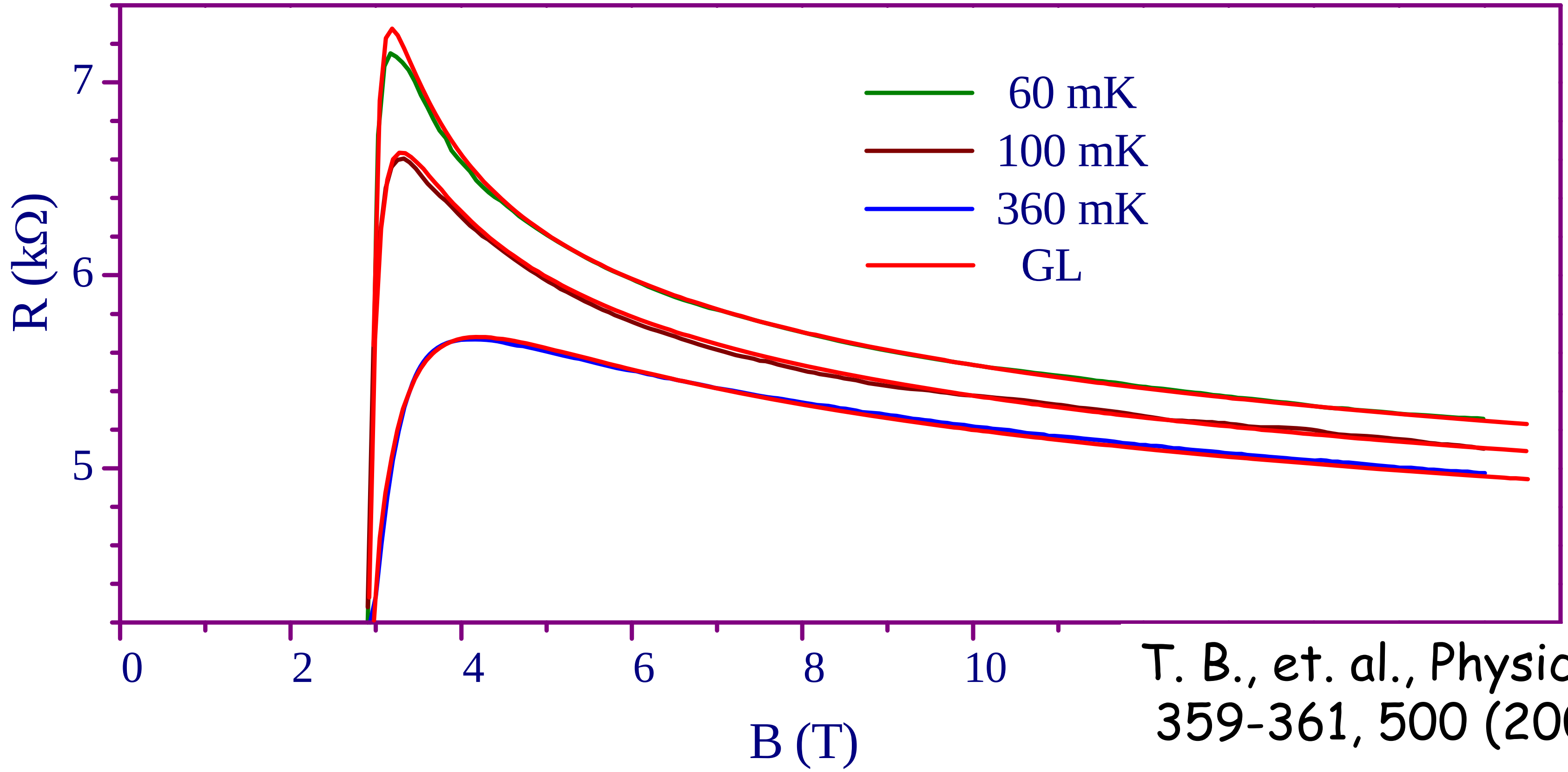
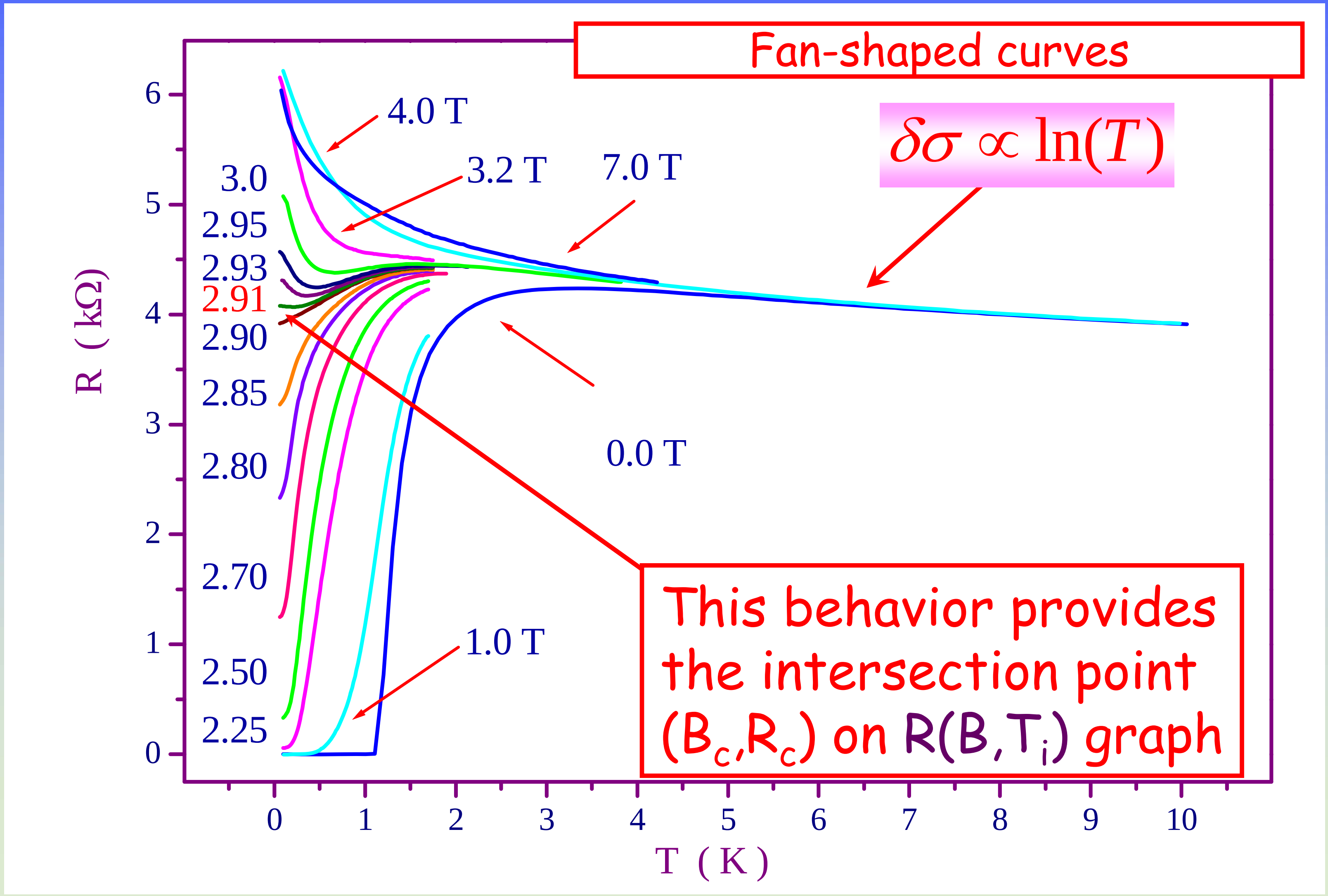


T. B., et. al., Physica B 359-361, 500 (2005)

Temperature dependence

Low-Resistive Sample

$R(T,B_i)$



LRS

Temperature dependence

comparison with Galitski - Larkin calculations of the quantum corrections

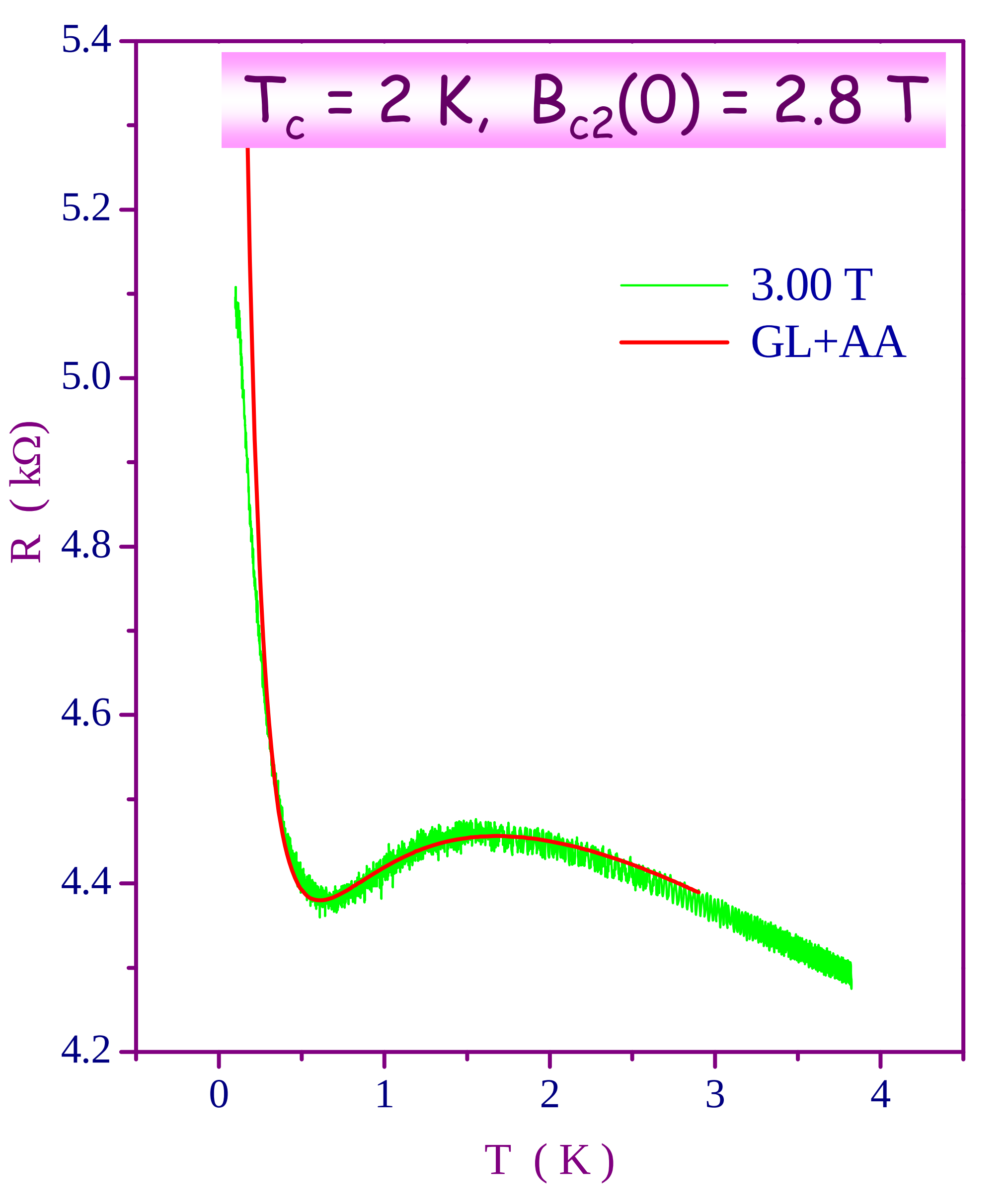
Cooper Channel

+

Aronov - Altshuler

$$\delta\sigma_{AA} \propto \ln(T)$$

Diffusion Channel

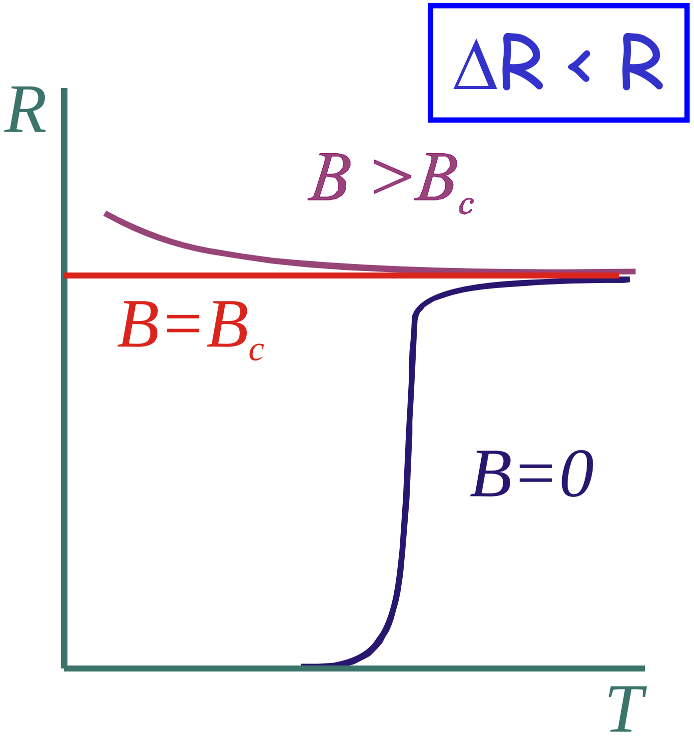


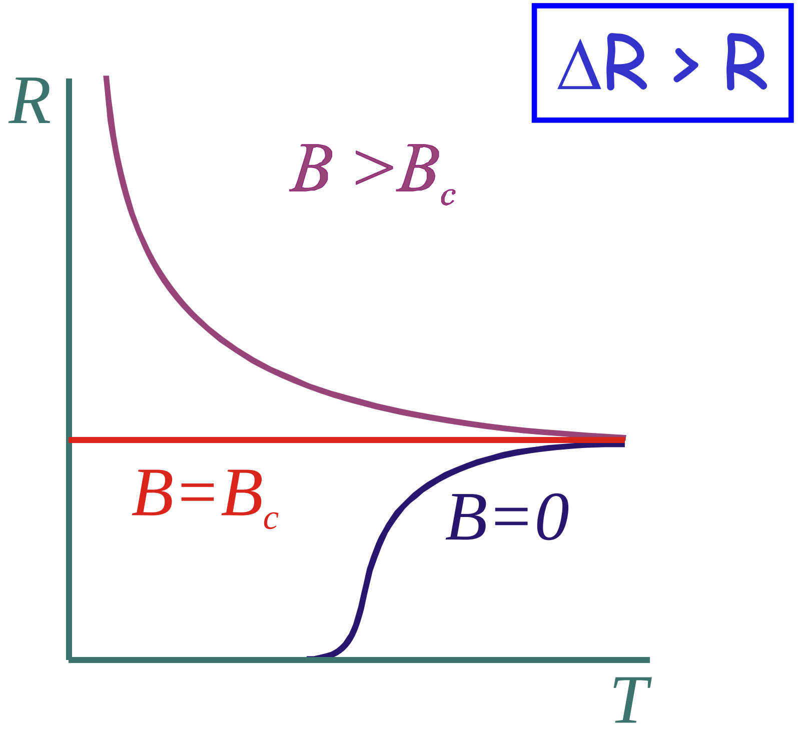
Suppression of Superconductivity by **Magnetic Field**

Field-induced...

superconductor – metal transition

superconductor – insulator transition





Superconducting fluctuations and SIT related behavior in low resistive superconducting films

superconductor – metal transition

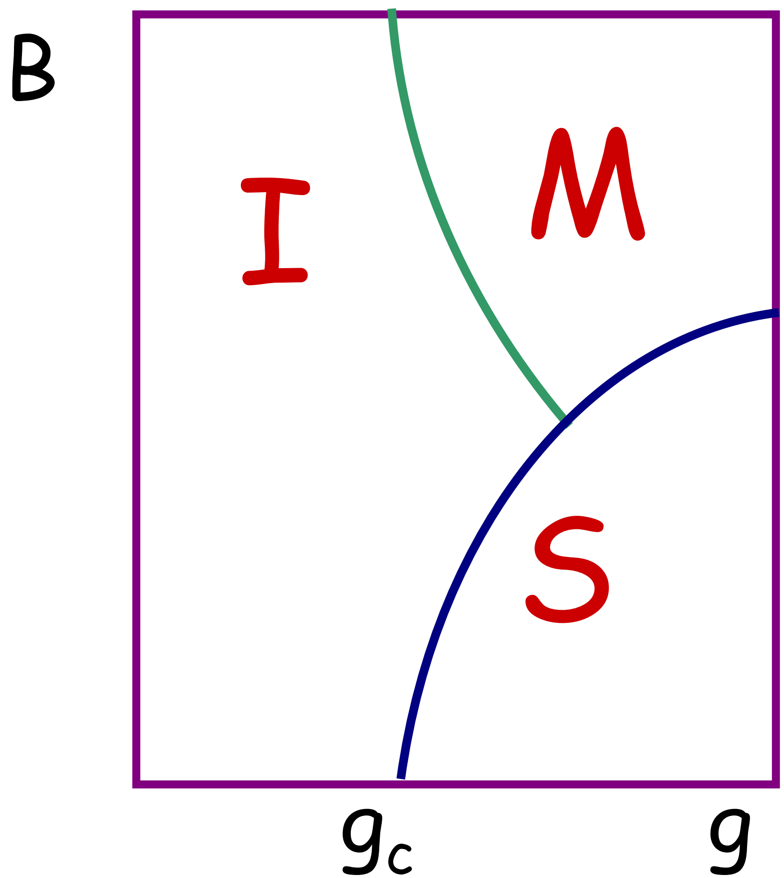
V.M. Galitski and A.I. Larkin, PRB **63**, 174506 (2001)

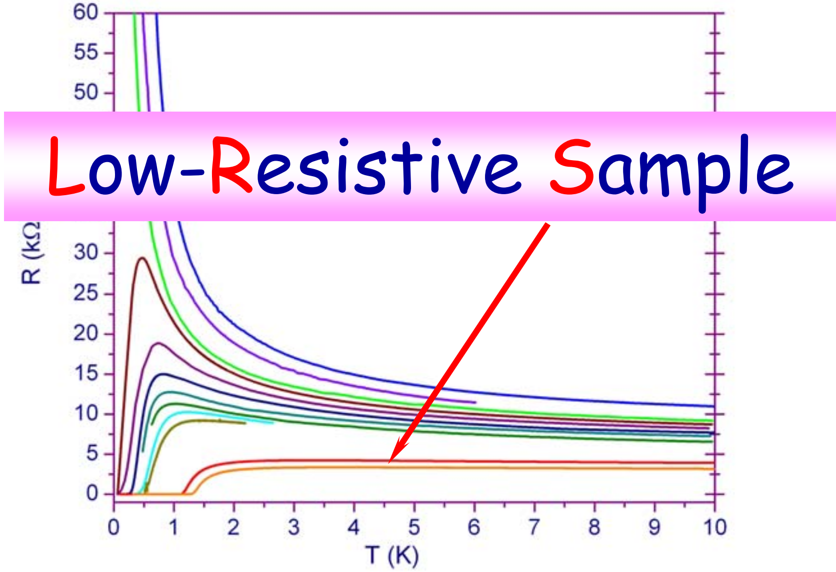
superconductor – insulator transition

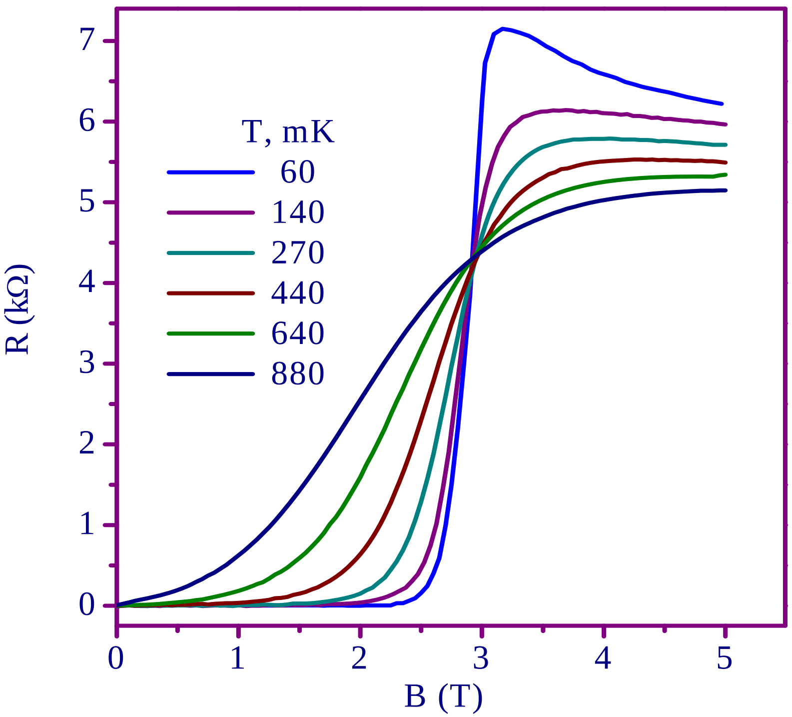
Common features

- ✓ Fan-shaped structure of $R(T,B_i)$ curves
- ✓ Negative magnetoresistance in high fields
- ✓ Scaling

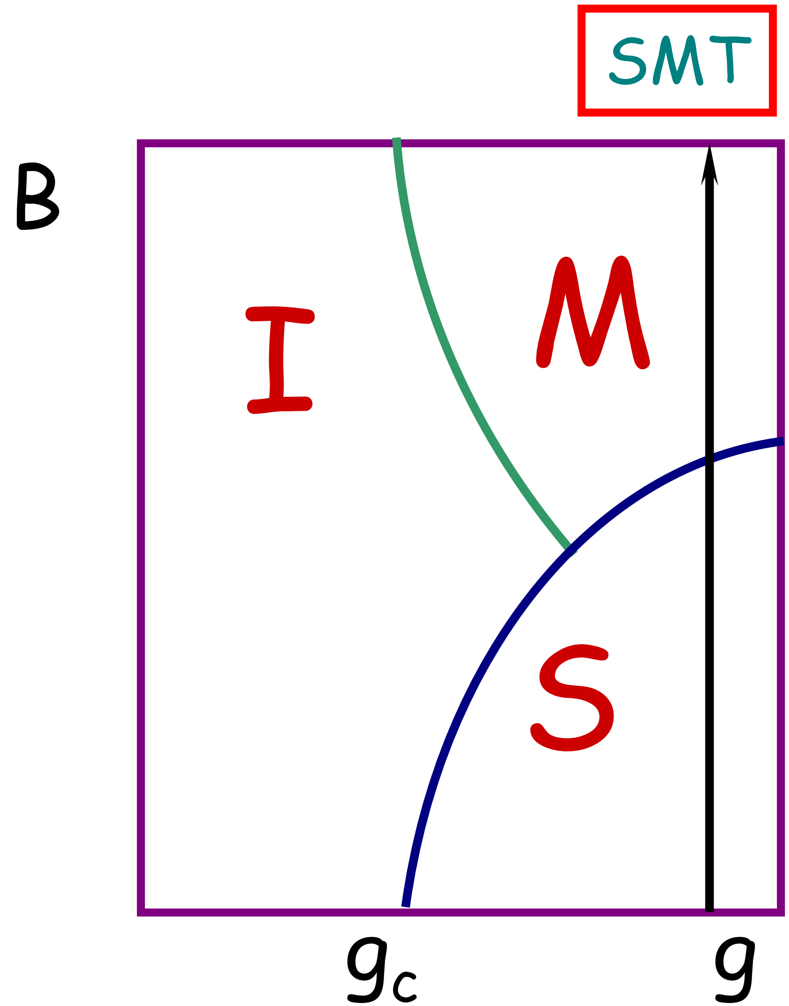
schematic phase diagram





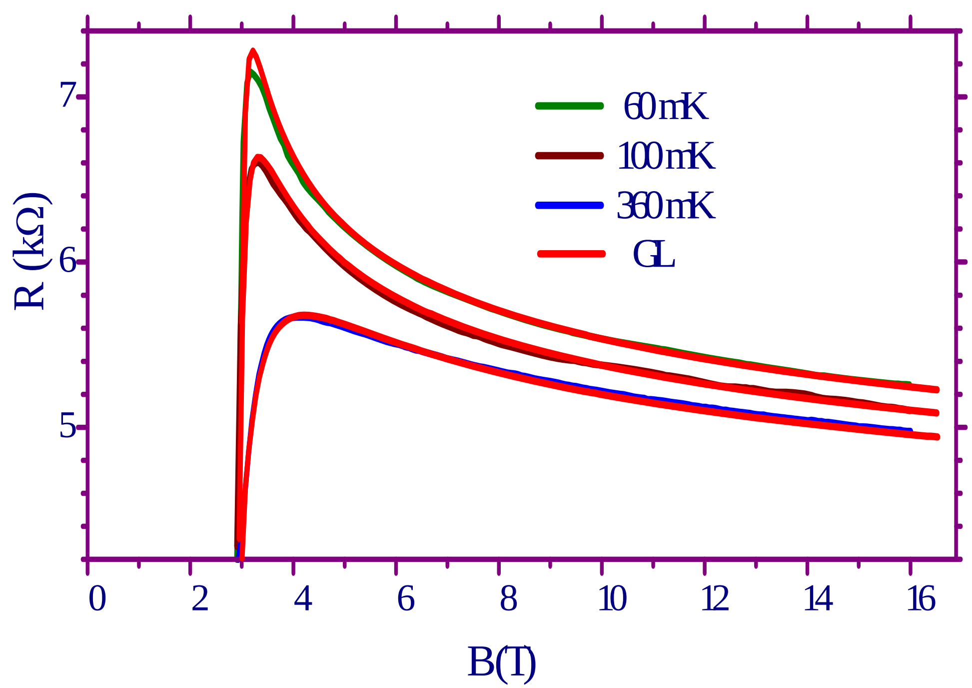


schematic phase diagram

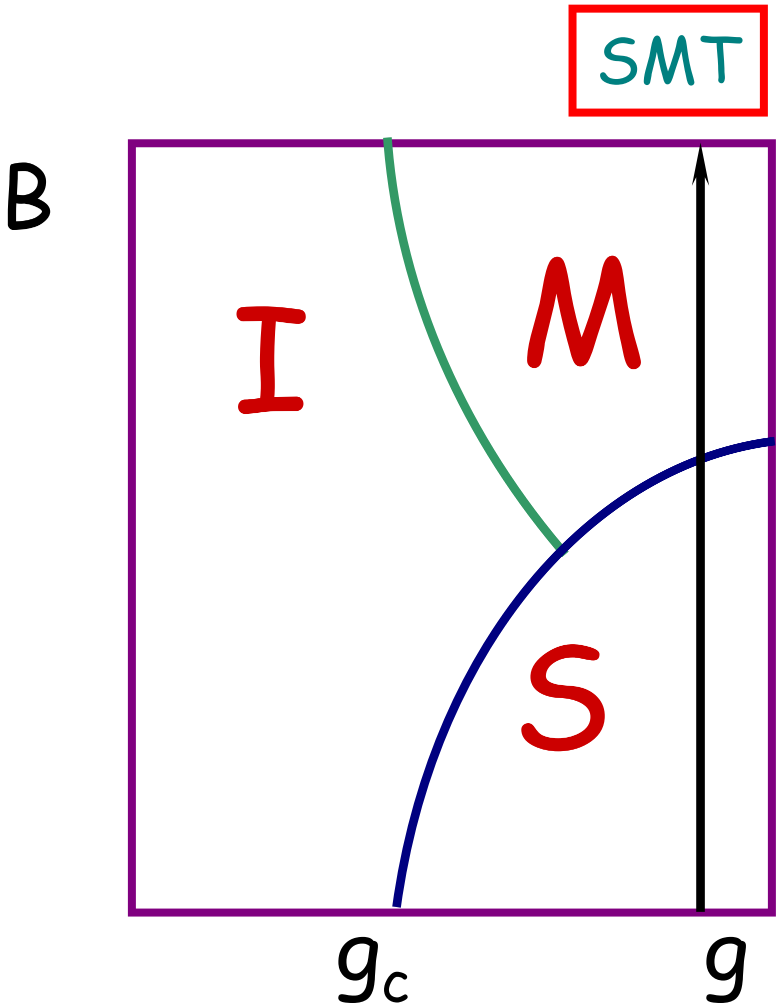


comparison with Galitski – Larkin calculations of the quantum corrections

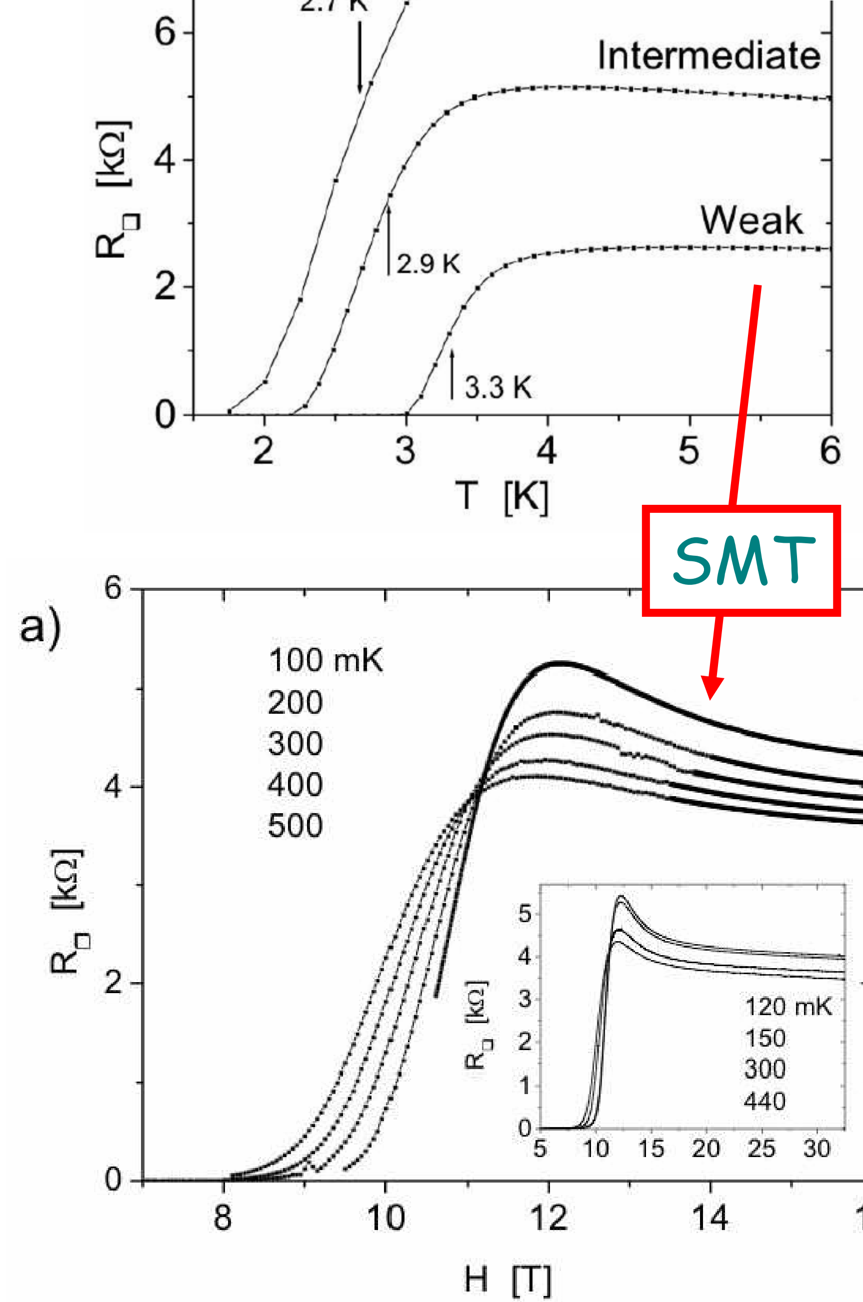
T. Baturina, et. al., Physica B 359-361, 500 (2005)



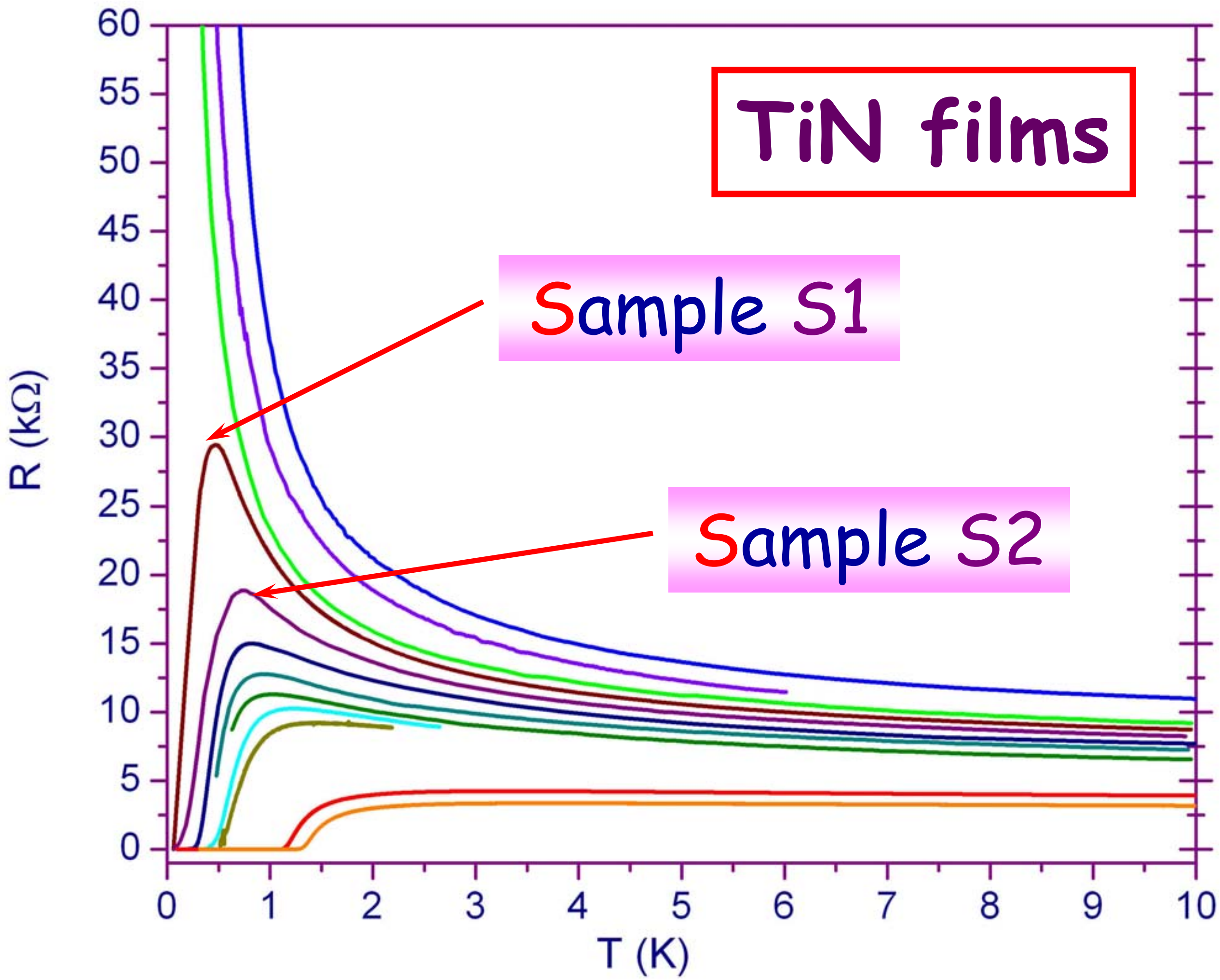
schematic phase diagram



InO_x films



T.I. Baturina, D.R. Islamov, J. Bentner, C. Strunk, M.R. Baklanov, and A. Satta, JETP Lett. 79, 337 (2004).
T.I. Baturina, C. Strunk, M.R. Baklanov, A. Satta, PRL 98, 127003 (2007).
T.I. Baturina, A.Yu. Mironov, V.M. Vinokur, M.R. Baklanov, and C. Strunk, cond-mat/0705.1602

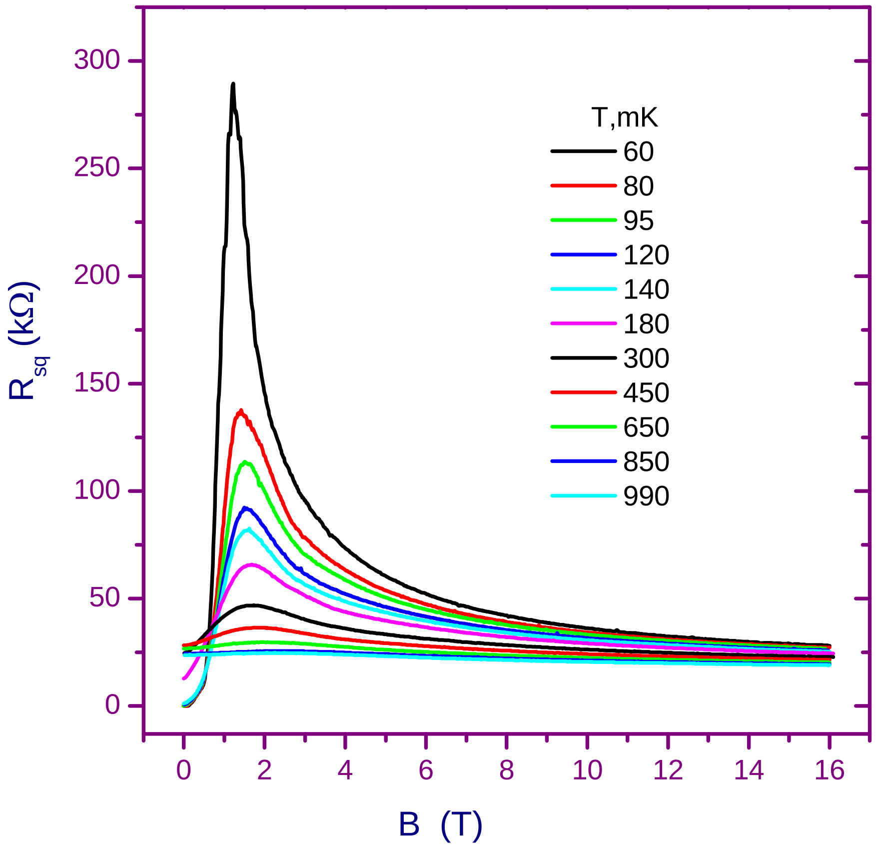


Experiment

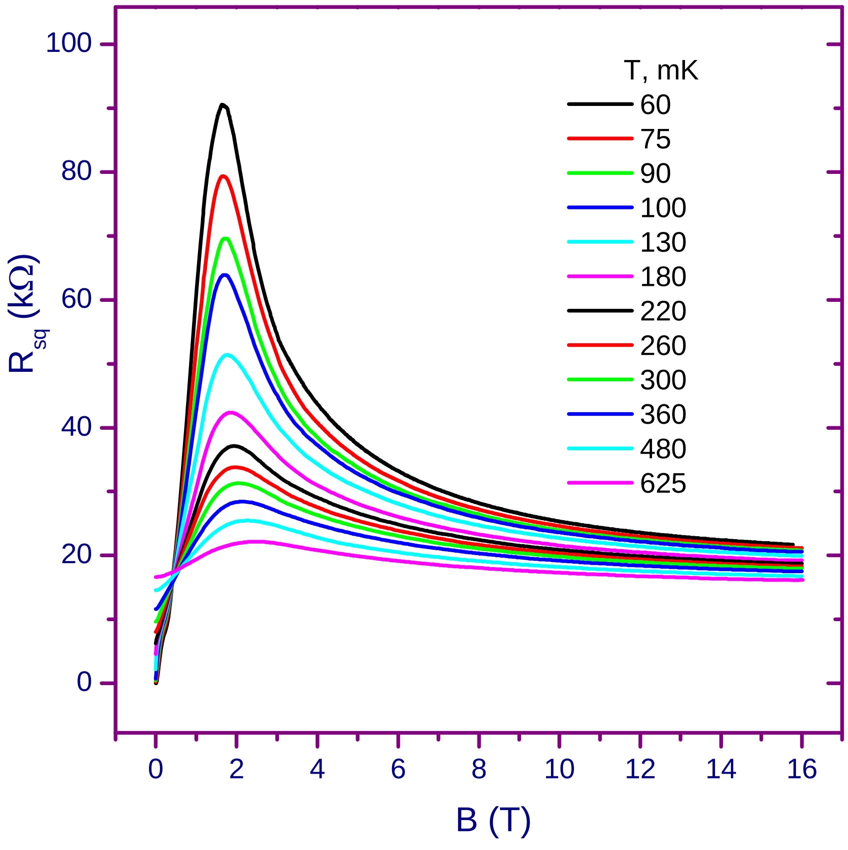
T. B., C. Strunk, M.R. Baklanov, A. Satta
PRL 98, 127003 (2007)

Magnetic-field-tuned superconductor – insulator quantum phase transition

Sample S1



Sample S2



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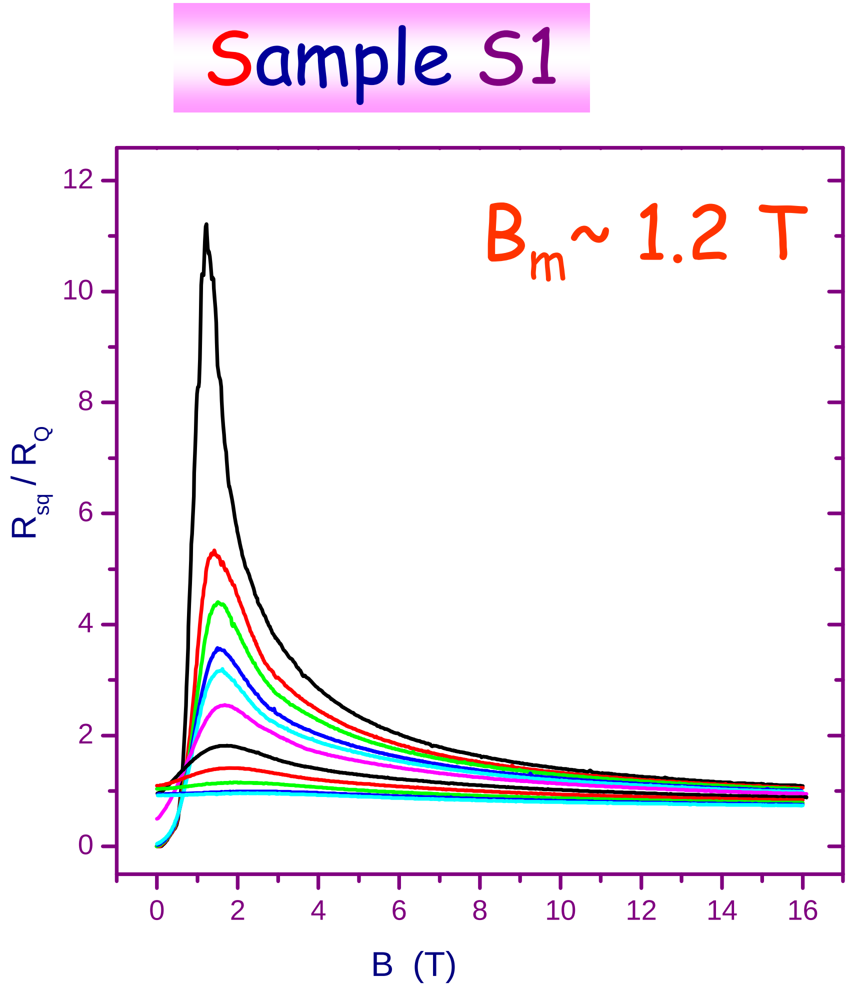
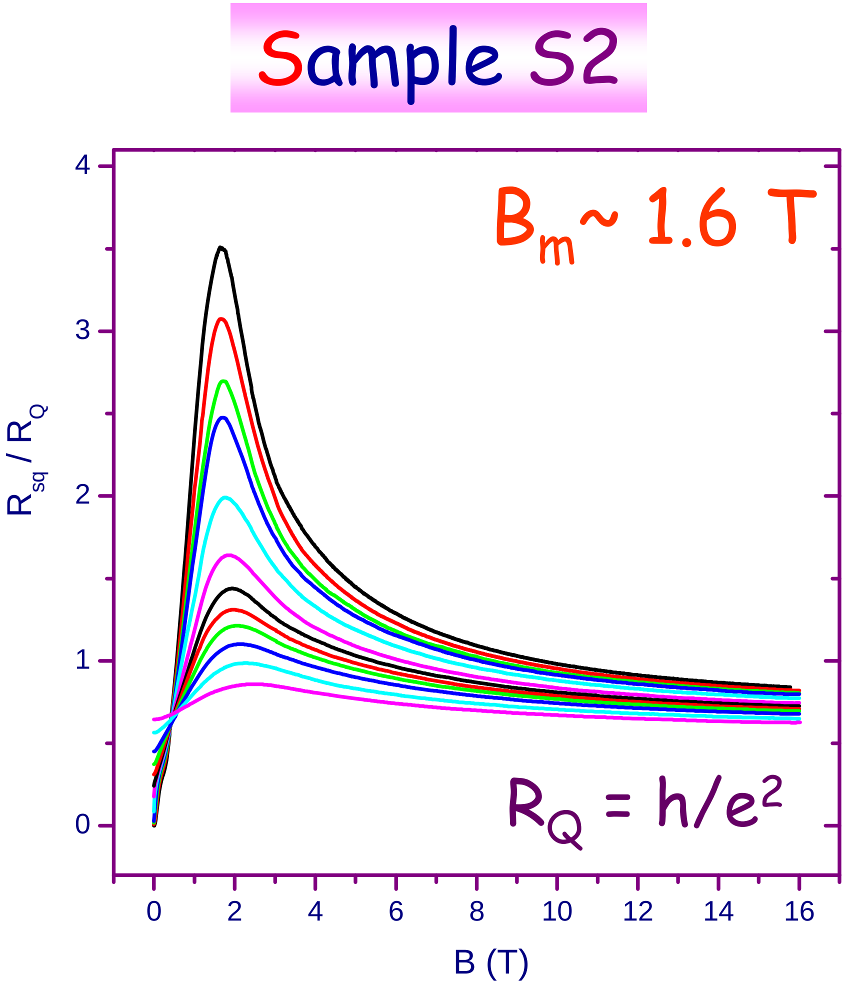
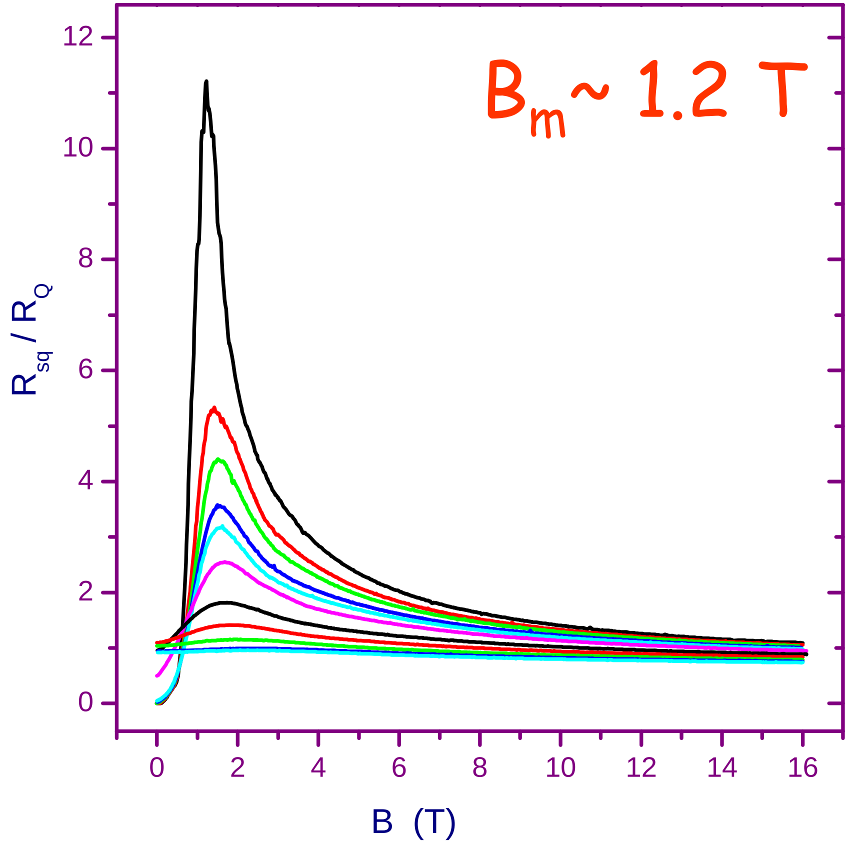




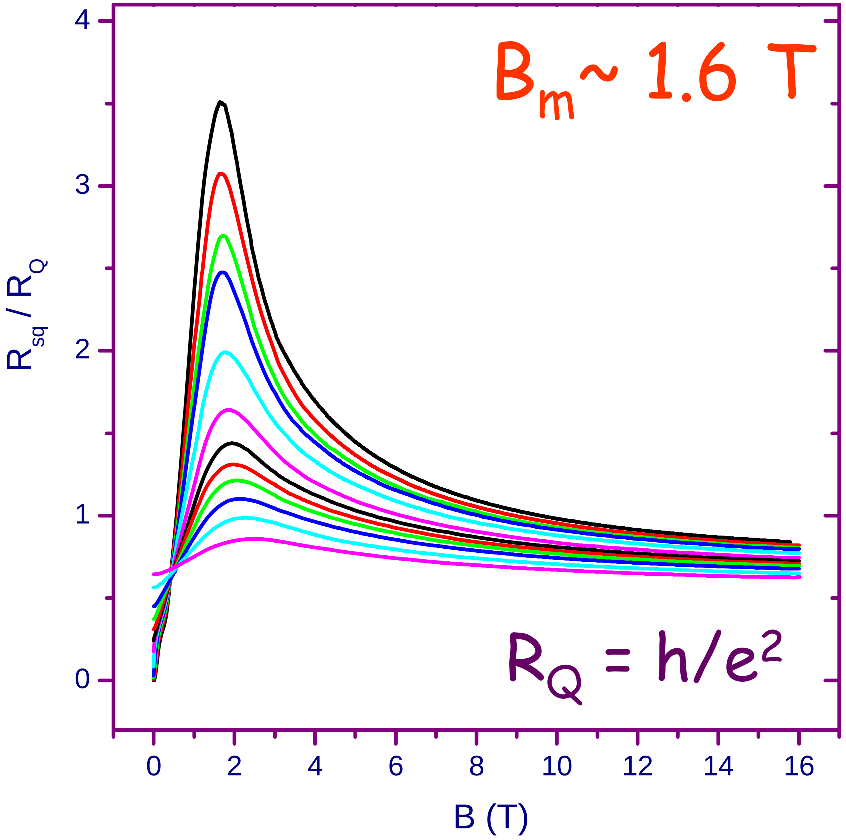
The saturation occurs at a resistance R_{sat}

near the quantum resistance h/e^2 **!!!**

Sample S1



Sample S2

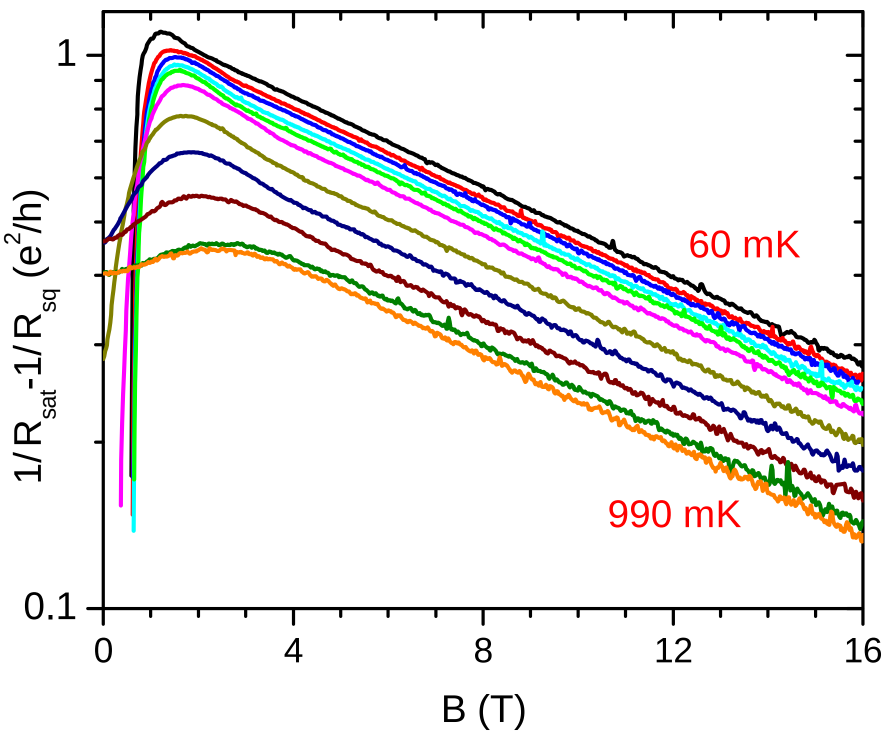


by varying the value of R_{sat} for each curve , we can linearize

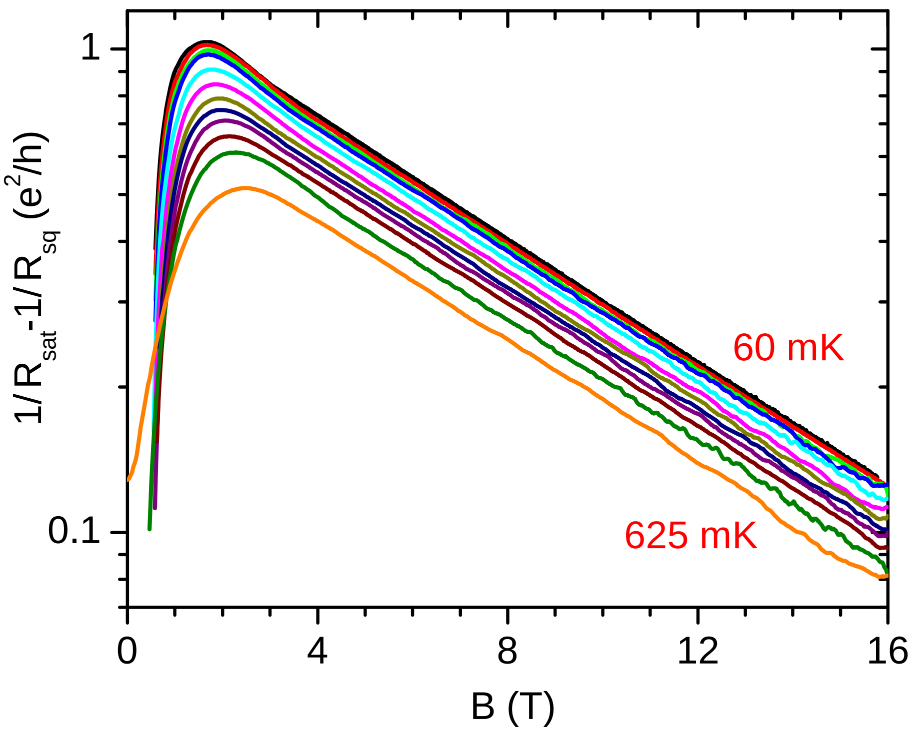
$\ln(1/R_{sat} - 1/R_{sq}(B))$ vs. B

over a large range of B
with T-independent slope !!!

Sample S1



Sample S2



by varying the value of R_{sat} for each curve , we can linearize

$\ln(1/R_{sat} - 1/R_{sq}(B))$ vs. B

over a large range of B
with T-independent slope !!!

$$G_{sq}(T,B)[=1/R_{sq}(T,B)] = 1/R_{sat}(T) - \beta(T)\exp(-B/B^*)$$

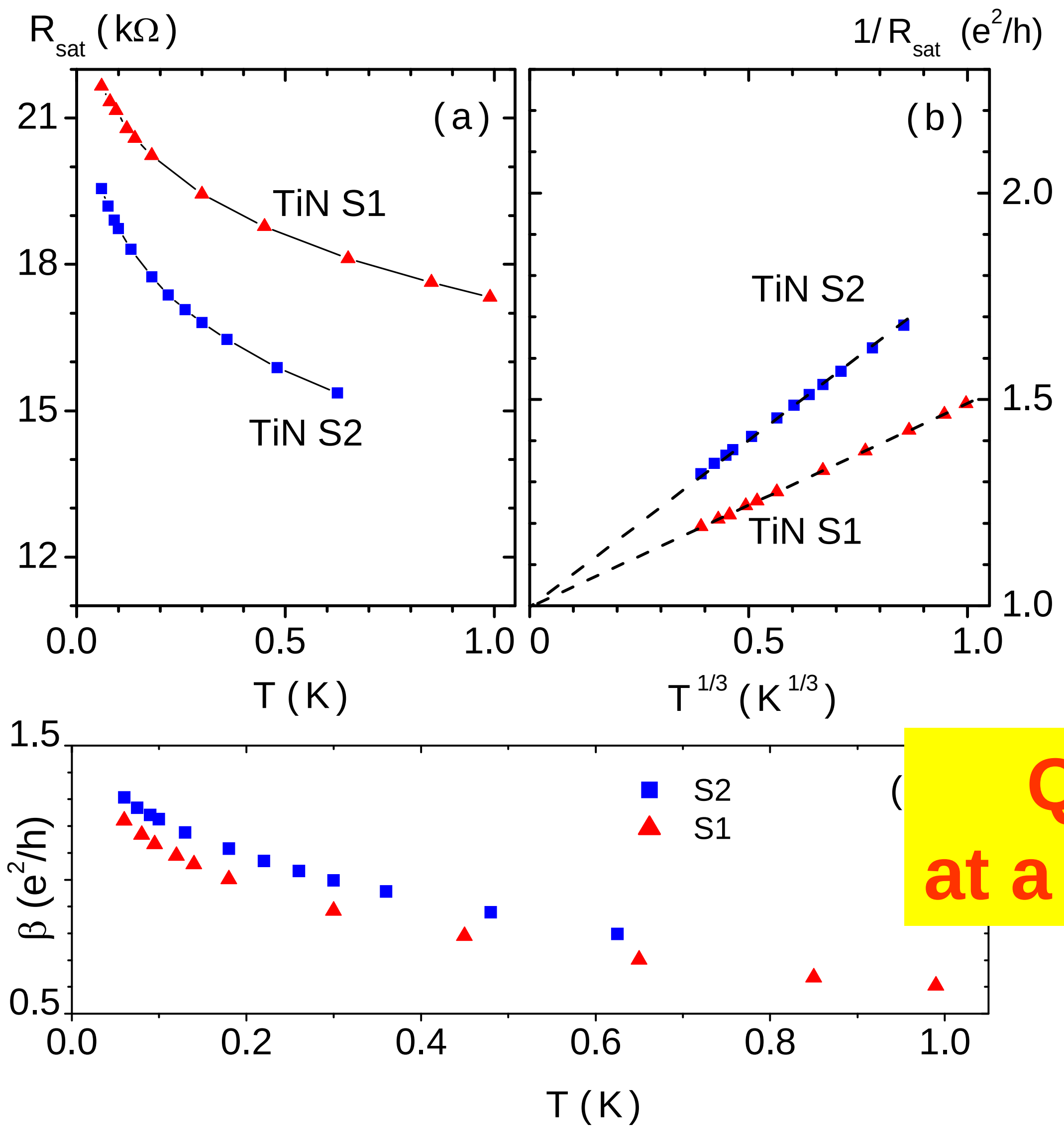
Sample S1

$B^* = 10.7$ T

Sample S2

$B^* = 6.8$ T

$$G_{sq}(T,B)[=1/R_{sq}(T,B)] = 1/R_{sat}(T) - \beta(T)\exp(-B/B^*)$$



$R_{sat}(T \rightarrow 0) \rightarrow h/e^2$

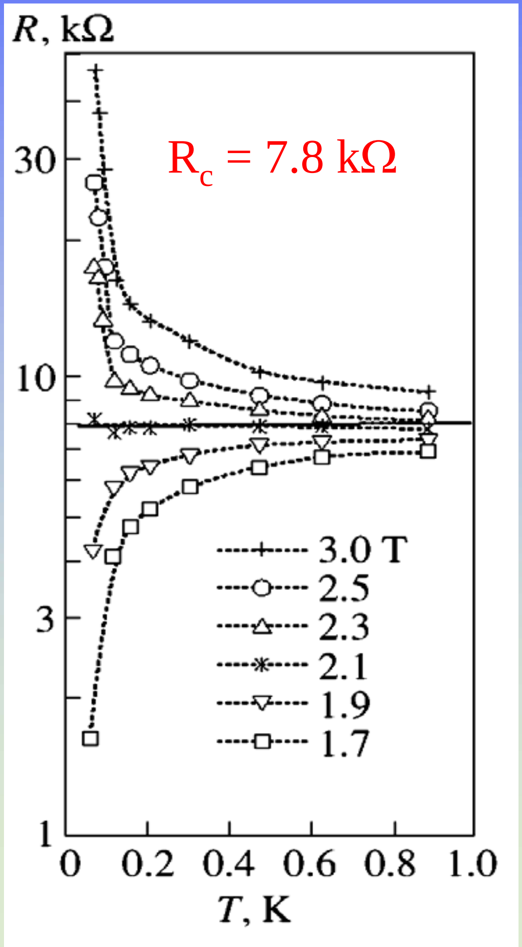
Quantum metallicity at a high-field side of SIT

Field-induced superconductor – insulator transition

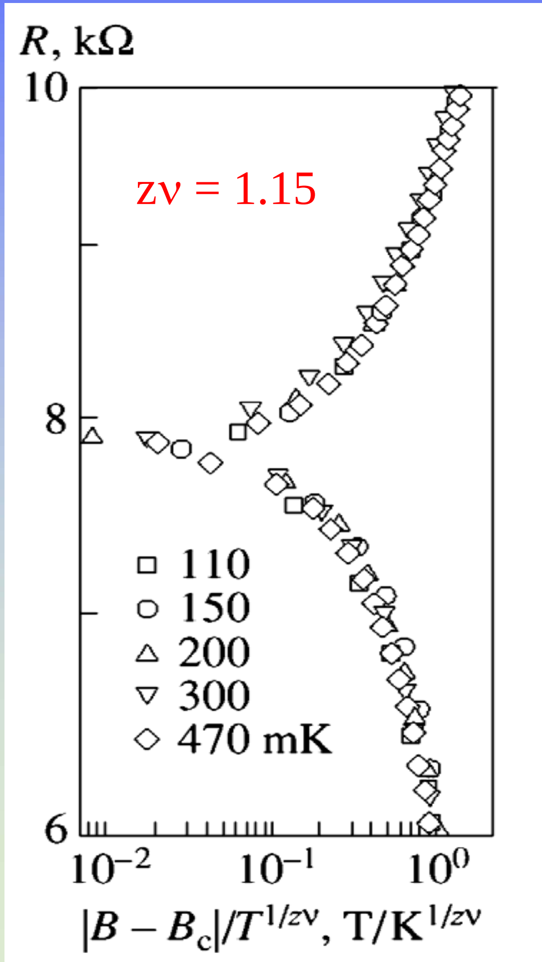
V. F. Gantmakher, M. V. Golubkov, V. T. Dolgopolov, A. A. Shashkin, G. E. Tsydynzhapov, JETP Lett. **71**, 160 (2000); **71**, 473 (2000)

a-InO_x

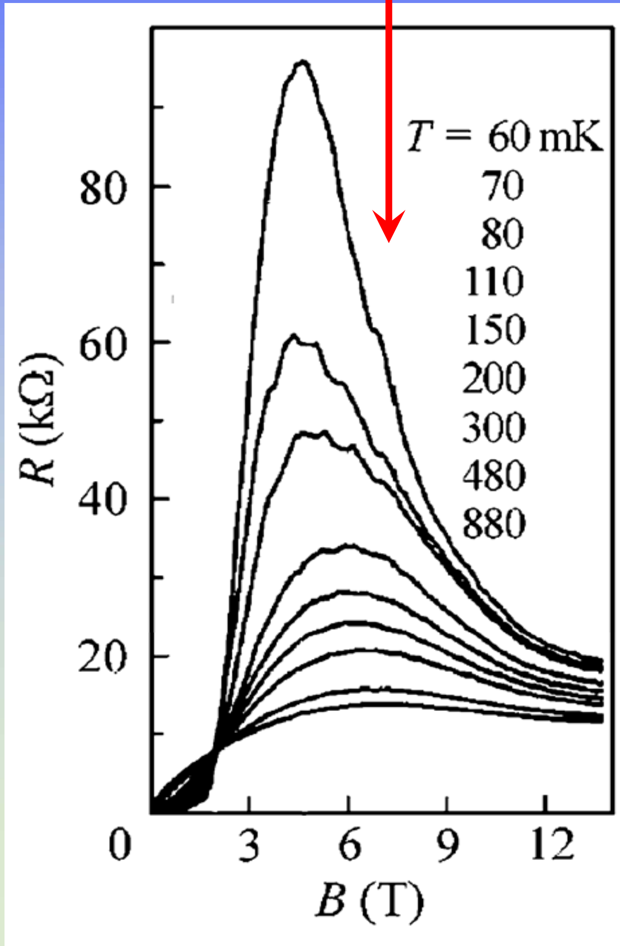
Fan-shaped curves



Scaling

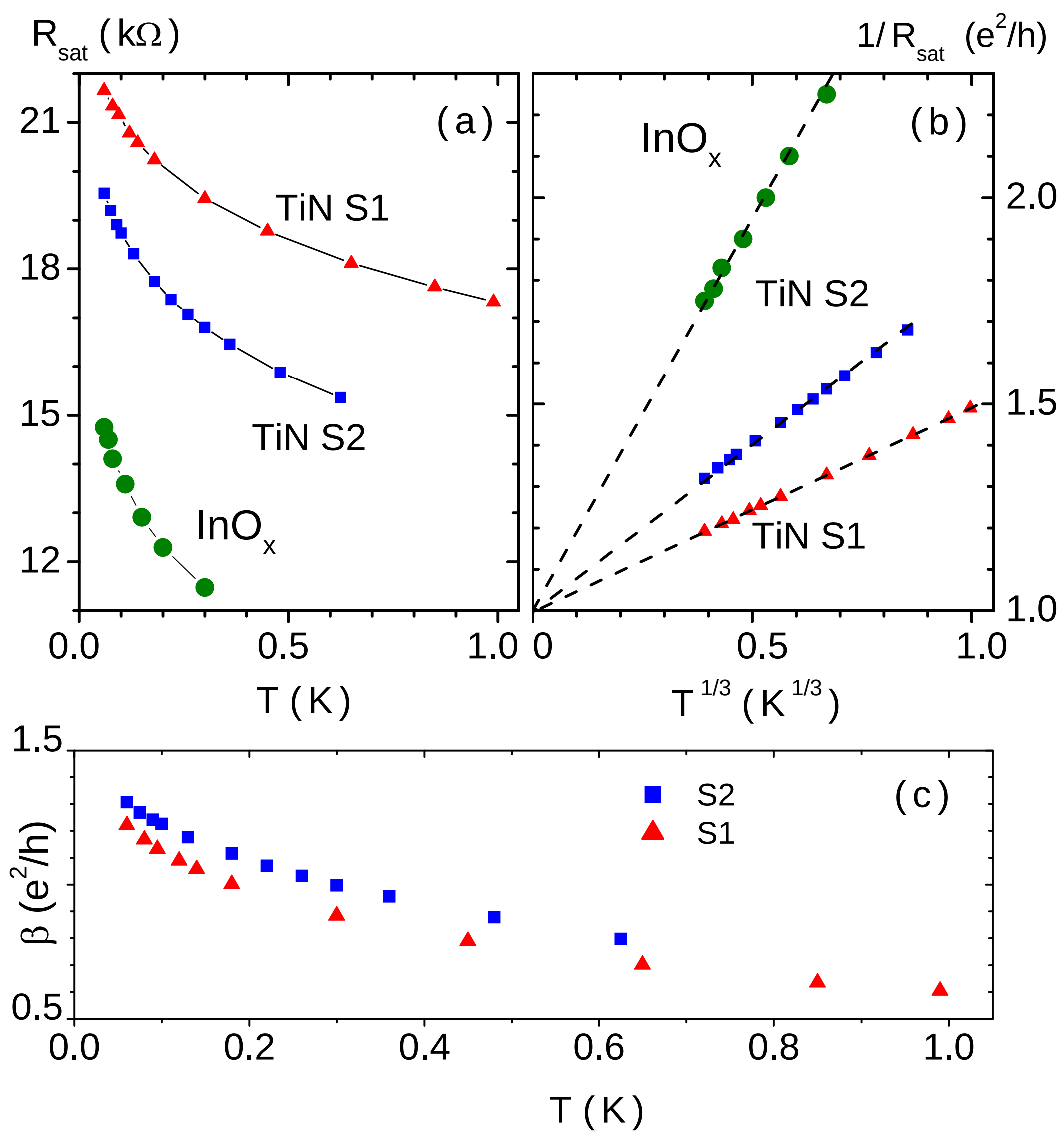


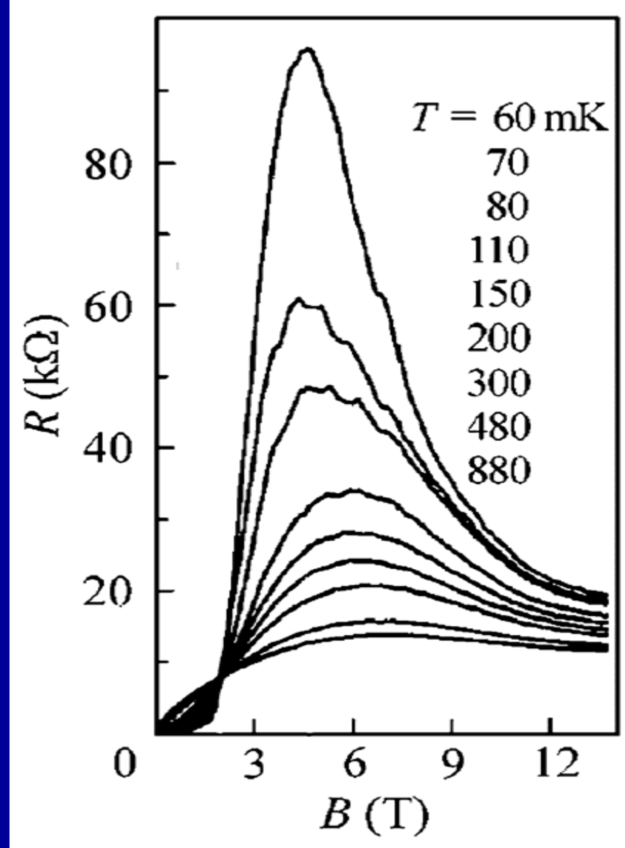
Negative magnetoresistance



V. F. Gantmakher, M. V. Golubkov, V. T. Dolgopolov, A. A. Shashkin, G. E. Tsydynzhapov, JETP Lett. **64**, 363 (1998).

InO_x film





Quantum metallicity in a two-dimensional insulator

V. Yu. Butko*† & P. W. Adams*

Nature 409, 161 (2001)

Be films

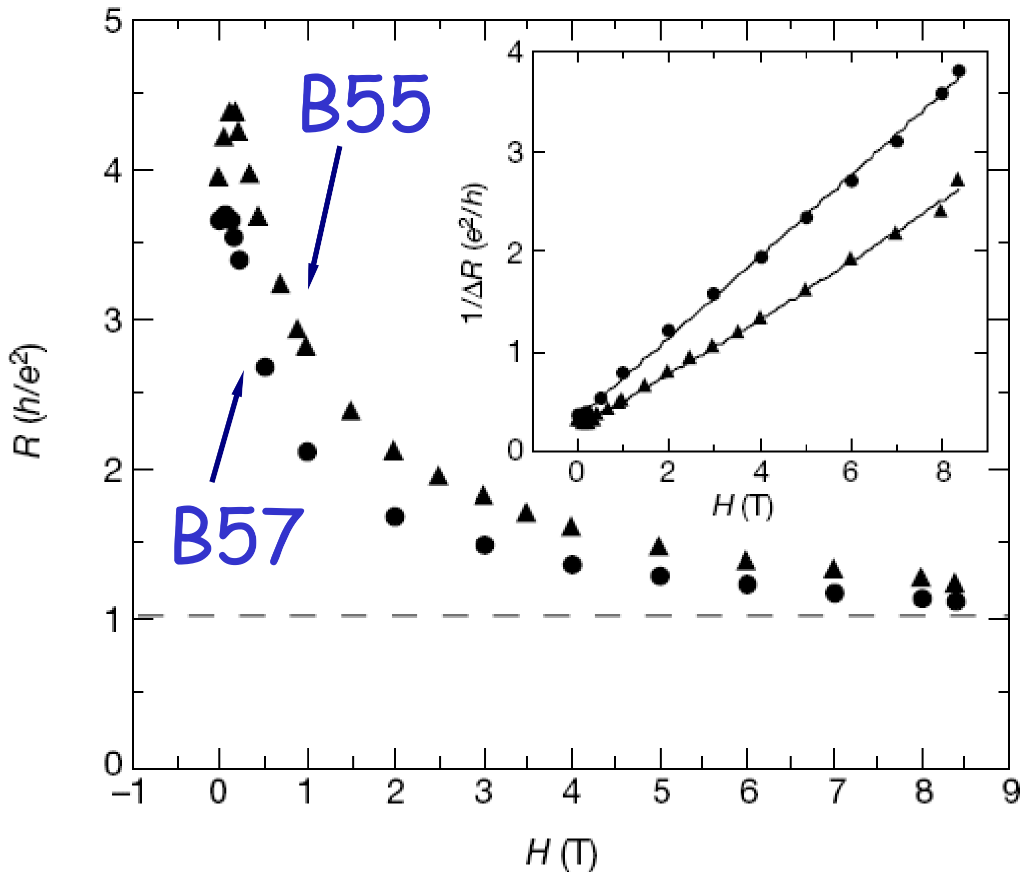


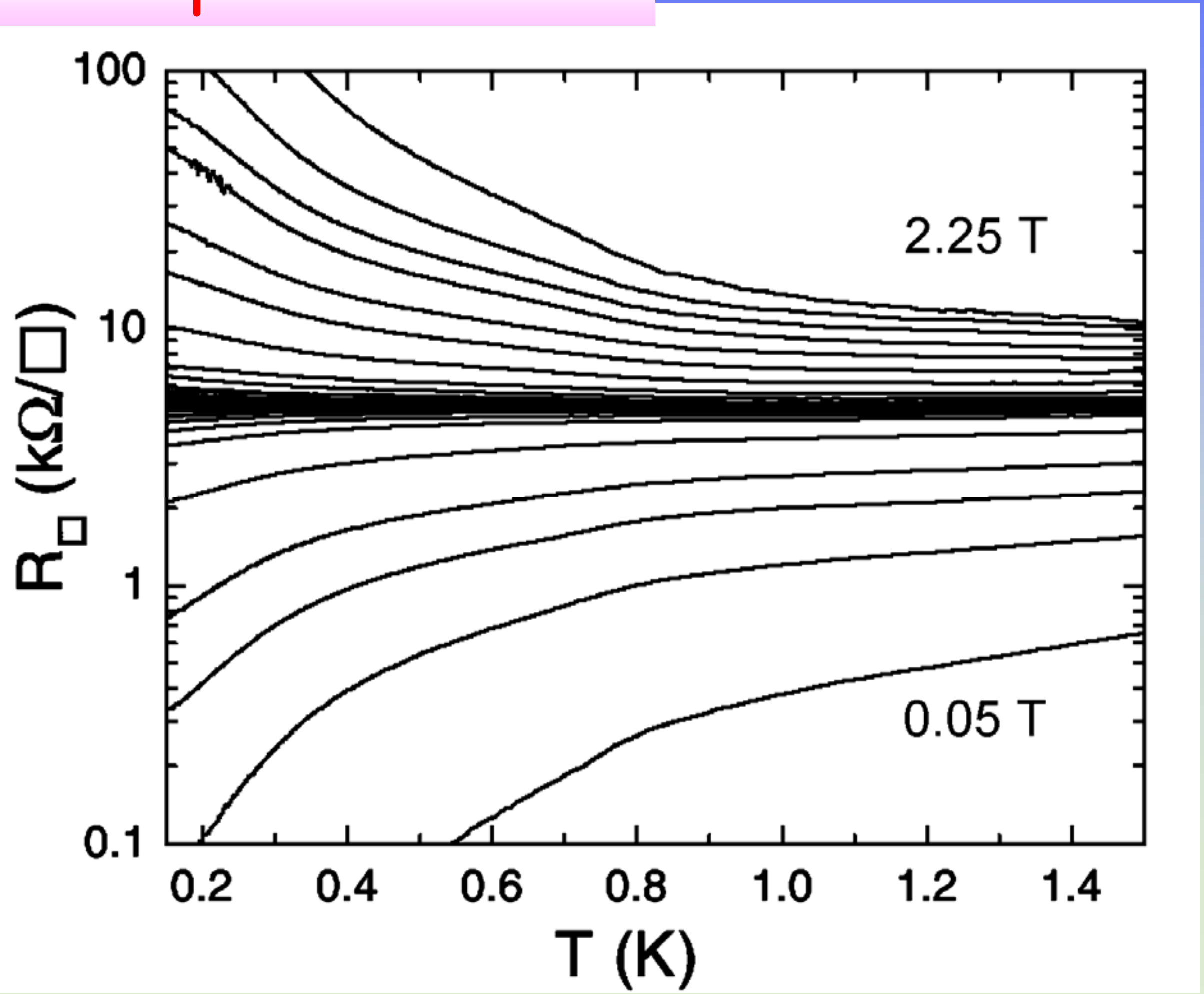
Figure 2 Low-temperature magnetoresistance. The figure shows the resistance in units of h/e^2 as a function of magnetic field H at $T = 40$ mK, for samples B57 (circles) and B55 (triangles). We note the saturation at $R \approx h/e^2$. Inset, linear behaviour after subtracting a saturation resistance of 0.85 h/e^2, $\Delta R = R - 0.85$. The solid lines are guides to the eye.

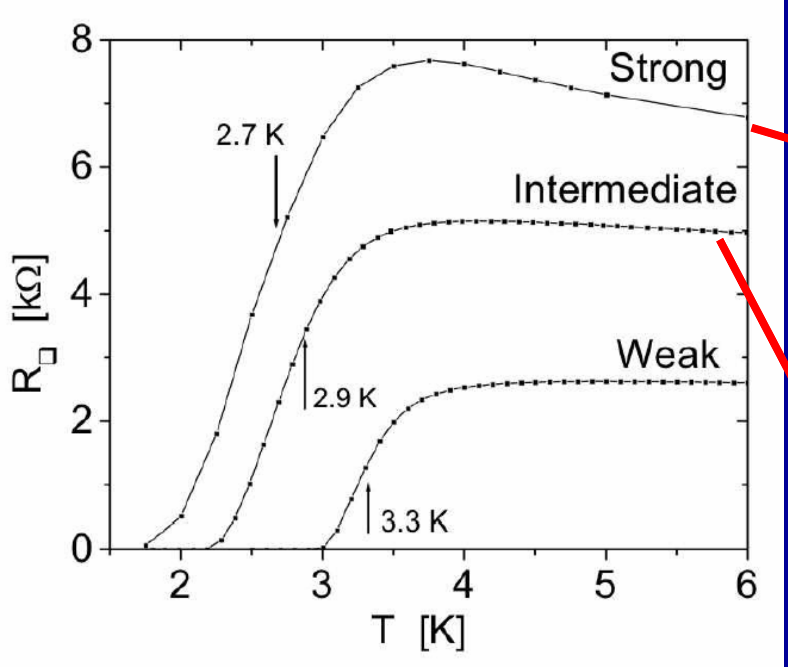
Field-induced superconductor – insulator transition

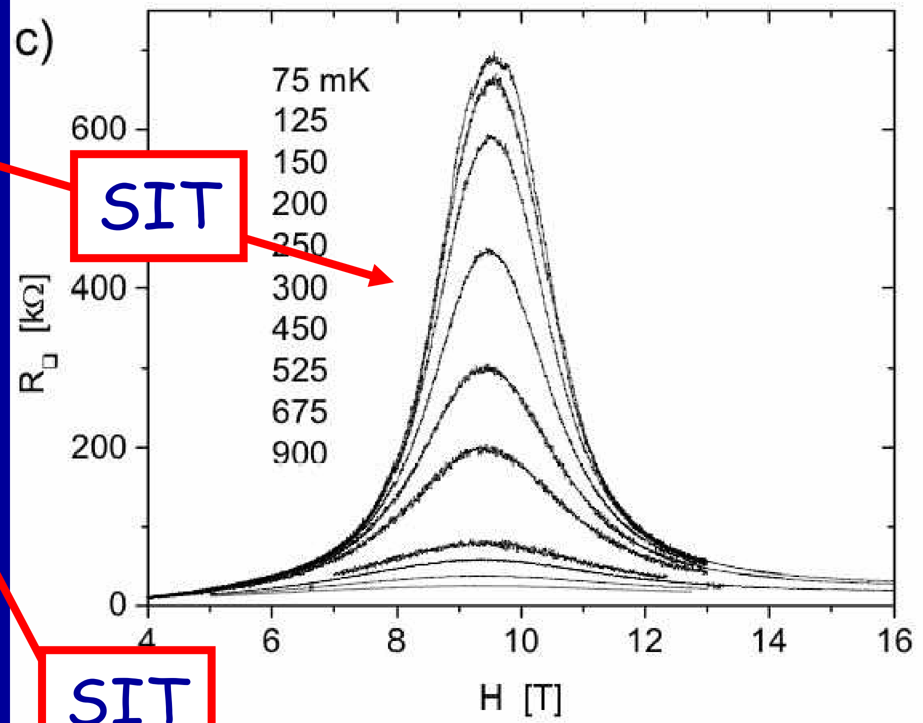
E. Bielejec and Wenhao Wu, PRL **88**, 206802 (2002)

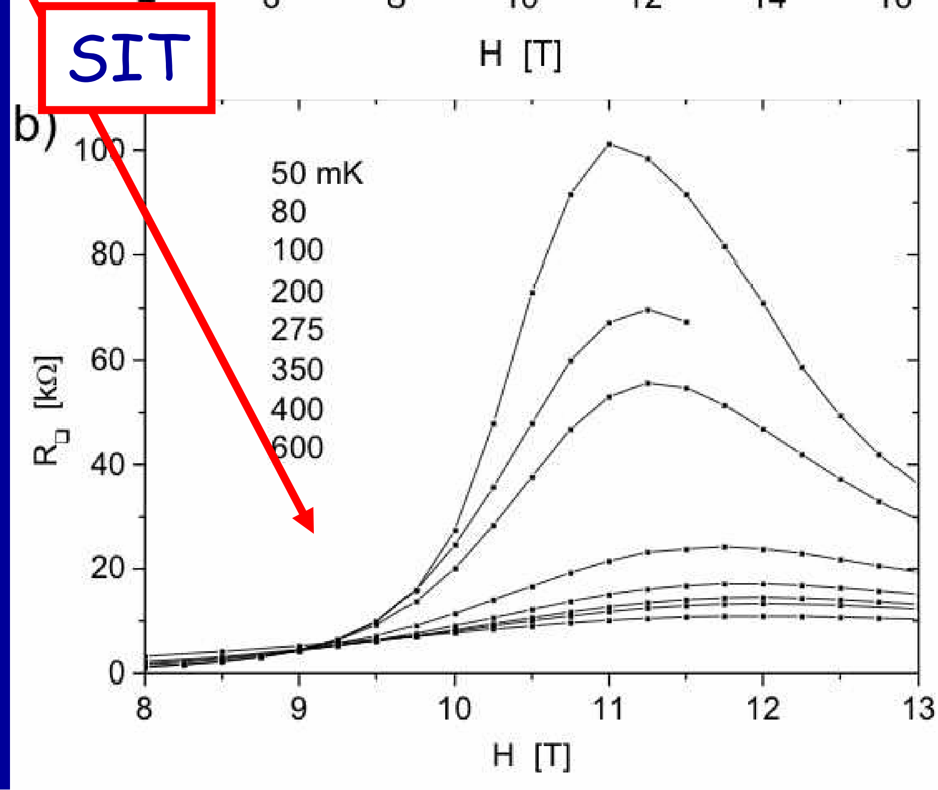
Be films

Fan-shaped curves



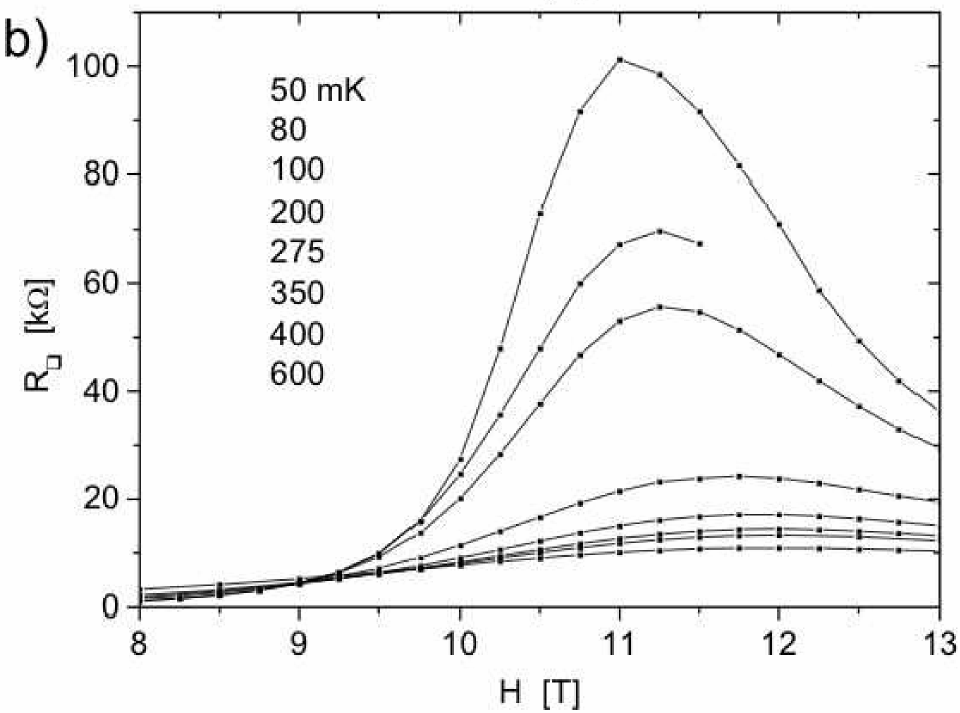


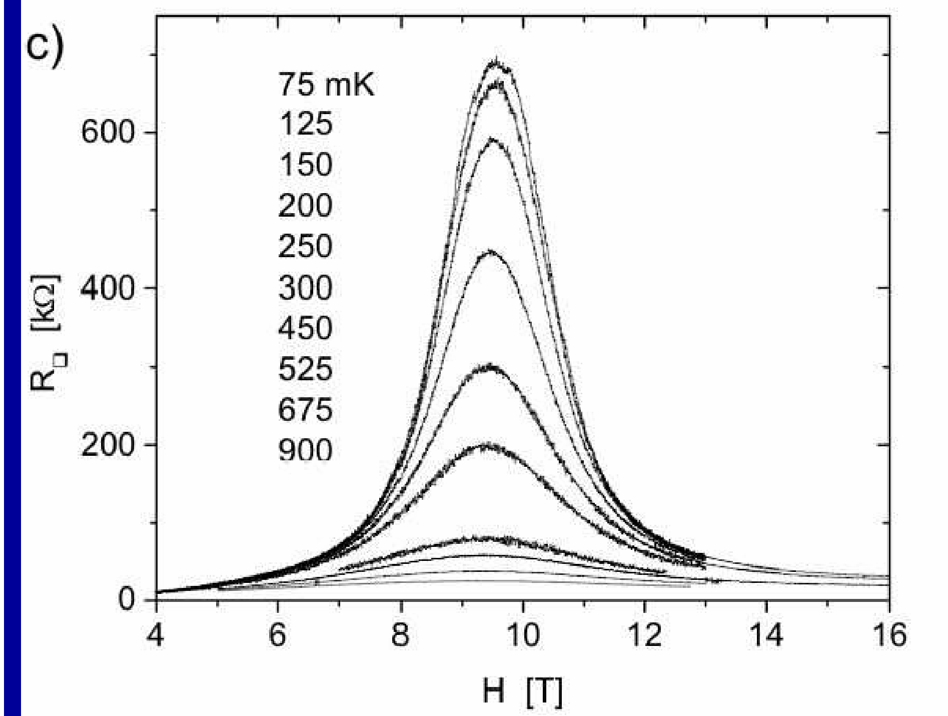




InO_x films

M. Steiner and A. Kapitulnik, Physica C **422**, 16 (2005)

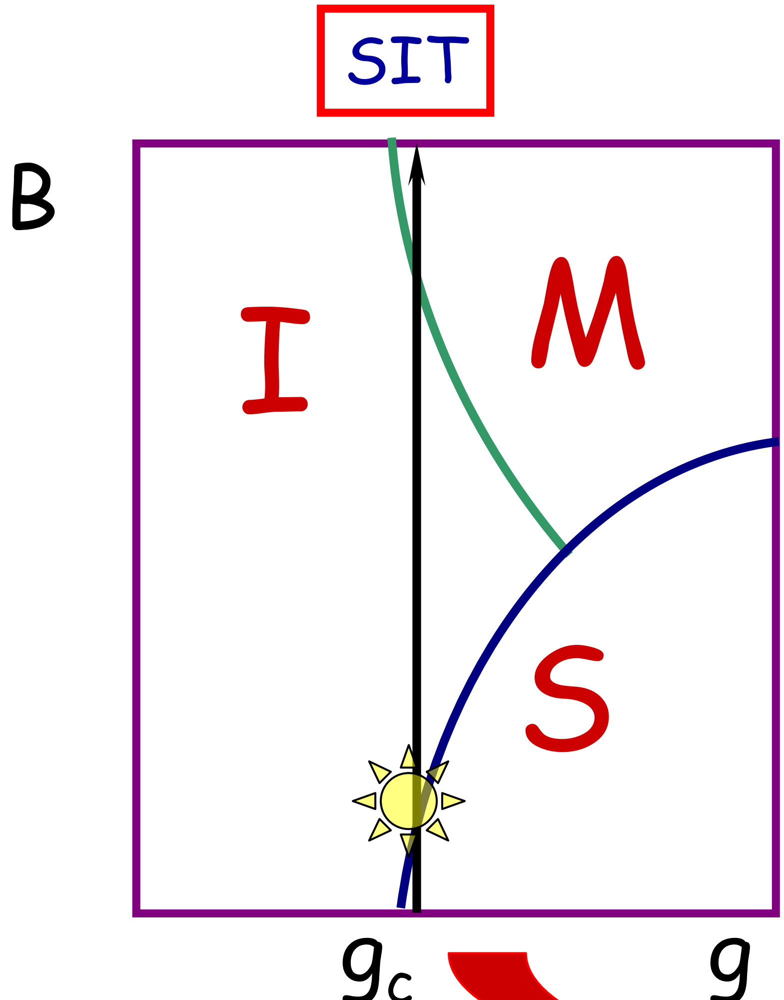




The insulating state above the crossing point becomes even more dramatic in the films with higher R_n. At low temperature and moderately high field these films reveal a new, extremely strong tendency towards the insulating phase, shown in Figures 4b and 4c. The resistance at the crossing point of both plots is comparable to that of the first film. We note, however, that the position of the crossing point shifts to lower field as the insulator strength increases. On the high field side of the peak the isotherms all decay to resistances $\leq 20\ \text{k}\Omega/\square$, above the normal resistance R_n, at the highest accessible fields.

schematic phase diagram

InO_x, Be, and TiN films



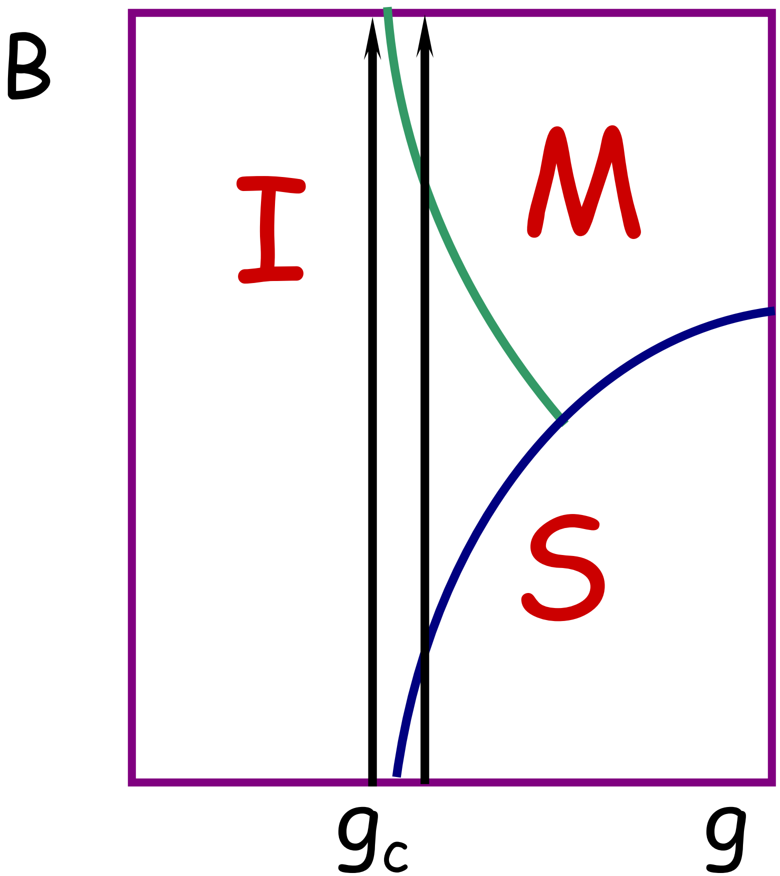
Quantum metallicity at a high-field side of SIT

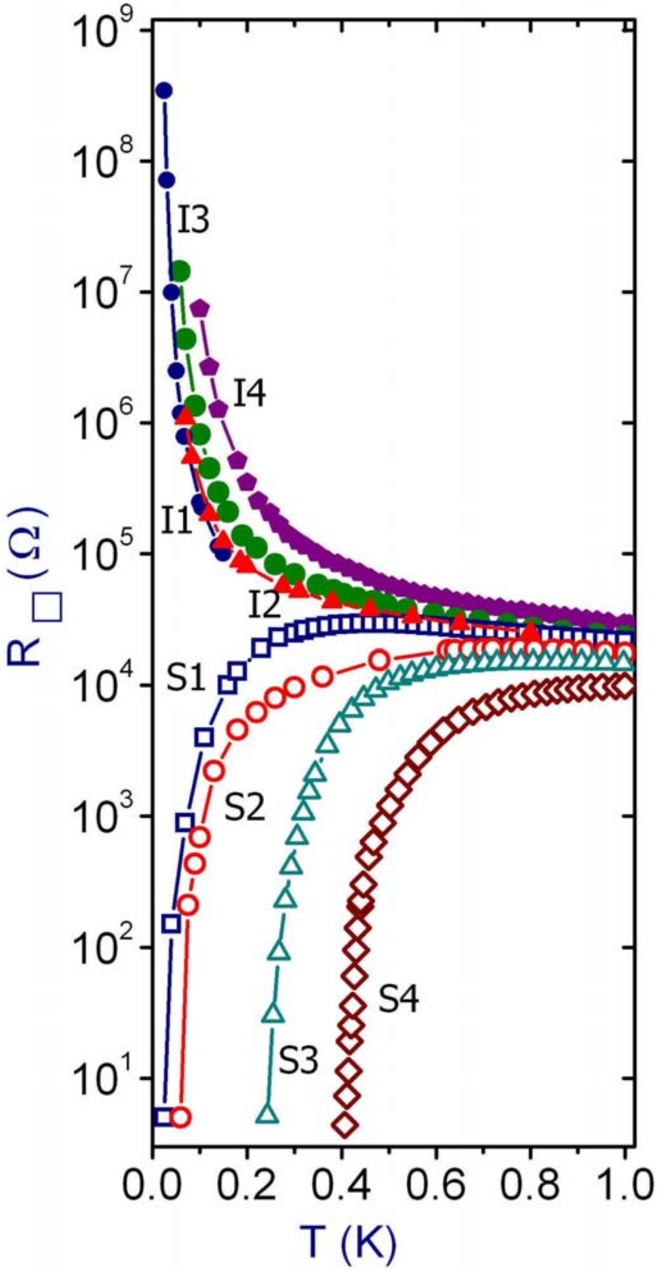
Magnetic-field-tuned superconductor–insulator quantum phase transition

Disorder-driven superconductor–insulator quantum phase transition

schematic phase diagram

TiN films



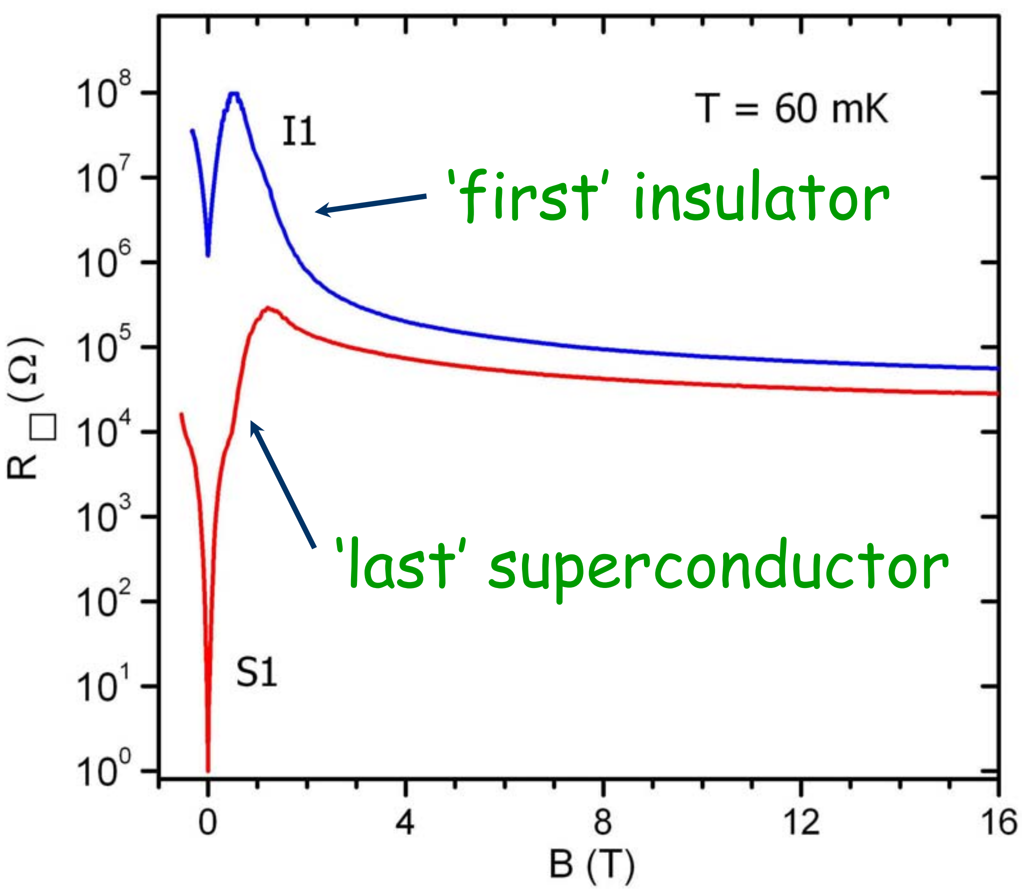


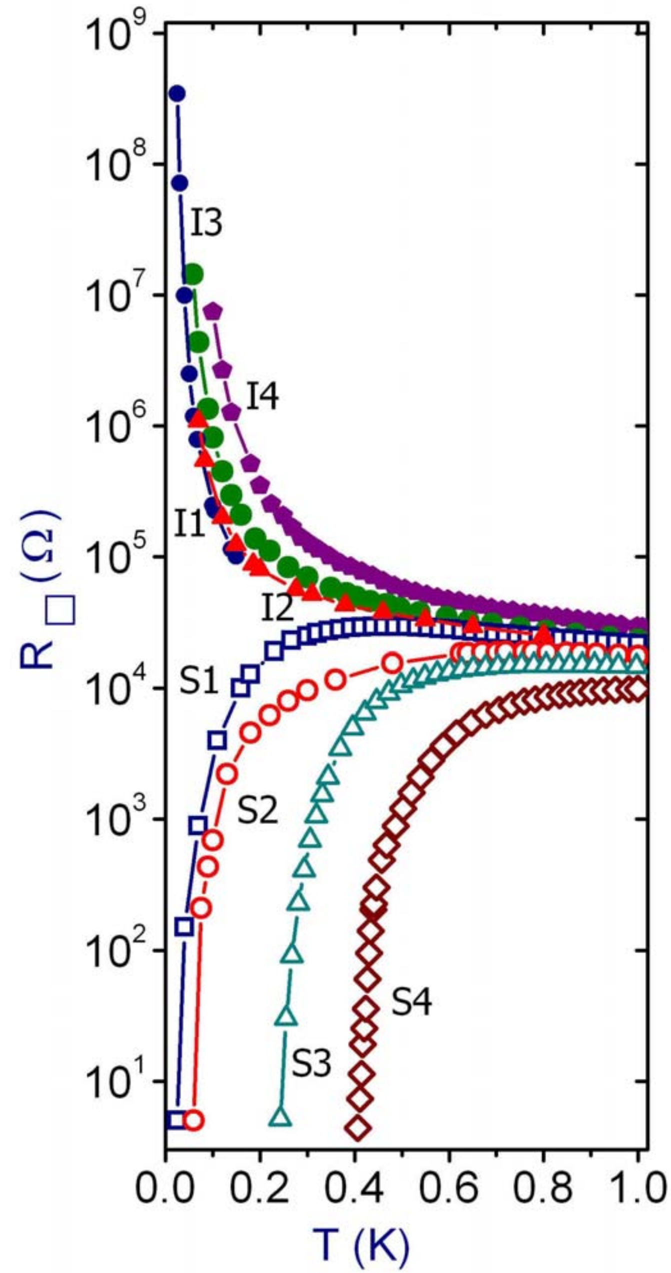
Critical Region of the Disorder-Driven Superconductor-Insulator quantum phase transition

T.I. Baturina et al., cond-mat/0705.1602
T.I. Baturina et al., Physica C, in press

Magnetoresistance

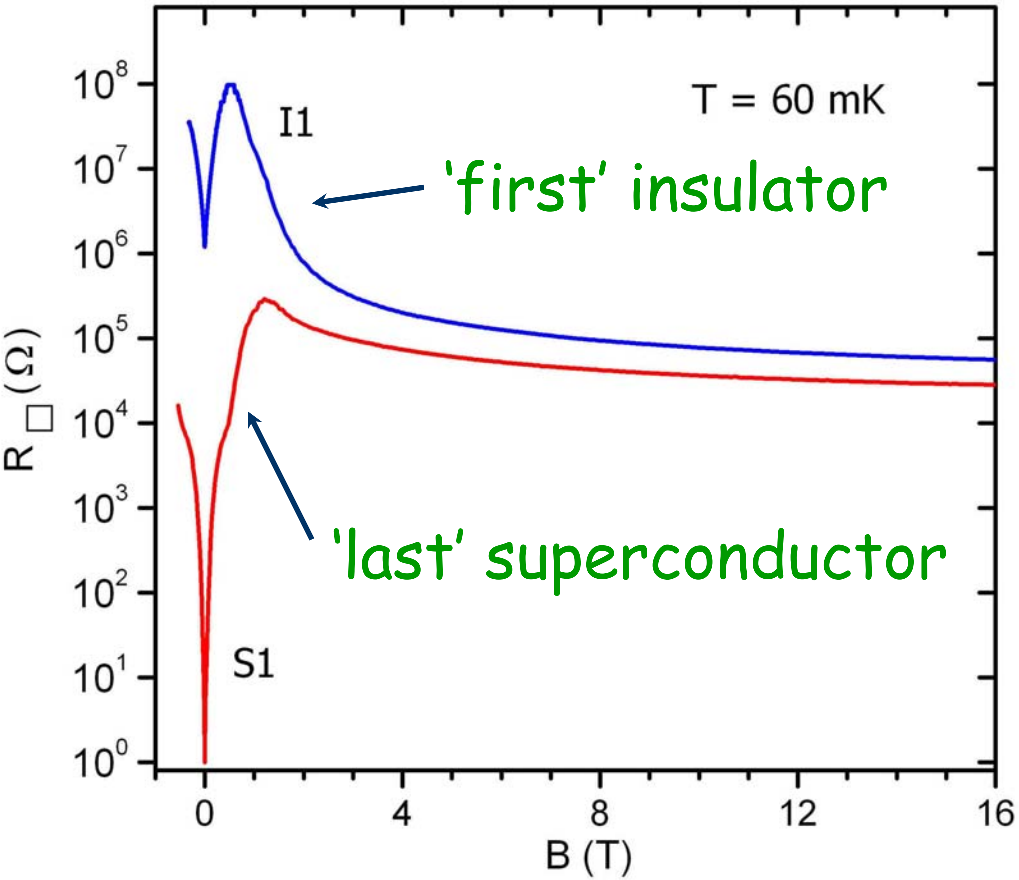
TiN films



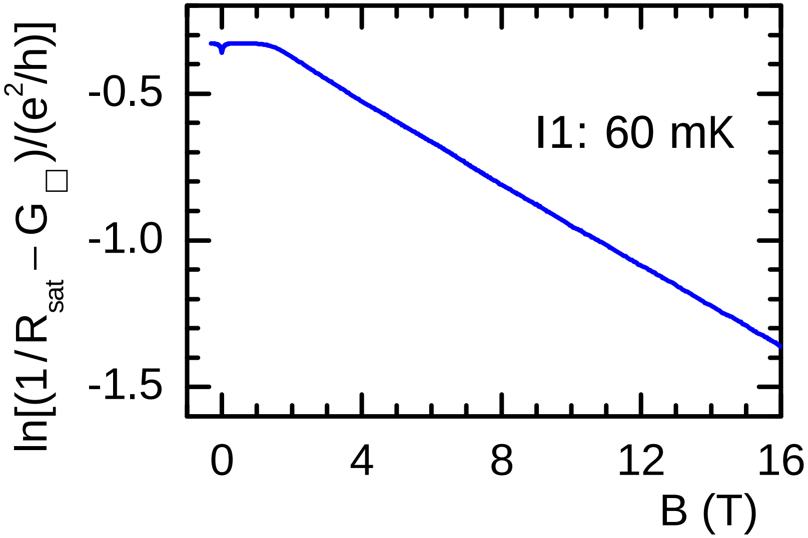


In all samples, including the insulating films, R(B) varies nonmonotonically with B, starting a positive magnetoresistance (PMR) at low fields, then reaching a maximum, followed first by a rapid drop and eventually saturating at higher magnetic fields

Magnetoresistance



Behavior in high magnetic field



$\ln(1/R_{sat} - 1/R_{sq}(B))$ vs. B

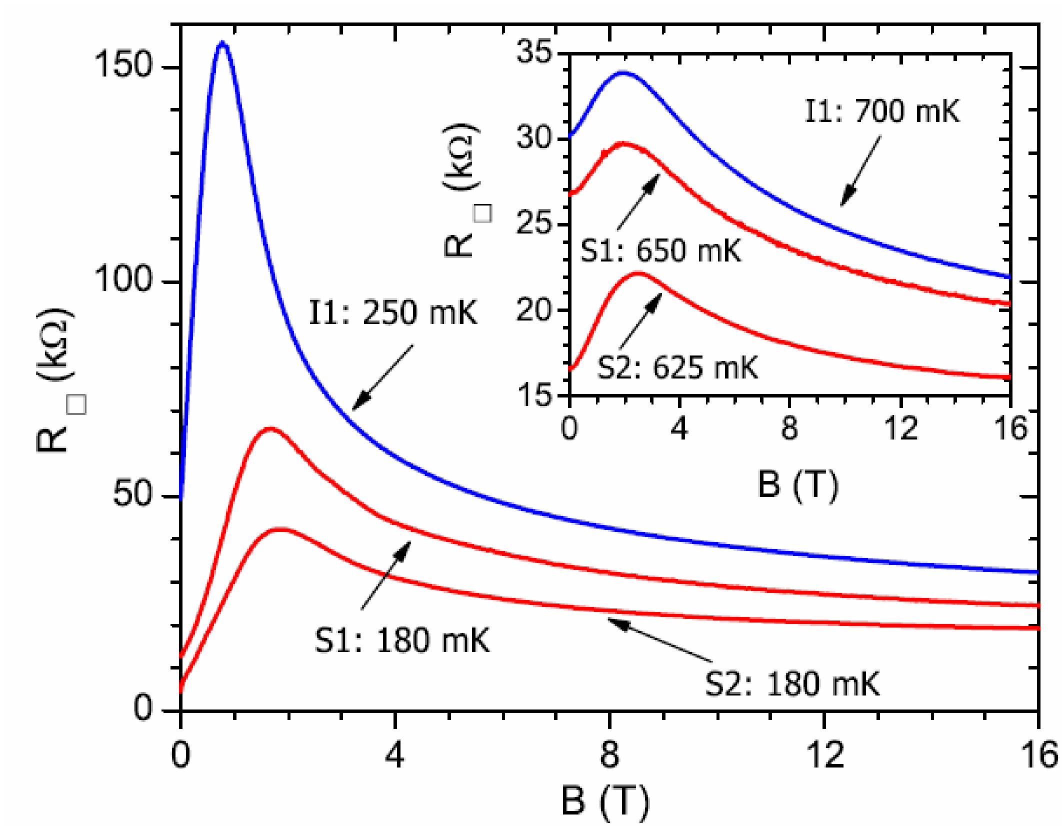
T.I. Baturina et al., Physica C, in press

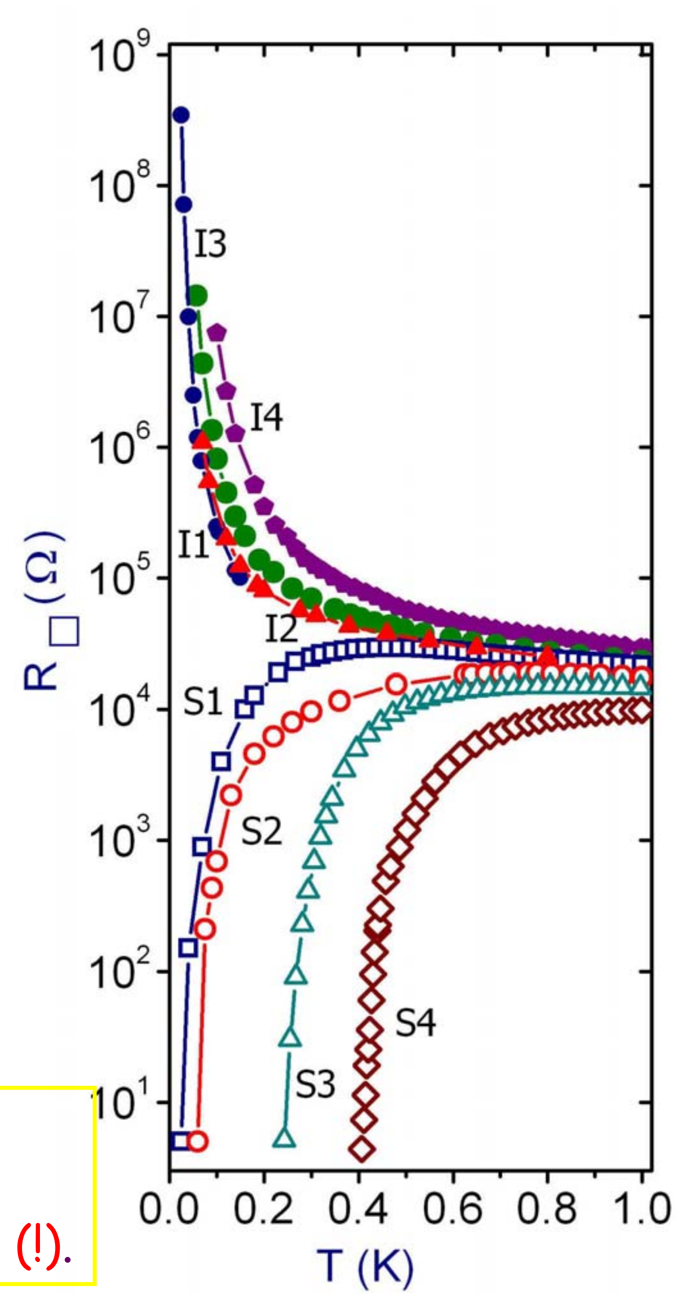
$R_{sat} \approx h/e^2$

Magnetoresistance

TiN films

While the difference between the insulating and superconducting samples is significant at the zero magnetic field and at low temperatures,
it vanishes at higher magnetic fields and temperatures





Relying on the high temperature data only
it is impossible to predict whether the film turns superconductor or insulator at lowest temperatures (!).

PMR and activated behavior

TiN films

I1

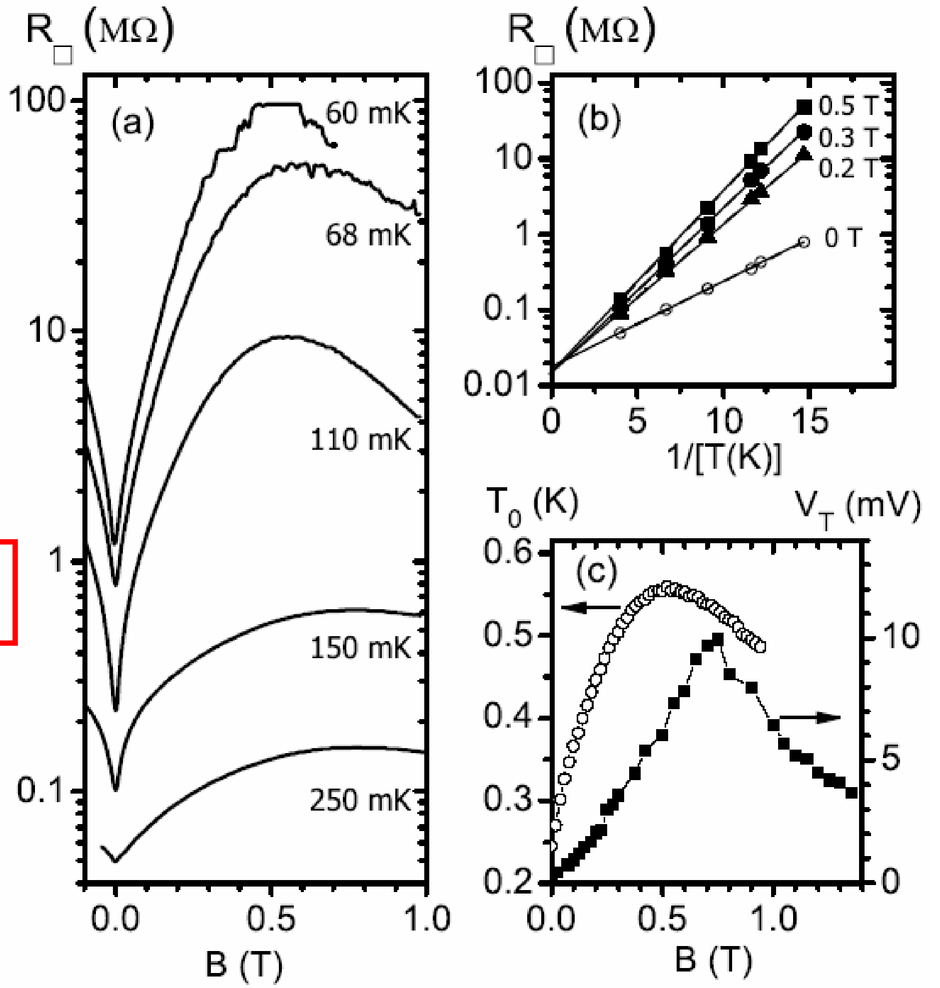
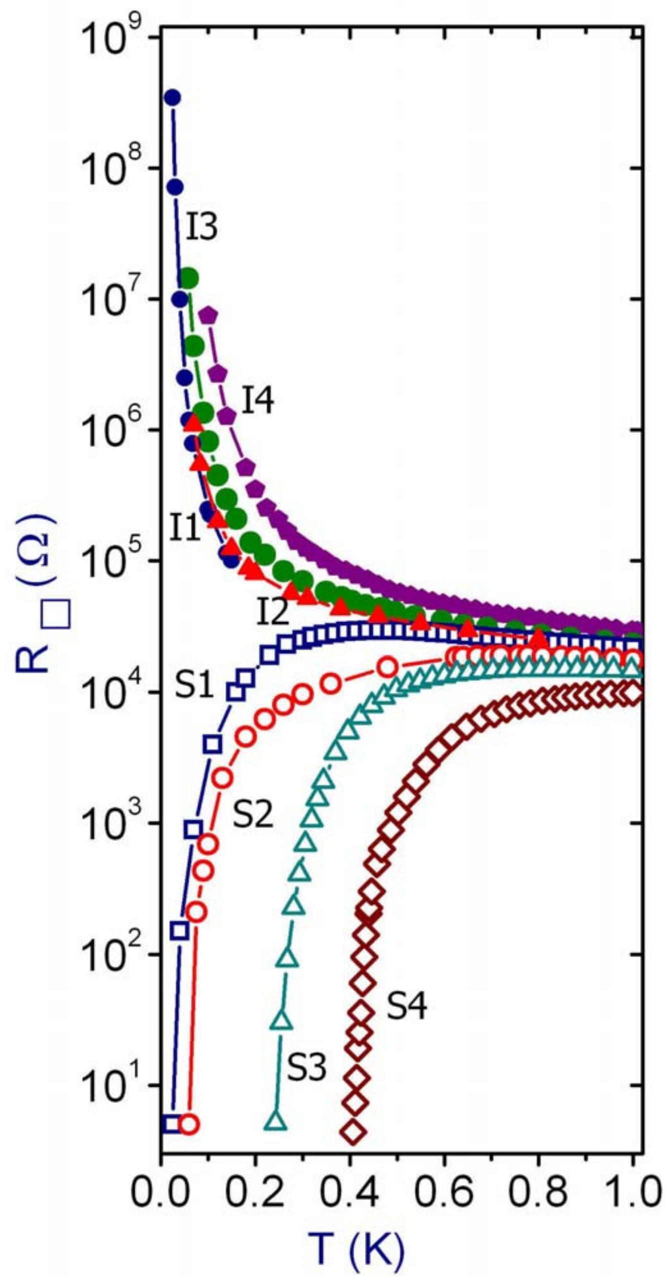


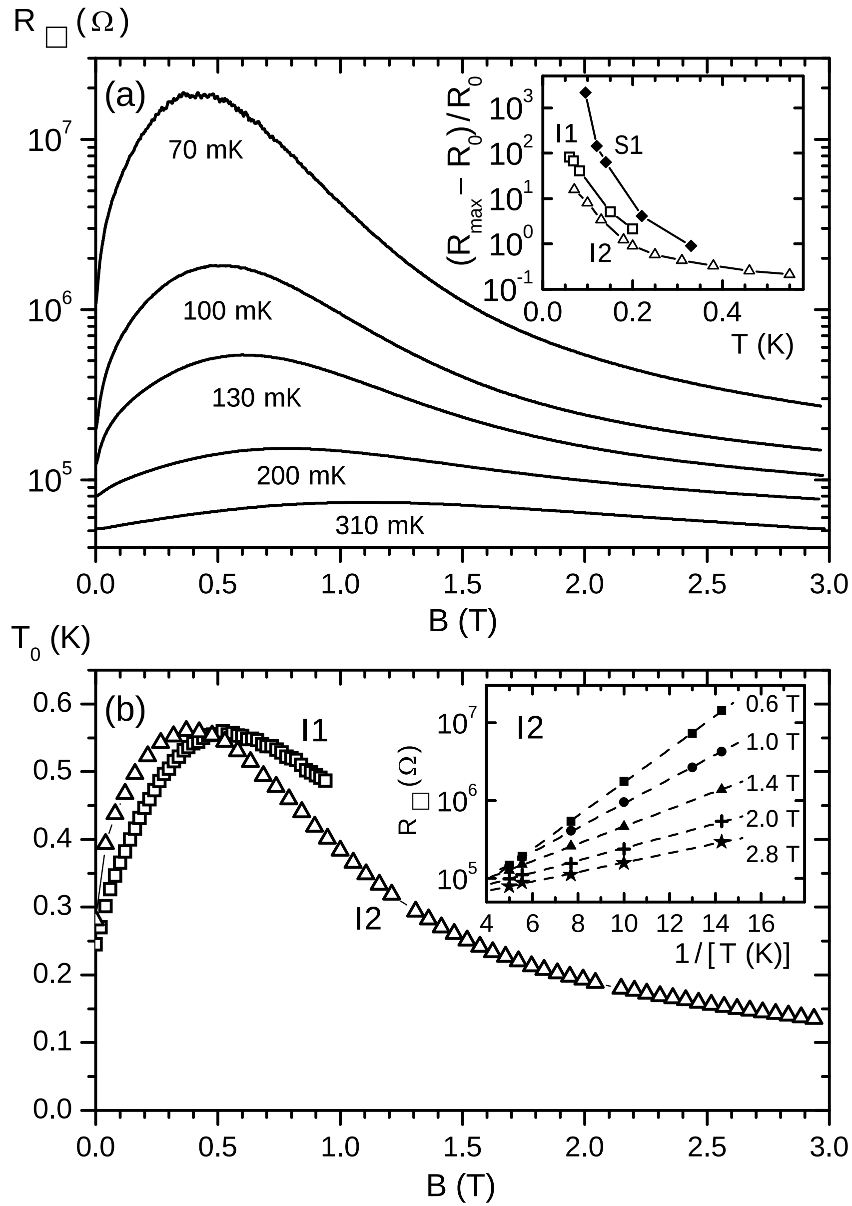
FIG. 3: (a) Sheet resistance of sample I1 as a function of the magnetic field at some temperatures listed. (b) R versus $1/T$ at $B = 0$ (open circles), 0.2 (triangles), 0.3 (filled circles), and 0.5 T (squares). The dashed lines are given by Eq. (1). (c) T_0 (left axis), calculated from fits to Eq. (1), and the threshold voltage V_T (right axis) as a function of B.

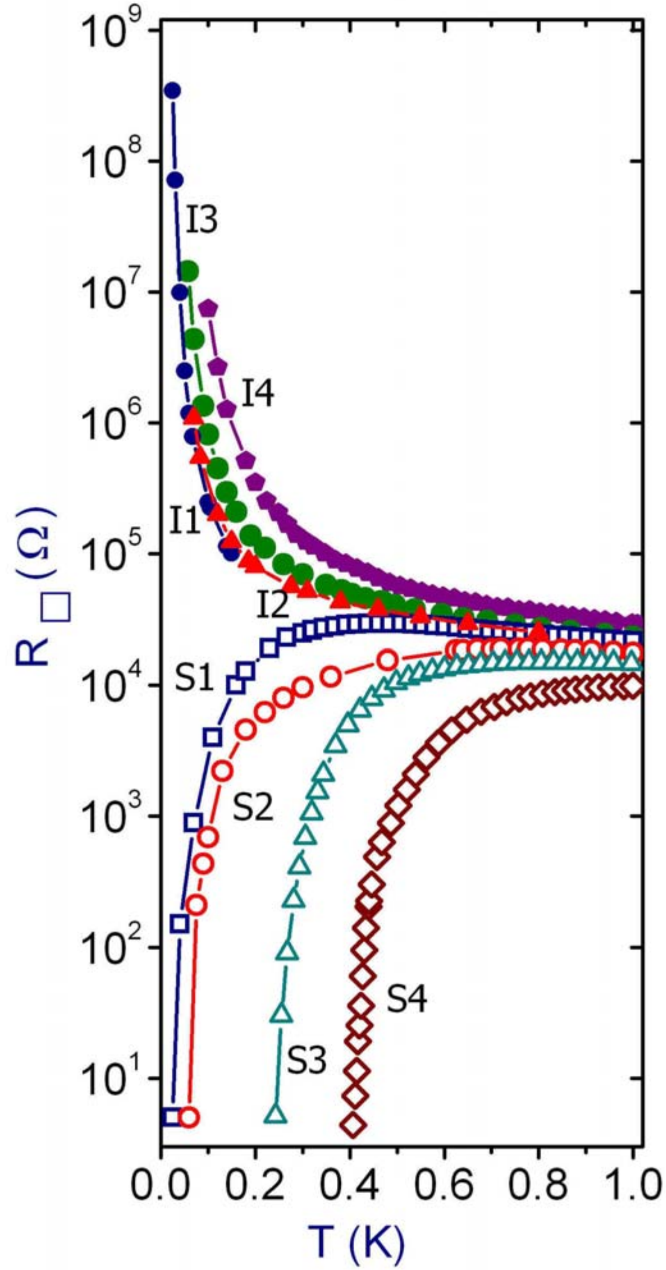


PMR and activated behavior

TiN films

I2





Magnetoresistance

InO_x films

V.F. Gantmakher *et al.*,
JETP 82, 951 (1996).

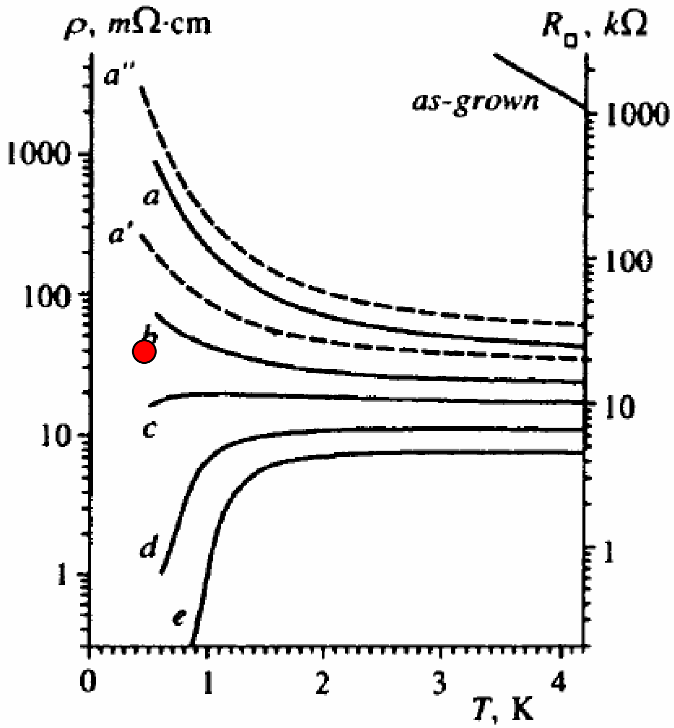
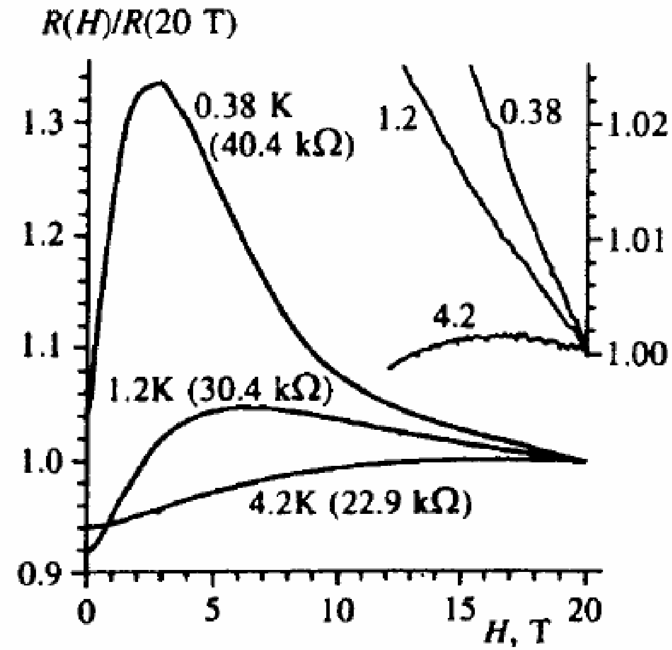


FIG. 2. Evolution of the temperature dependence of the resistance of a-In_2O_x films in zero magnetic field after different treatments. Film No. 1: states a (initial)–e, film No. 2: states a' (initial) and a''. A part of the dependence $R(T)$ for the as-grown film from the inset of Fig. 1 is also plotted.



Field dependence $R(H)$ normalized to $R(20\ T)$ at three different
ıtures. Inset: high-field part of the curves at ten times the vertical
ilm No. 3, state b.

Magnetoresistance

Be films

E. Bielejec, J. Ruan, and W. Wu,
PRB 63, 100502(R) (2001).

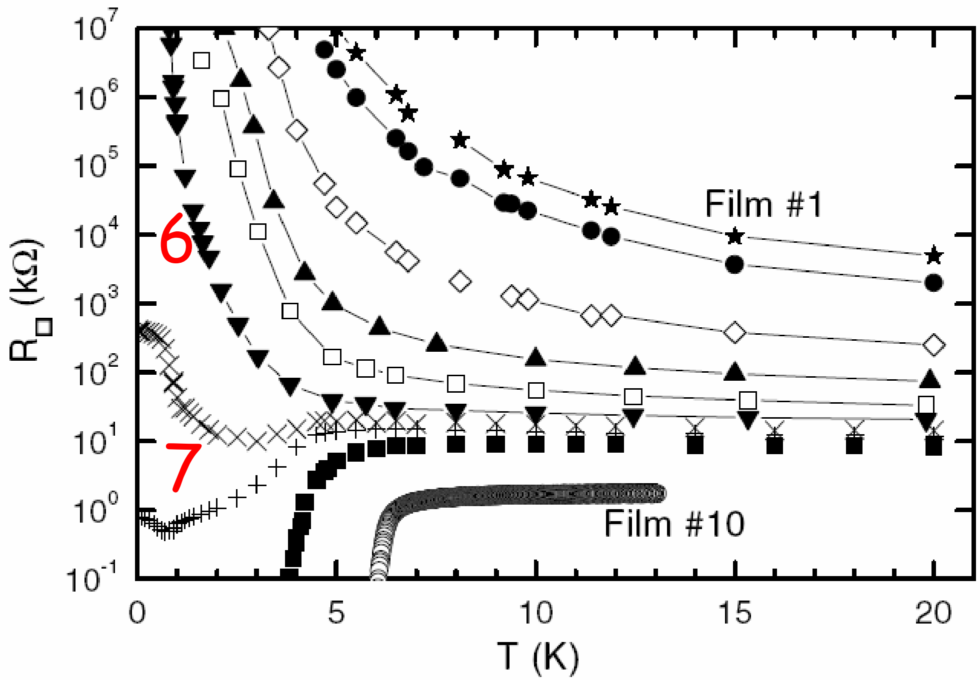
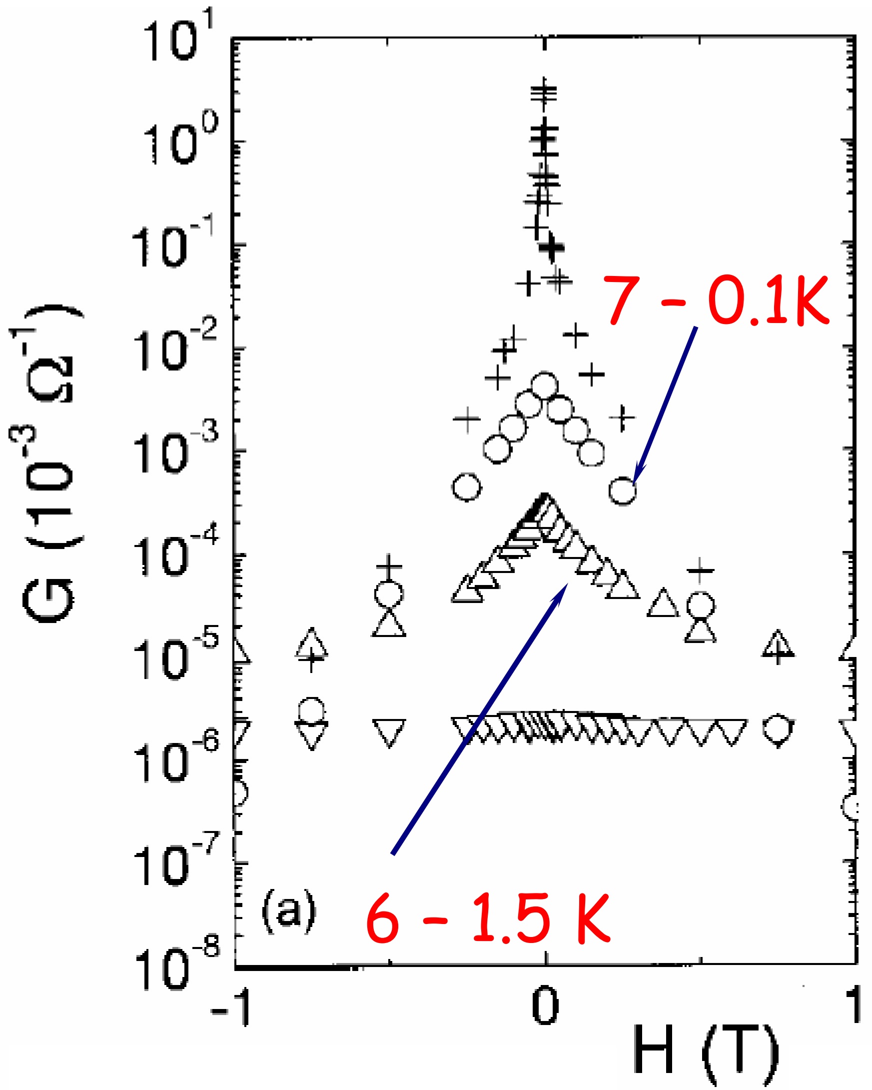
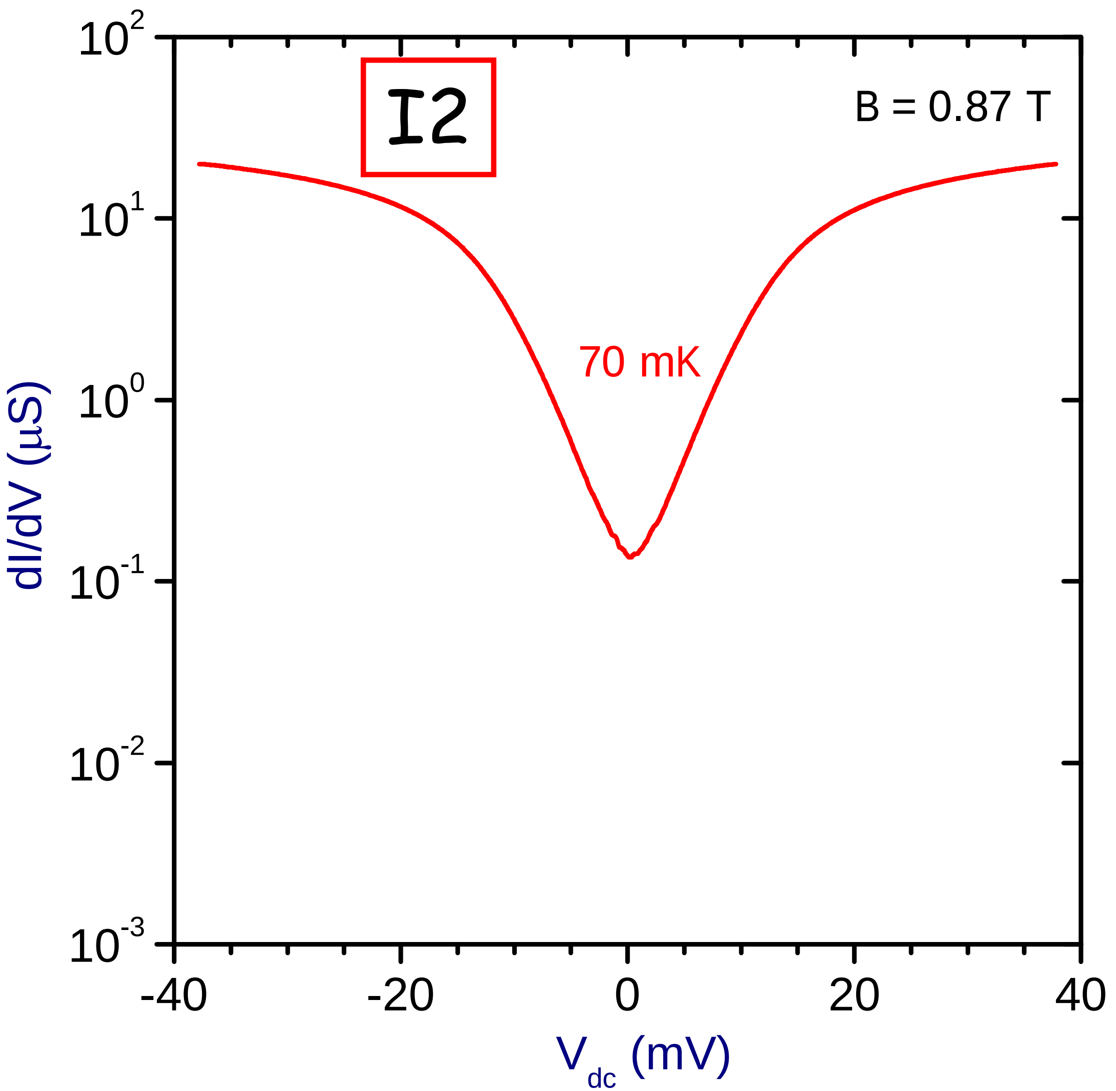


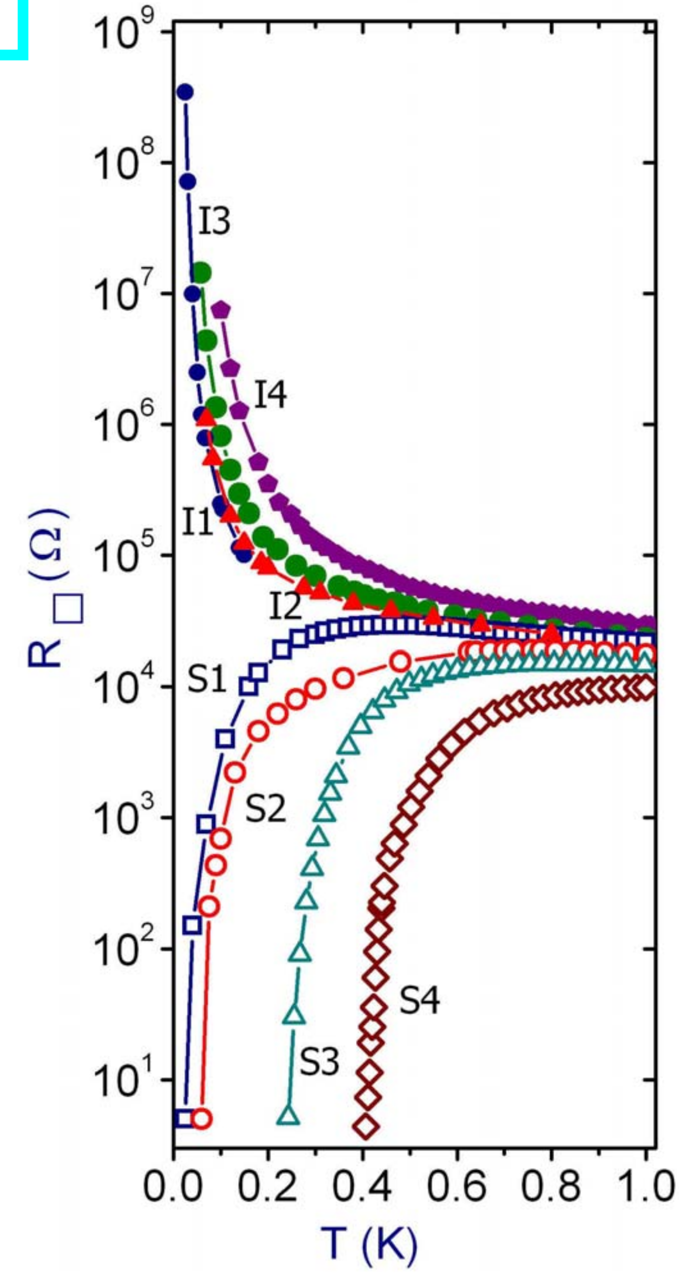
FIG. 1. Curves of film sheet resistance as a function of temperature measured on one film section following a series of deposition steps to increase film thickness. For curves from top to bottom, we label them as Film #1 to Film #10, respectively. The thickness for these films changed from 4.6 to 15.5 Å.



Collective insulating state: Threshold behavior of dI/dV vs V_{dc}

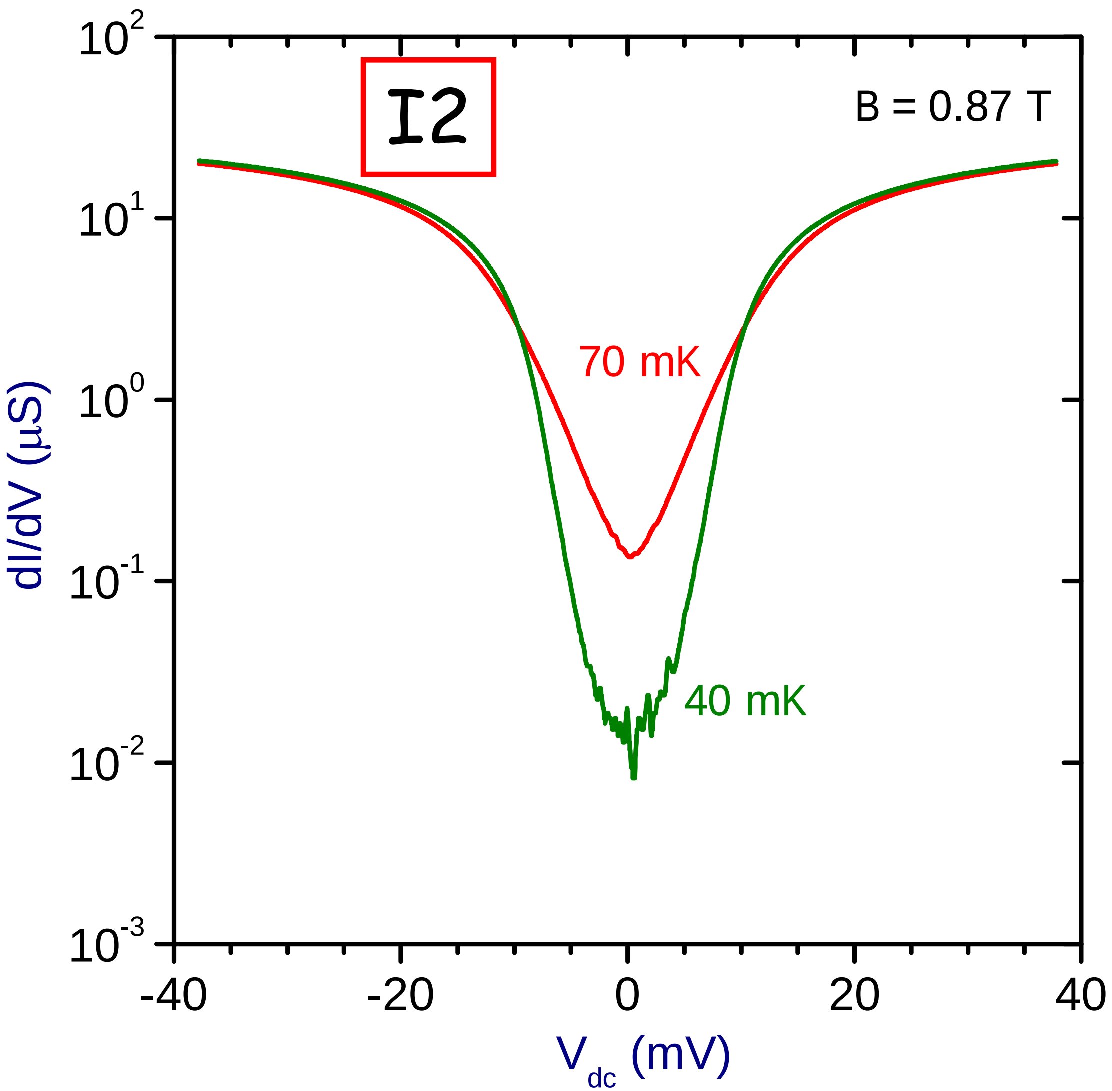
TiN films

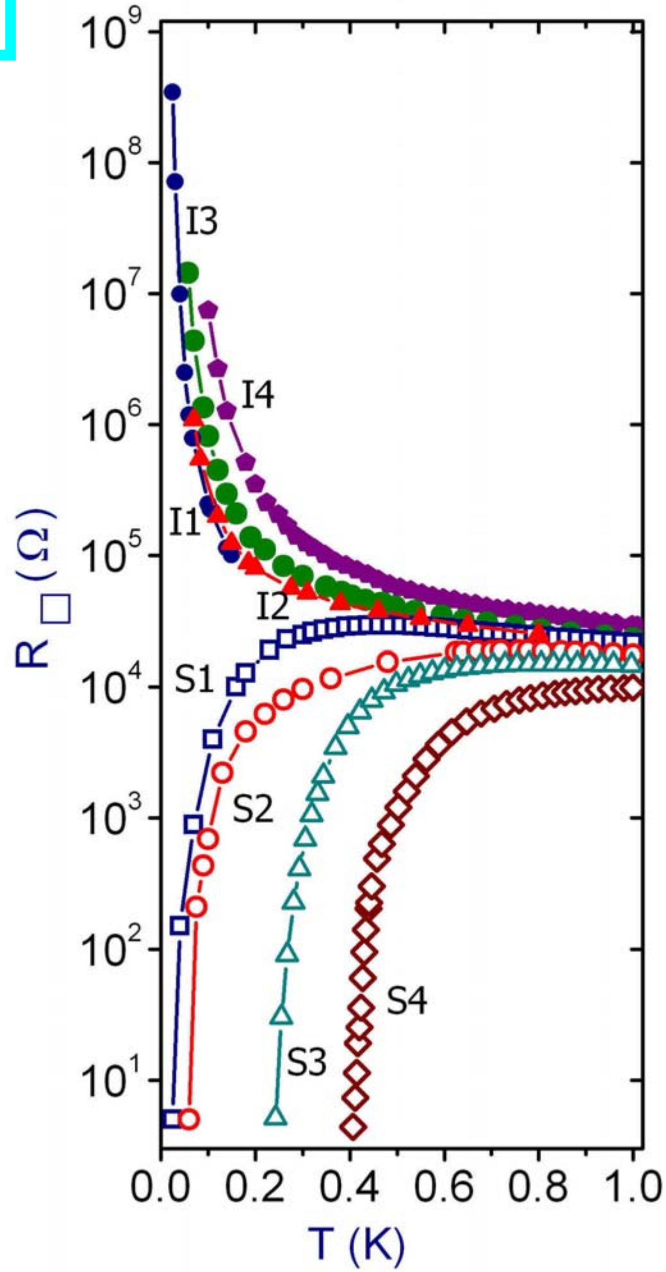




Collective insulating state: Threshold behavior of dI/dV vs V_{dc}

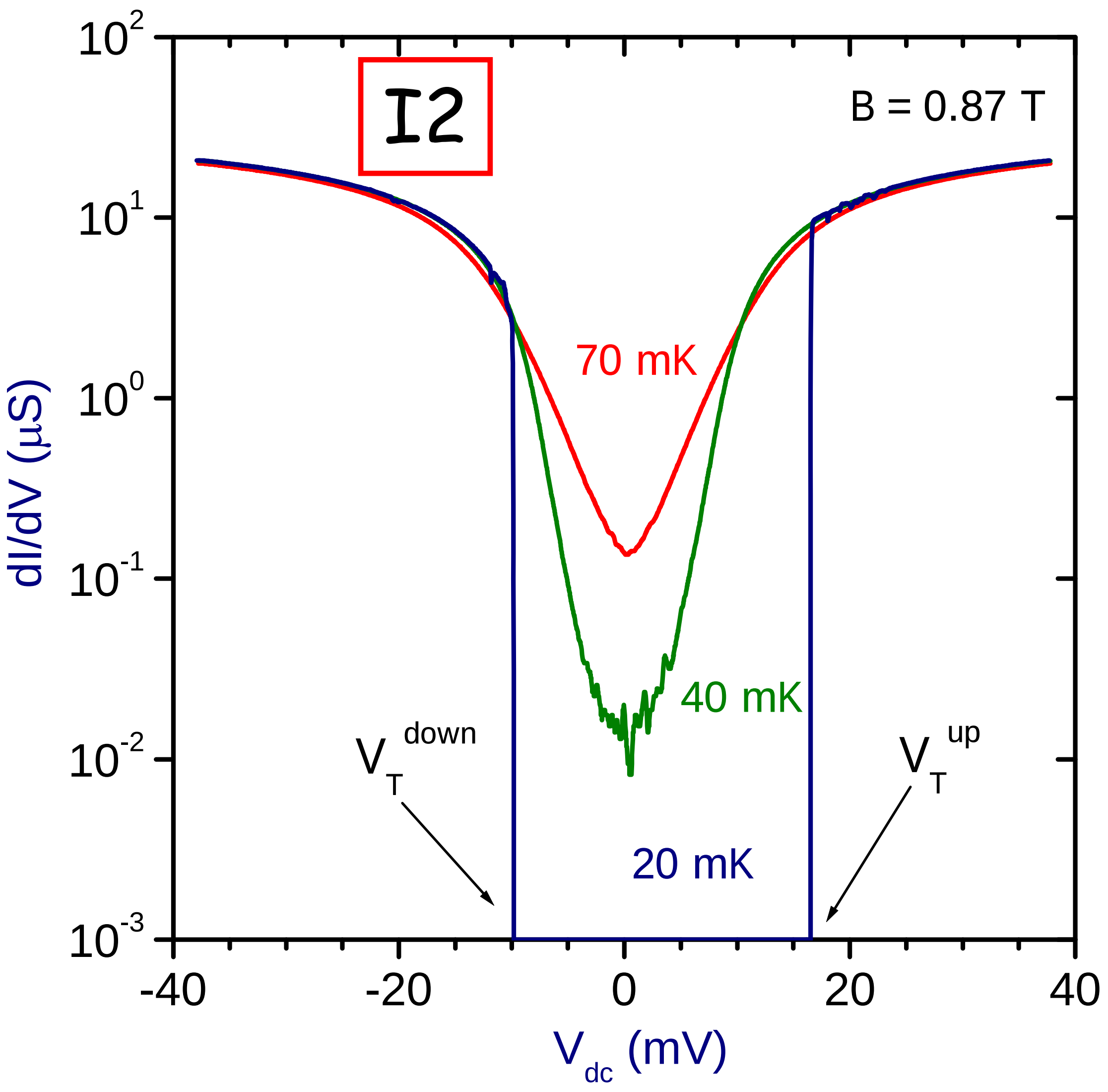
TiN films

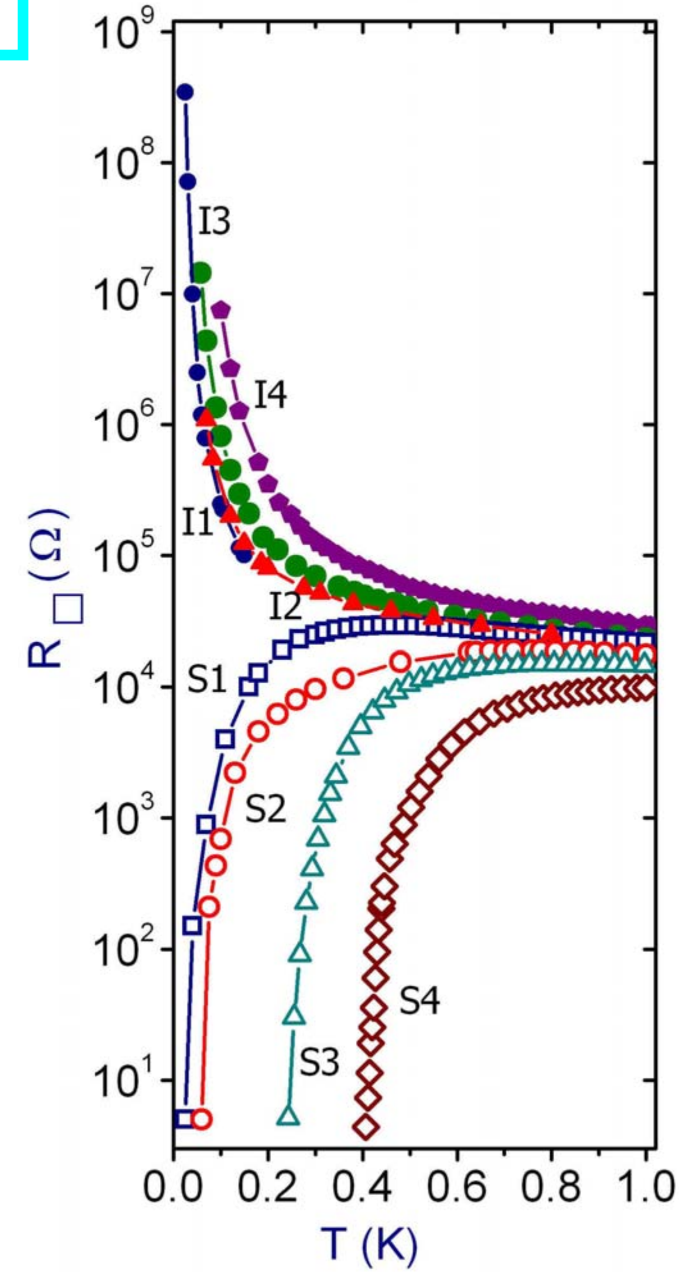




Collective insulating state: Threshold behavior of dI/dV vs V_{dc}

TiN films

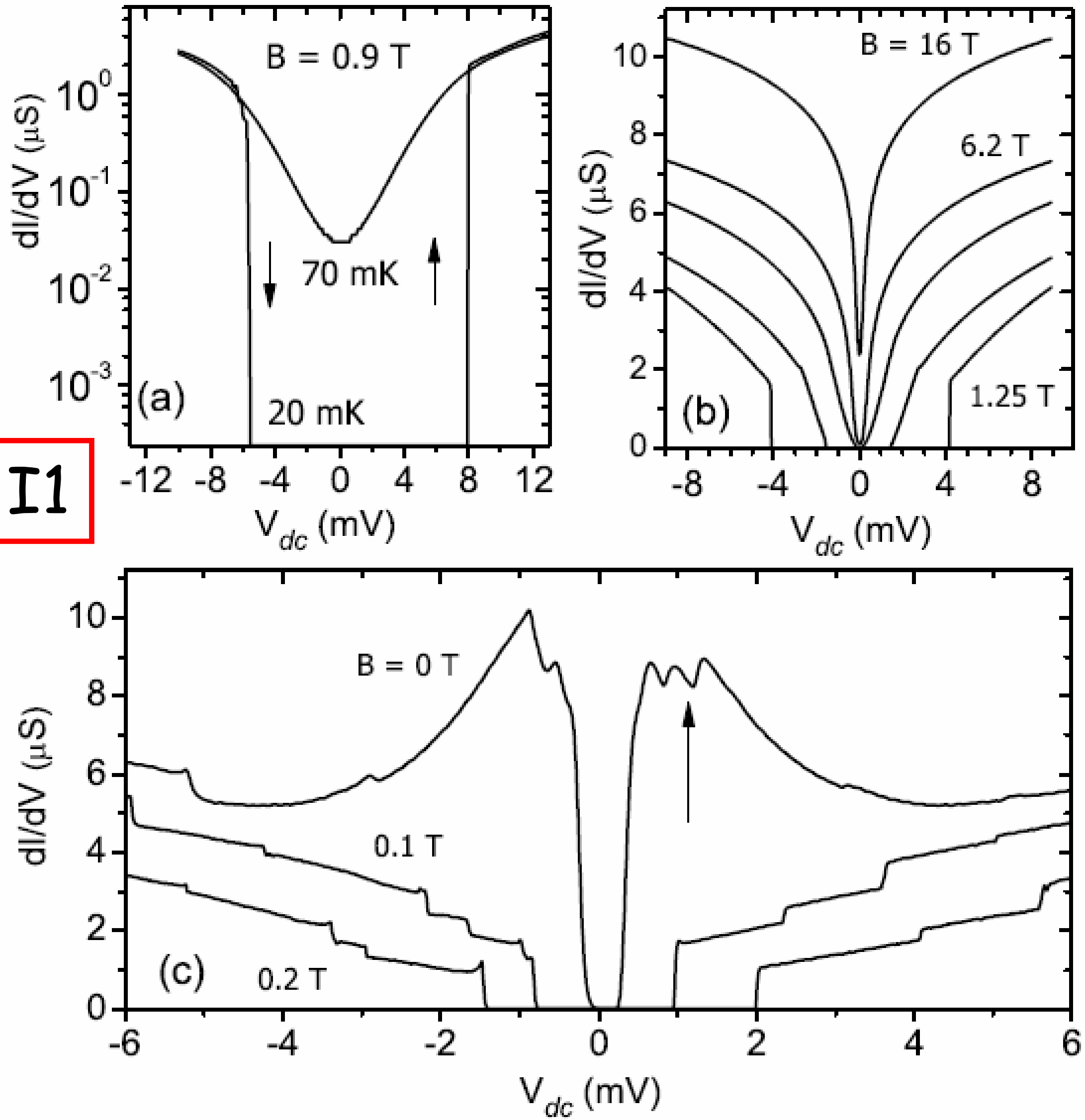


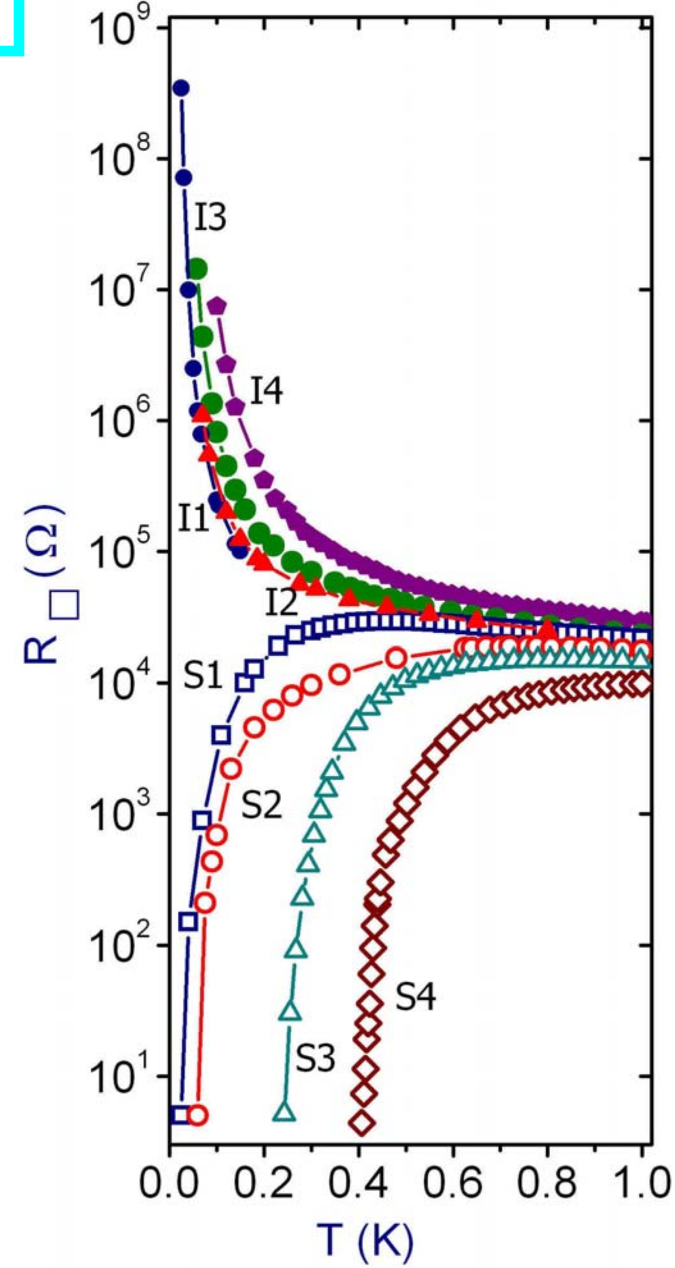


Collective insulating state: Threshold behavior of dI/dV vs V_{dc}

TiN films

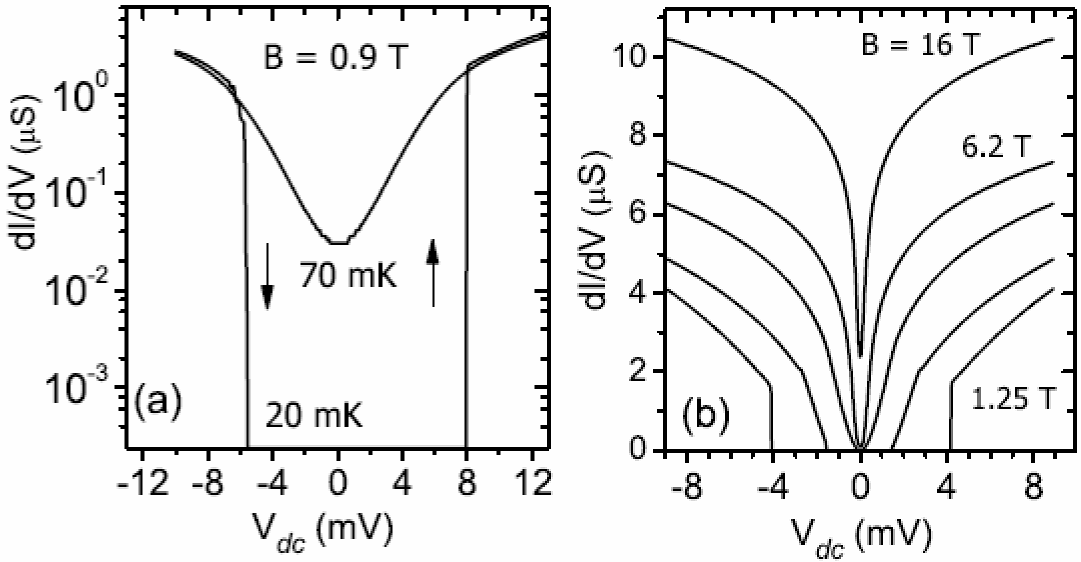
I1

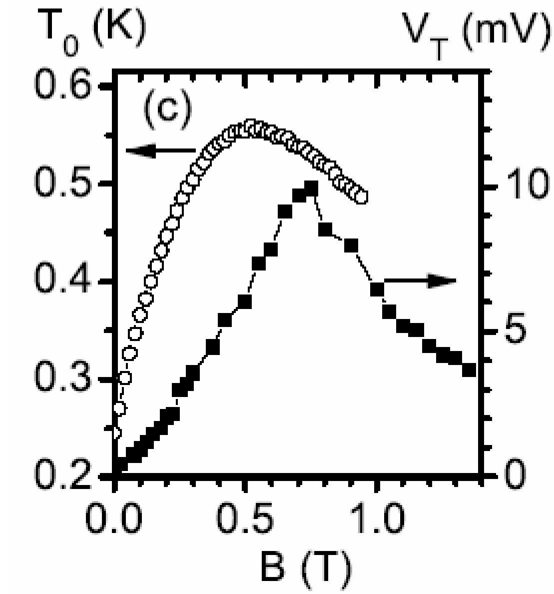


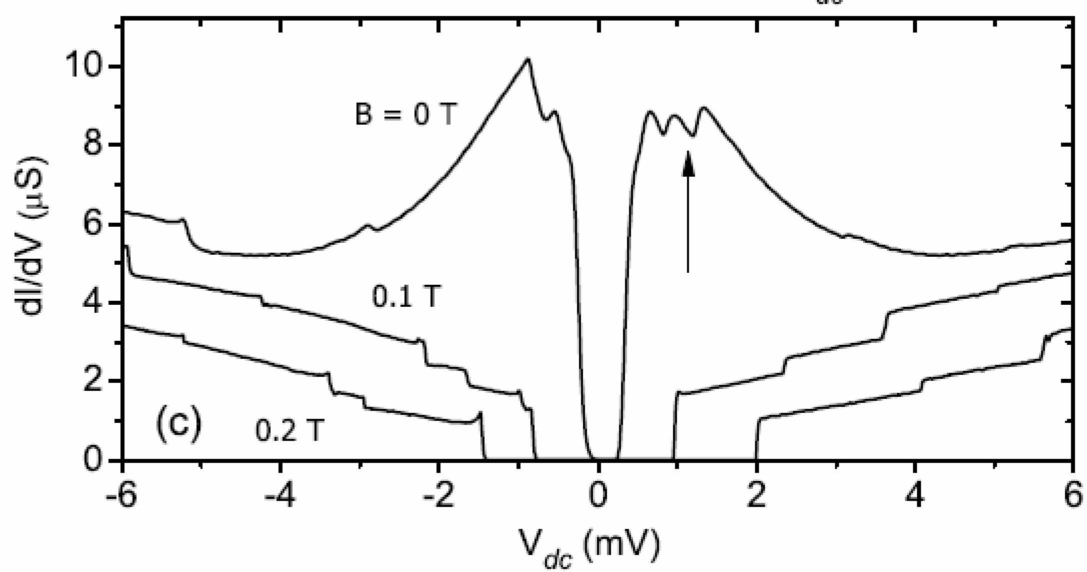


Collective insulating state: Threshold behavior of dI/dV vs V_{dc}

I1



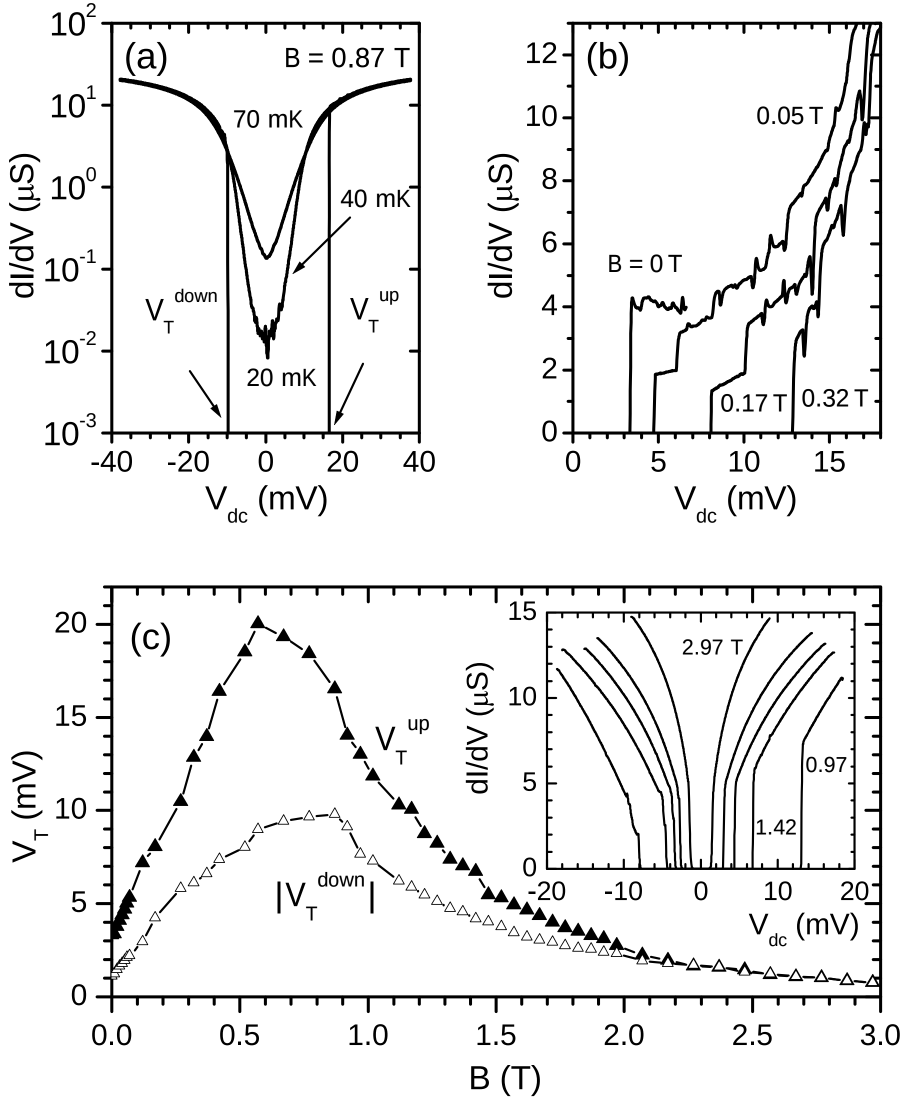




The threshold voltage changes nonmonotonically upon magnetic field

Collective insulating state: Threshold behavior of dI/dV vs V_{dc}

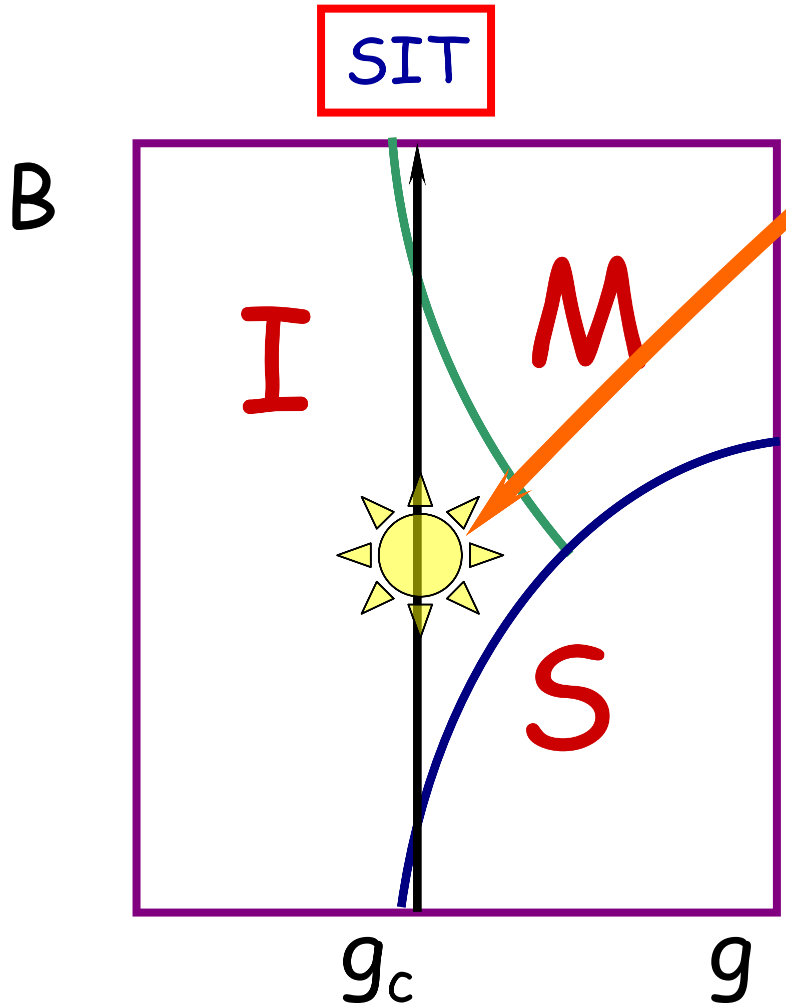
I2



The threshold voltage changes nonmonotonically upon magnetic field

schematic phase diagram

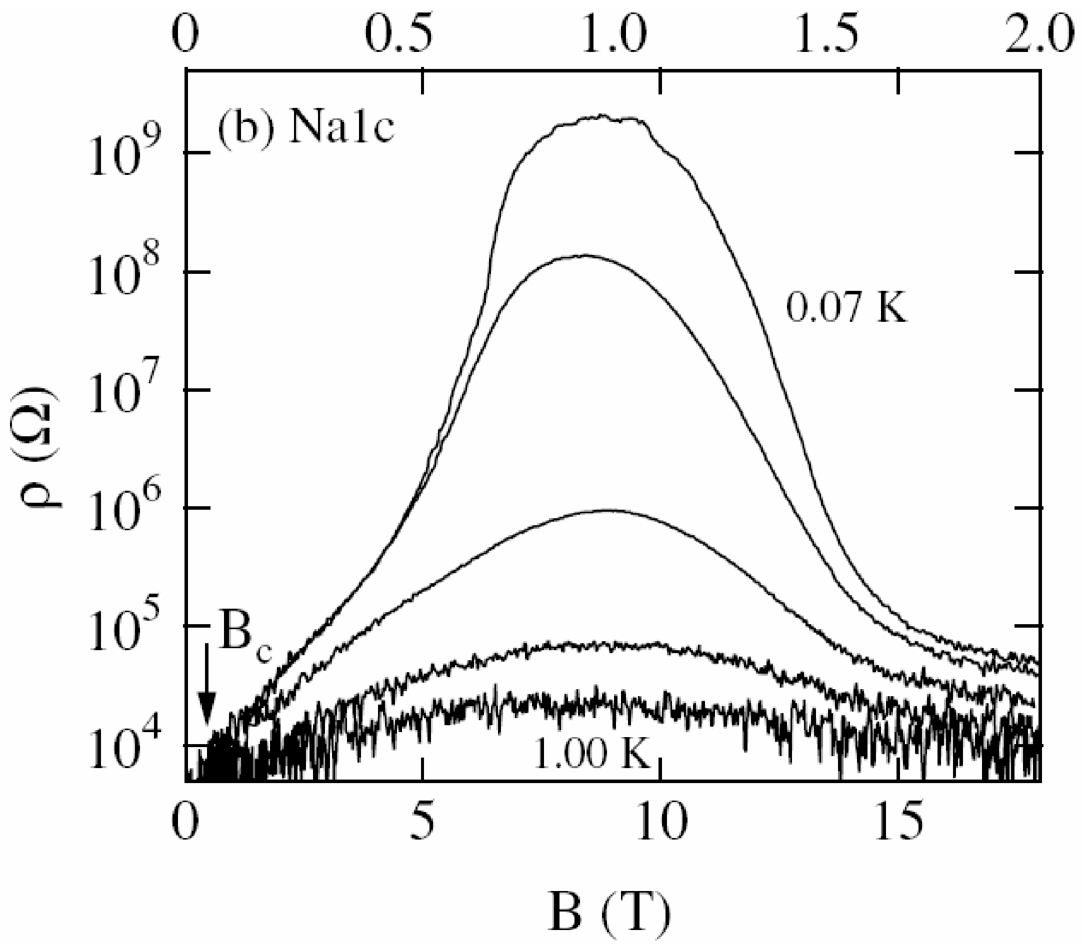
Magnetic-field-induced insulating phase



InO_x films

Magnetic-field-induced insulating phase

InO_x films



G. Sambandamurthy,
L.W. Engel,
A. Johansson,
and D. Shahar,
PRL 92, 107005 (2004).

for sample Na1c at $T = 0.07$, 0.16, 0.35, 0.62, and 1.00 K.

Magnetic-field-induced insulating phase

InO_x films

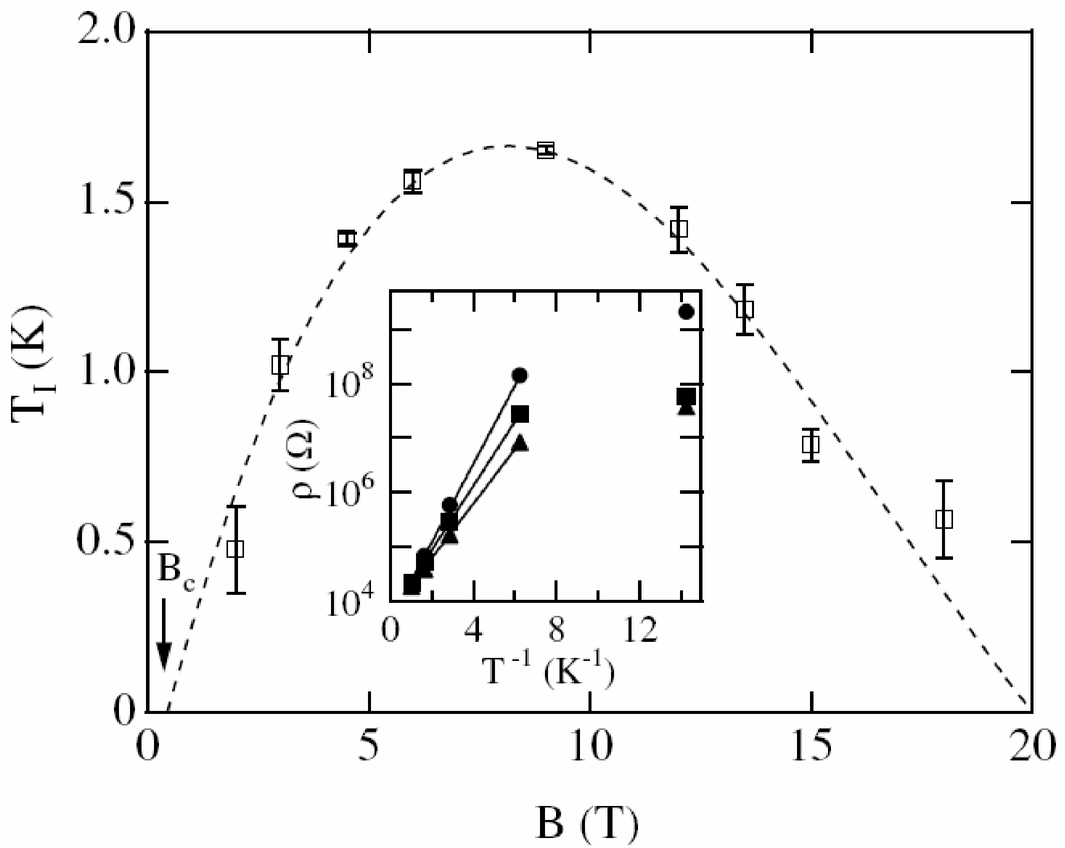
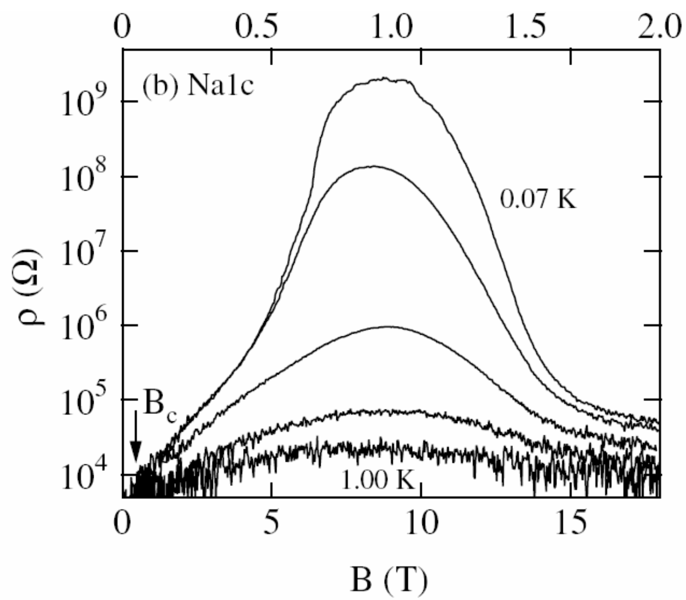


FIG. 3. Inset: ρ versus T^{-1} at $B = 6$ (squares), 9 (circles), and 12 T (triangles) for sample Na1c. The solids lines are fits to Eq. (1). The lowest T data points do not fit to the Arrhenius behavior. The main figure shows T_I, calculated from the fits to Eq. (1), as a function of B. T_I has a peak at 9 T. T_I estimates for 4 T $> B >$ 14 T suffer from large errors since the low-T ρ value is not high enough to ensure activated behavior. The vertical arrow marks B_c ($= 0.45$ T), where $T_I = 0$. The dashed line is a guide to the eye.

G. Sambandamurthy,
L.W. Engel,
A. Johansson,
and D. Shahar,
PRL 92, 107005 (2004).



Magnetic-field-induced insulating phase

InO_x films

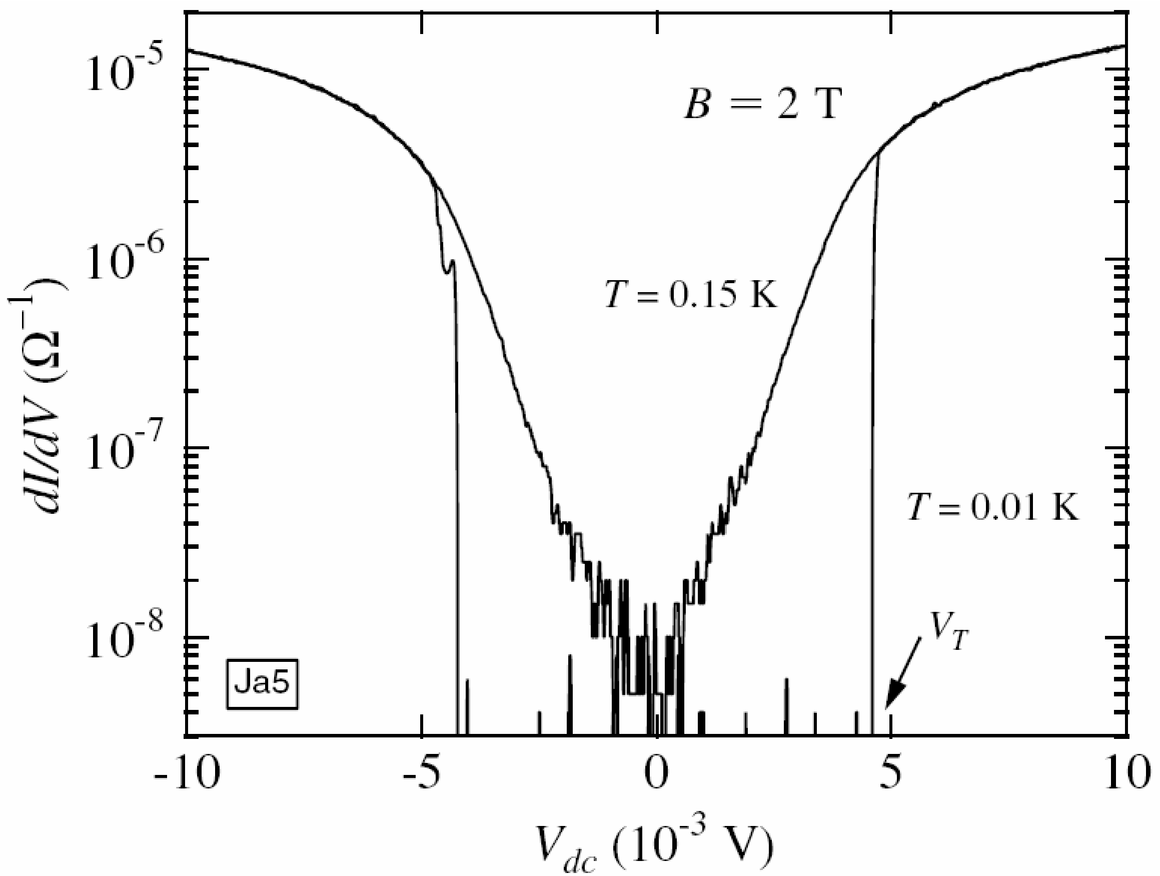


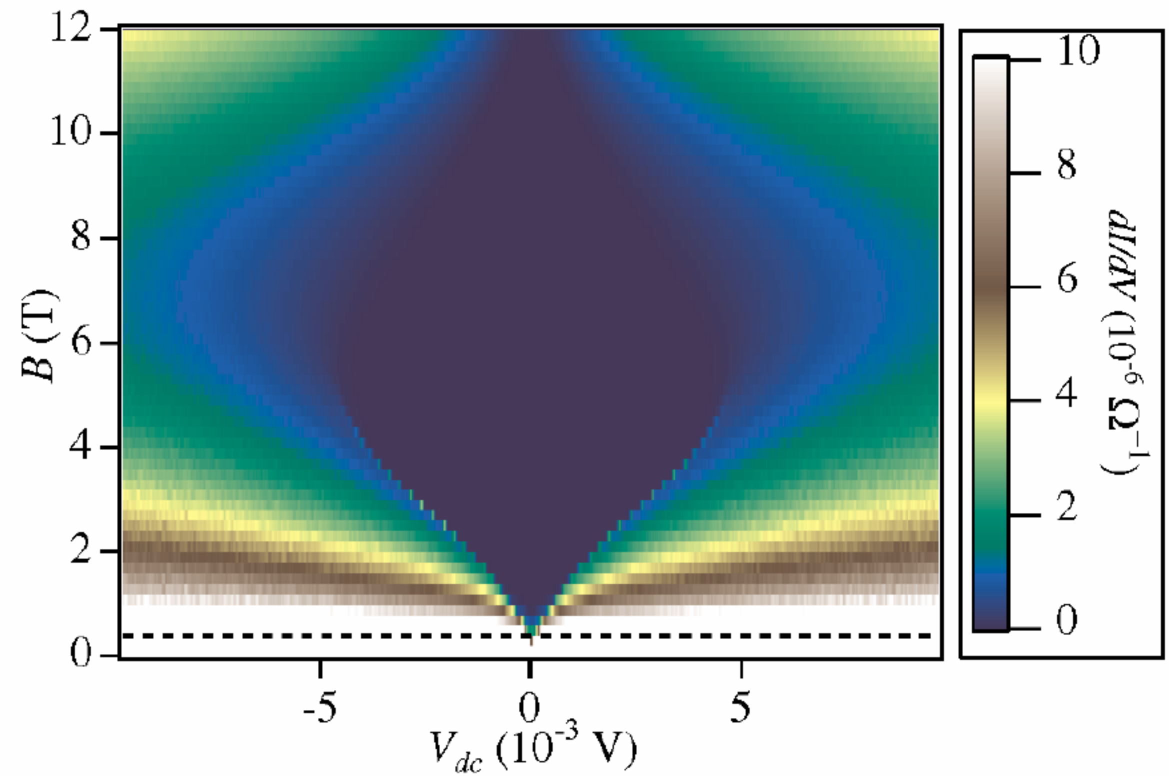
FIG. 2. Comparison of the current-voltage characteristics of the B-driven insulating phase at two T's (0.15 and 0.01 K). The traces show the two-terminal differential conductance measured at $B = 2$ T as a function of dc voltage. The ac excitation voltage applied is 10 μV. The sample used is Ja5 with $B_c = 0.4$ T. V_T marks the threshold voltage for conduction at $T = 0.01$ K.

G. Sambandamurthy,
L.W. Engel,
A. Johansson,
E. Peled
and D. Shahar,
PRL 94, 017003 (2005).

Collective insulating state:
Threshold behavior
of dI/dV vs V_{dc}

Magnetic-field-induced insulating phase

InO_x films



G. Sambandamurthy, L.W. Engel, A. Johansson, E. Peled and D. Shahar, PRL 94, 017003 (2005).

Collective insulating state: Threshold behavior of dI/dV vs V_{dc}

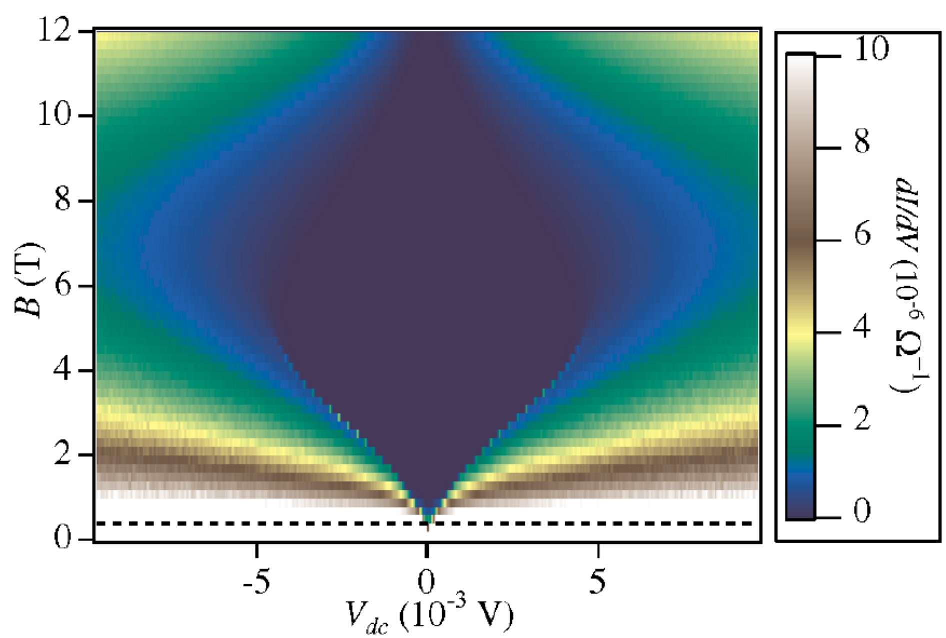
FIG. 4 (color). Two-dimensional map of the dI/dV values in the $B - V_{dc}$ plane. For the sample of Fig. 2 (Ja5), we have measured dI/dV traces as a function of V_{dc} at B intervals of 0.2 T and at $T = 0.01$ K. The color scale legend on the right-hand side shows the various colors used to represent the values of dI/dV. The horizontal dashed line denotes B_c ($= 0.4$ T) of this sample.

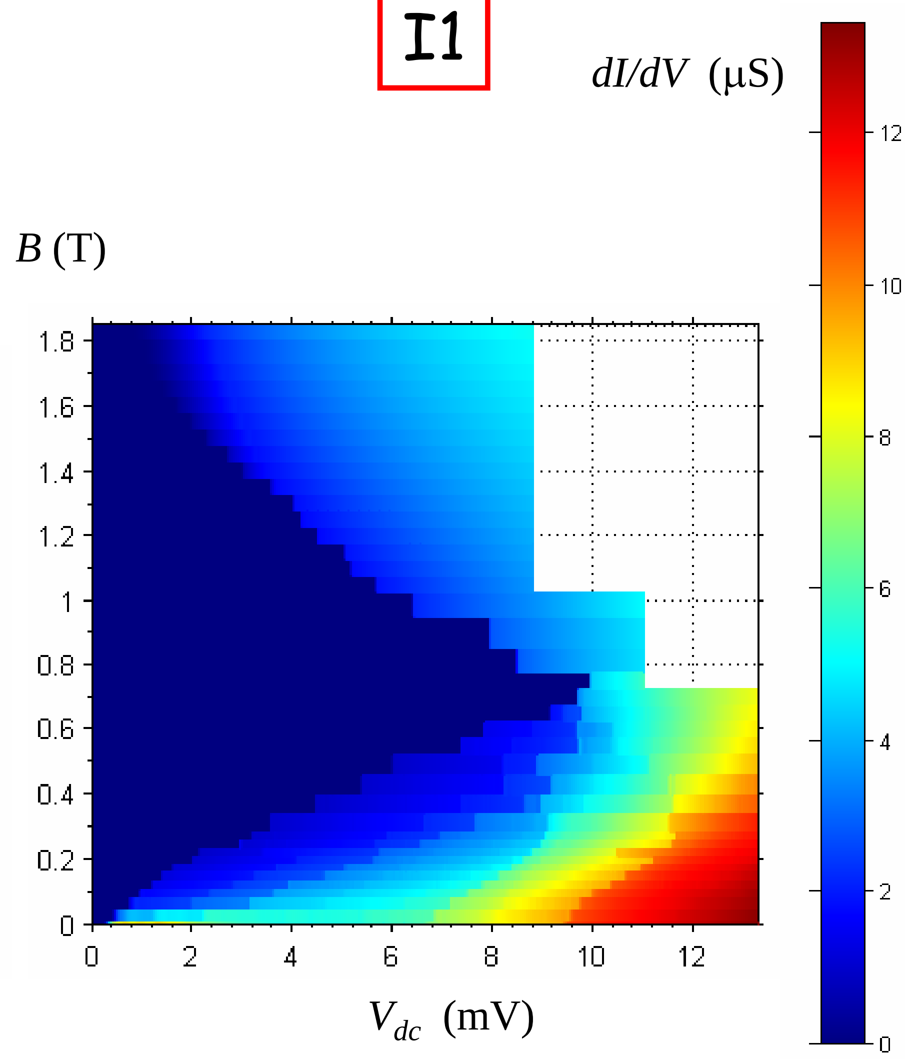
InO$_x$ film
Sc at B=0

Collective insulating state:
Threshold behavior
of dI/dV vs V_{dc}

TiN film
Ins. at B=0

I1

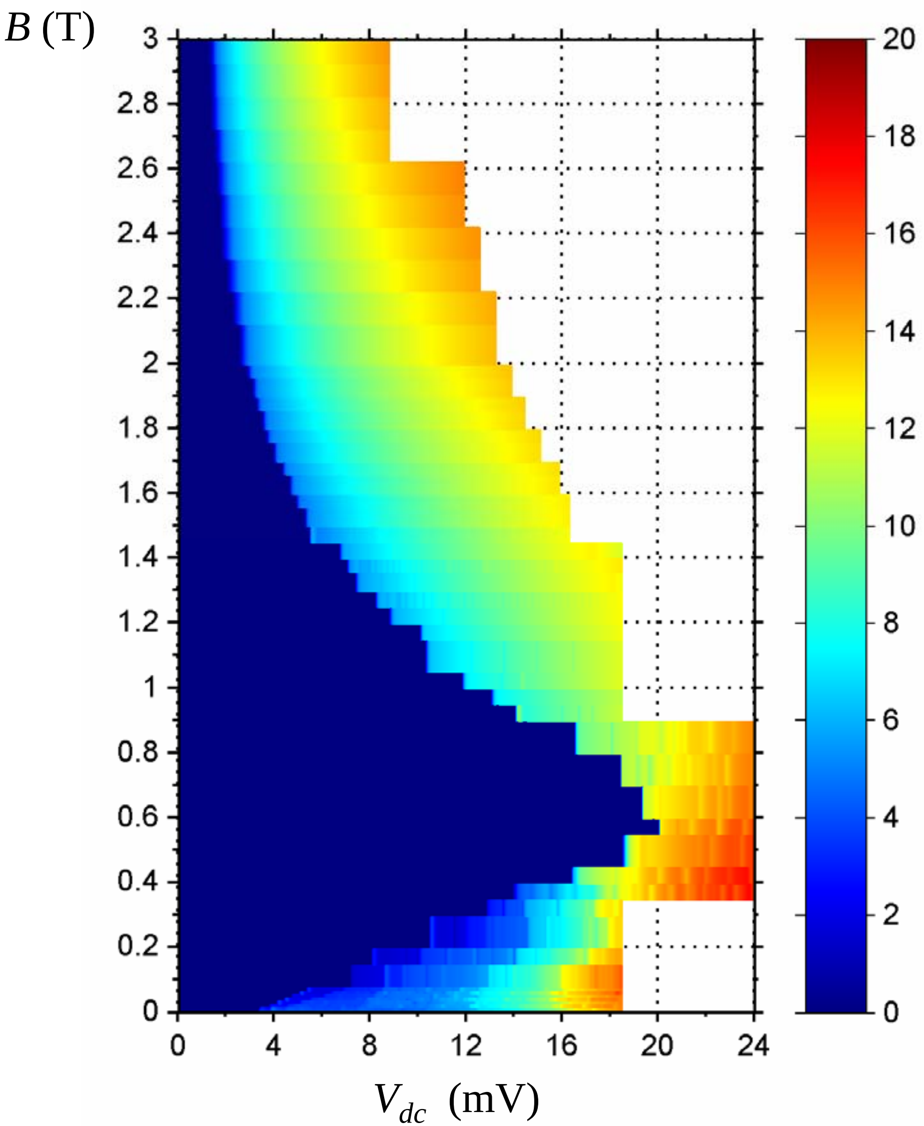


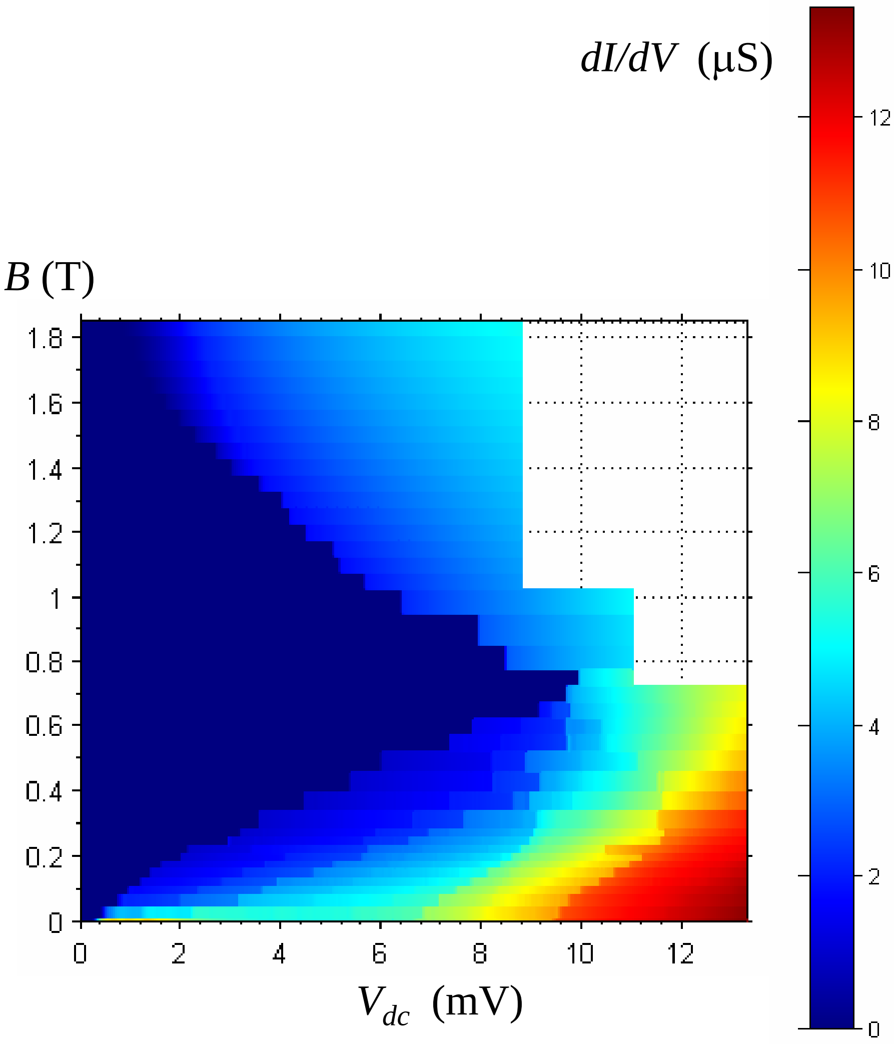


TiN film I2

Collective insulating state: Threshold behavior of dI/dV vs V_{dc}

TiN film I1





Critical Region of the Disorder-Driven Superconductor-Insulator quantum phase transition

Aggregate of Experimental Features

- ✓ thermally activated behavior of the conductivity
- ✓ positive magnetoresistance at low magnetic field
- ✓ negative magnetoresistance with a saturation near h/e^2 in high magnetic fields
- ✓ voltage threshold for conductivity

in the vicinity of the D-SIT,
the response to applied magnetic and/or electric fields, is the same irrespectively of whether the underlying ground state is superconducting or insulating

It looks like...

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

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

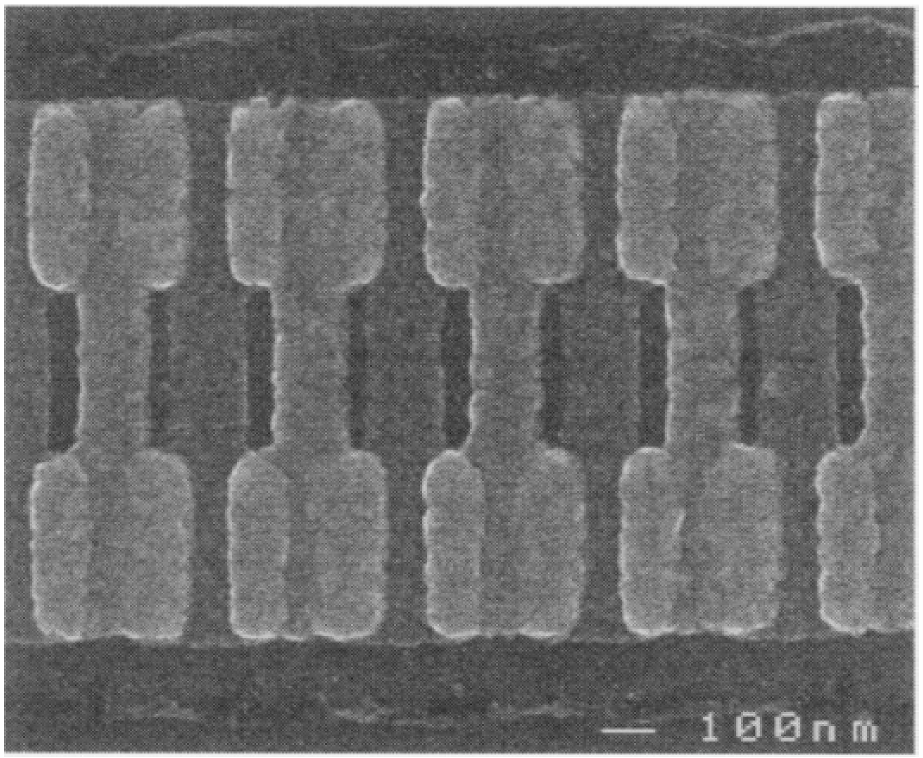


FIG. 1. A scanning electron micrograph of a section of the Josephson junction array. Tunnel junctions are formed at the overlap between the base electrode (darker gray) and the top electrode (lighter gray). The hole between neighboring electrodes forms the SQUID geometry.

$Al/Al_2O_3/Al$ tunnel junctions

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

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

$R_T = 4.9\ k\Omega \pm 6\%$

$C \simeq 3.5$ fF

electrostatic screening length

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

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

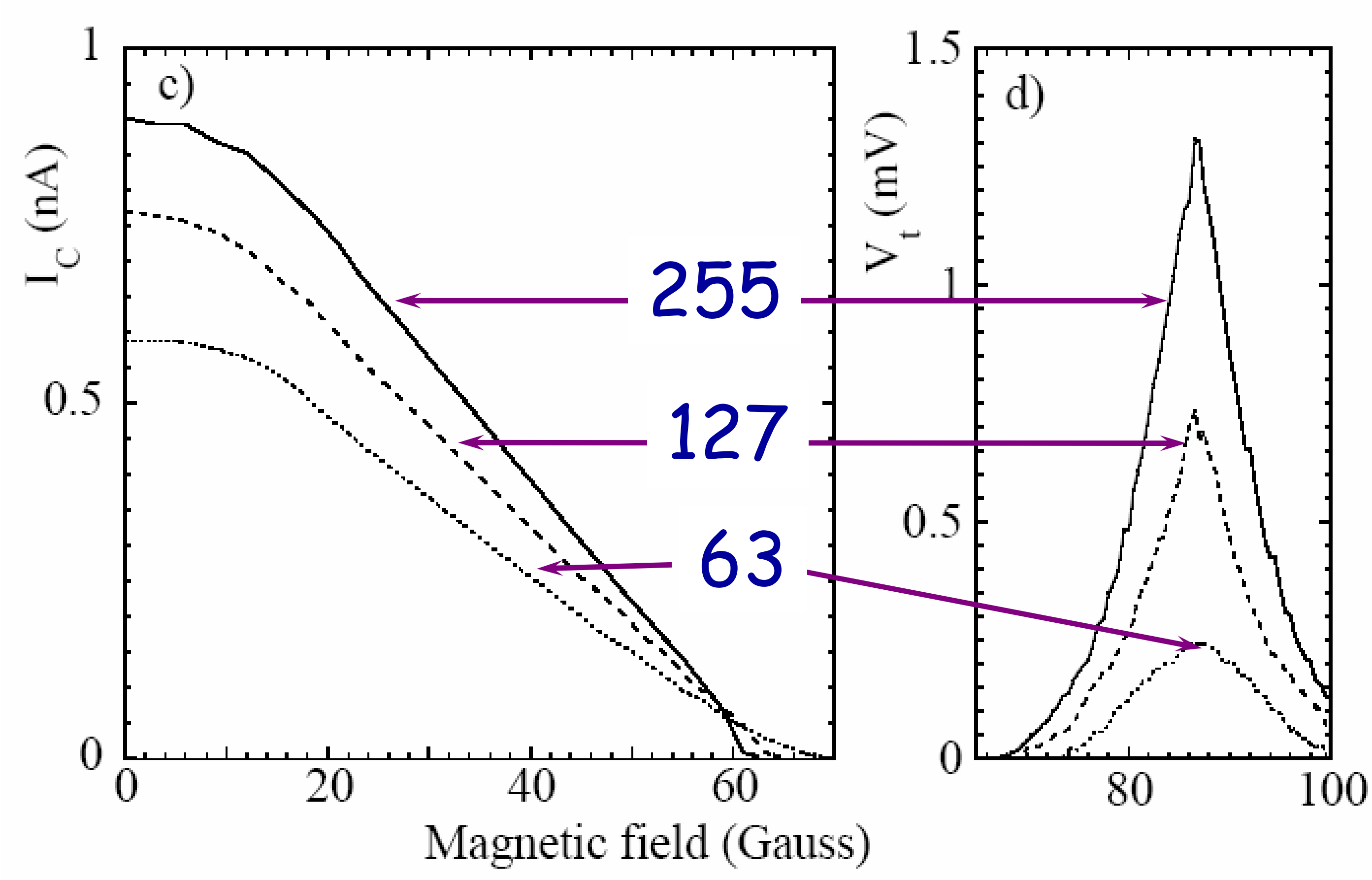
$$E_J = E_{J0}|\cos \pi B A_{loop}/\Phi_0|$$

It looks like...

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

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

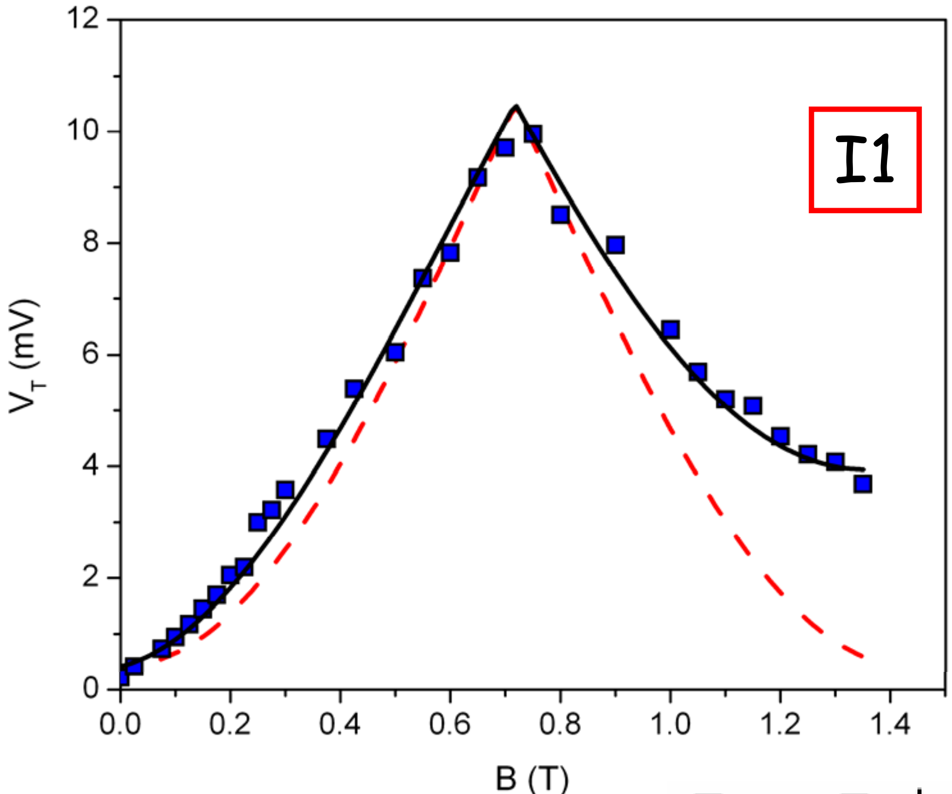
T = 50 mK

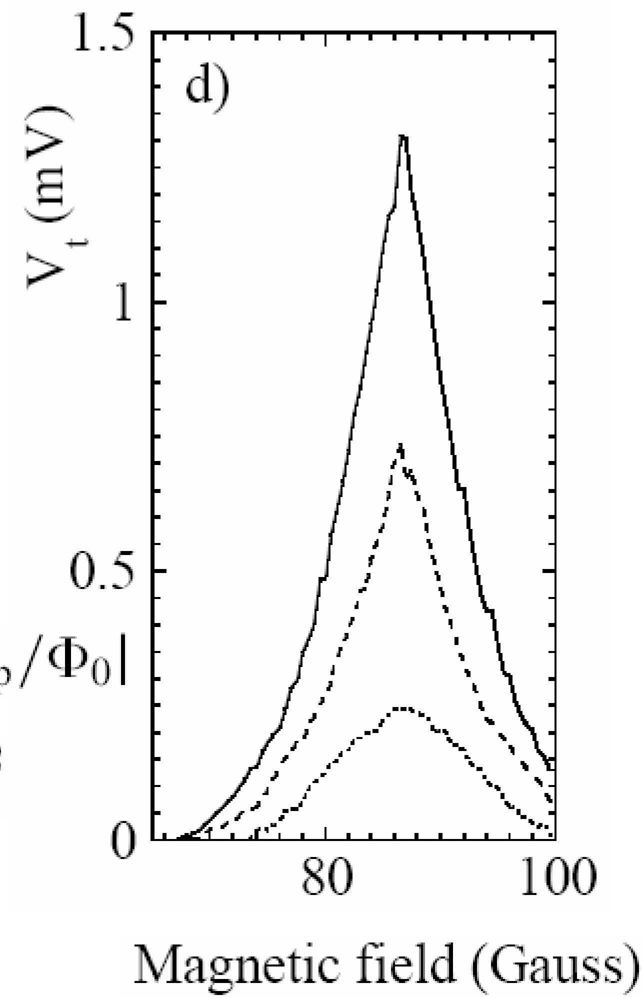


TiN film
Ins. at B=0

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

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





$V_T(B) = V_0(1 - \alpha E_J(B)/E_c)$, $E_J = E_{J0}|\cos \pi B A_{loop}/\Phi_0|$

$\alpha E_{J0}/E_c = 0.96$ and $A_{loop} = 1.44 \cdot 10^{-3}\ \mu m^2$

$\alpha E_{J0}/E_c = 0.96 - 0.0024 \cdot B$

M.V. Fistul, V.M. Vinokur, T. B., cond-mat/0708.2334