Сверхизолятор и топологический фазовый переход Березинского-Костерлица-Таулесса

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ИФП СО РАН

Всероссийская конференция Физика ультрахолодных атомов
19 - 21 декабря 2016 года

1. Введение. Топологические фазовые переходы.

2. Сверхпроводник и топологический фазовый переход.

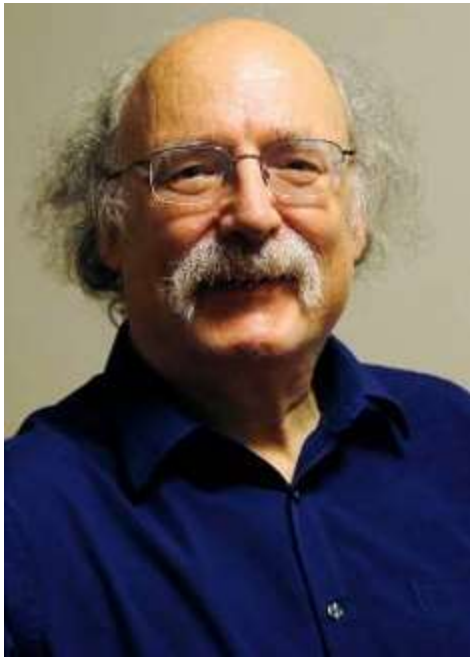
3. Сверхизолятор и и топологический фазовый переход.

Лауреаты Нобелевской премии по физике 2016 года

за теоретические открытия топологических фазовых переходов и топологических фаз материи

Майкл Костерлиц
John Michael Kosterlitz

Дэйвид Таулесс
David James Thouless



Данкан Холдейн
Frederick Duncan
Michael Haldane

Фазовые переходы

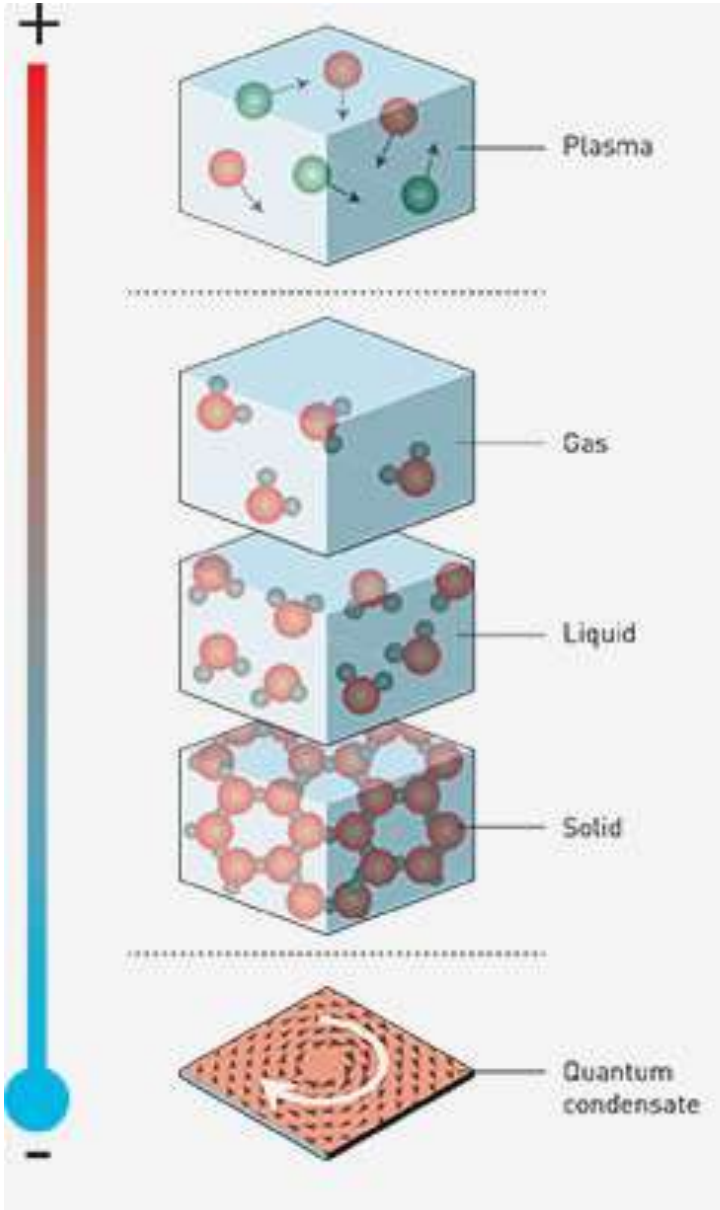


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

критическое состояние

3D

кристалл

«жидкость»

???

2D

???

«жидкость»

температура

Топологические фазовые переходы

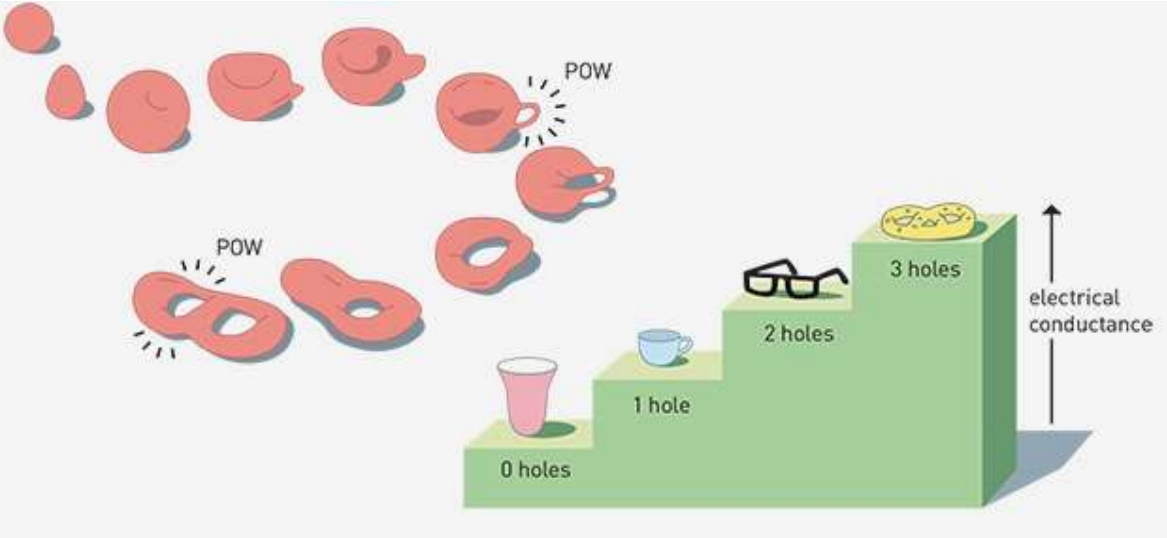
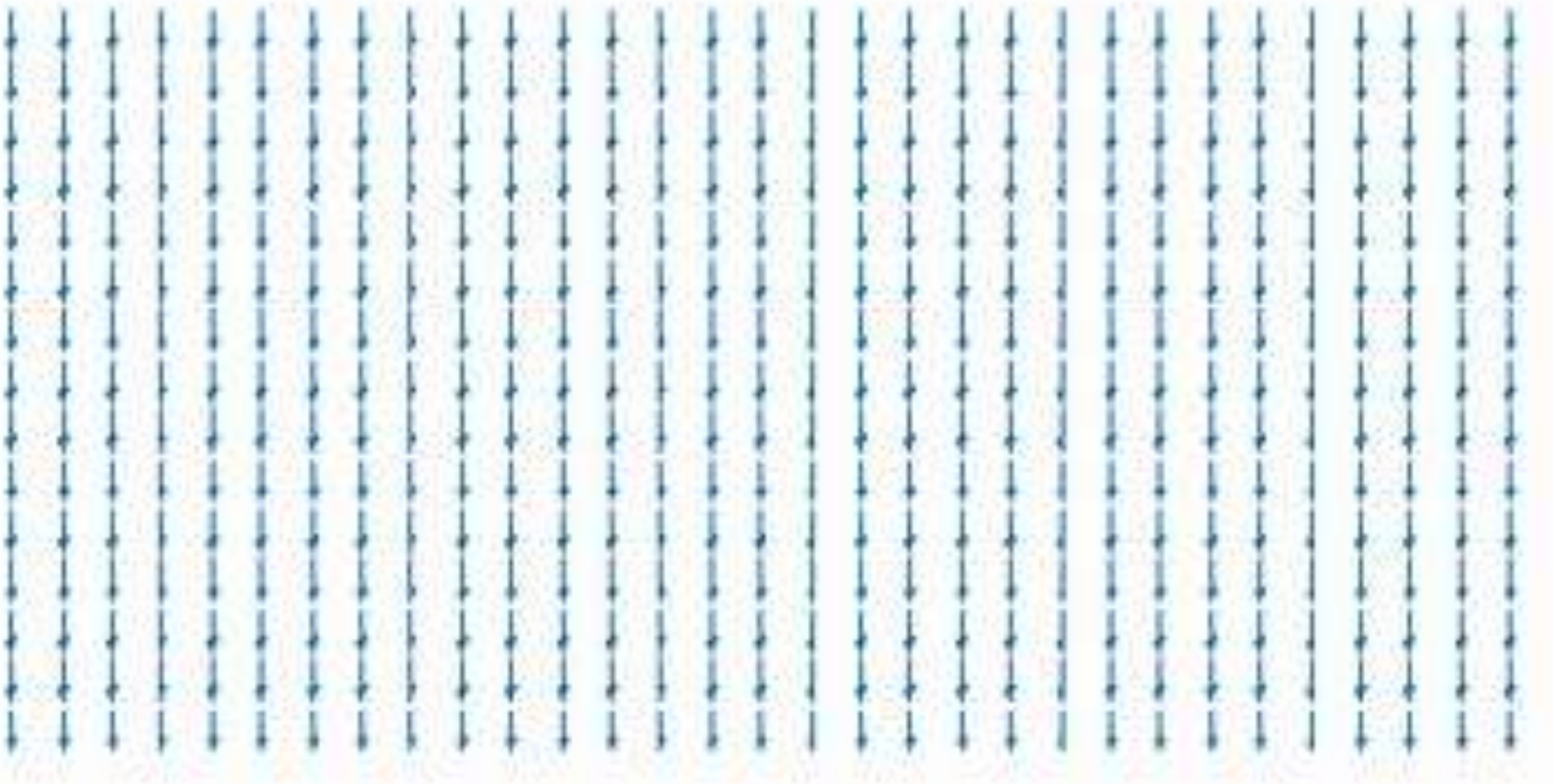


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

Рождение и исчезновение пары вихрь-антивихрь
Затрачиваемая энергия очень мала
(Березинский Вадим Львович, 1935-1980)
В.Л. Березинский, ЖЭТФ 59, 907 (1970); ЖЭТФ 61, 1144 (1971);



Топологический фазовый переход при повышении температуры от газа практически не взаимодействующих связанных пар вихрь-антивихрь к газу взаимодействующих вихрей

(Майкл Костерлиц, Дэйвид Таулесс)

J.M. Kosterlitz and D. Thouless, J.Phys. C 6, 1181 (1973);

D.R. Nelson and J.M. Kosterlitz, Phys. Rev. Lett. 39, 1201 (1977)

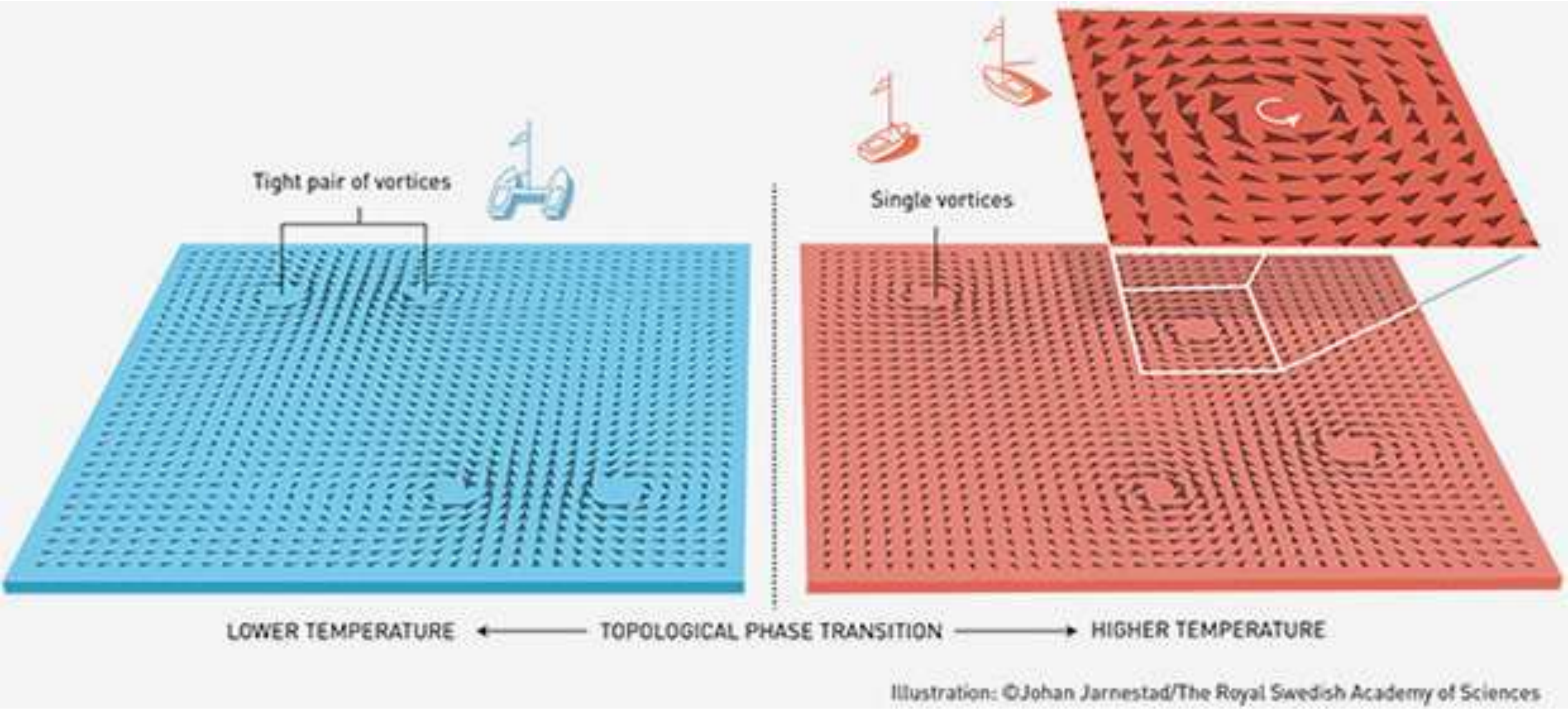


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

Топологический фазовый переход Березинского-Костерлица-Таулесса

Энергия взаимодействия вихрей: $U = E_0 \ln (R / r_0)$

Энтропия: $S = 2k_B \ln (R / r_0)$
(r_0 - размер ядра вихря)

Свободная энергия: $F = U - TS = E_0 \ln (R / r_0) - 2k_B T \ln (R / r_0)$

Переход ВКТ при $T = T_{BKT} = E_0 / 2k_B$

Необходимо логарифмическое взаимодействие между элементами.

Сверхпроводимость и сверхизоляция в тонких плёнках на основе сверхпроводящих материалов

The object

✓Thin Disordered Superconducting films

quasi-2D:
electronic spectrum is 3D

$$\boxed{l,\ l_F < d < x,\ l_T}$$

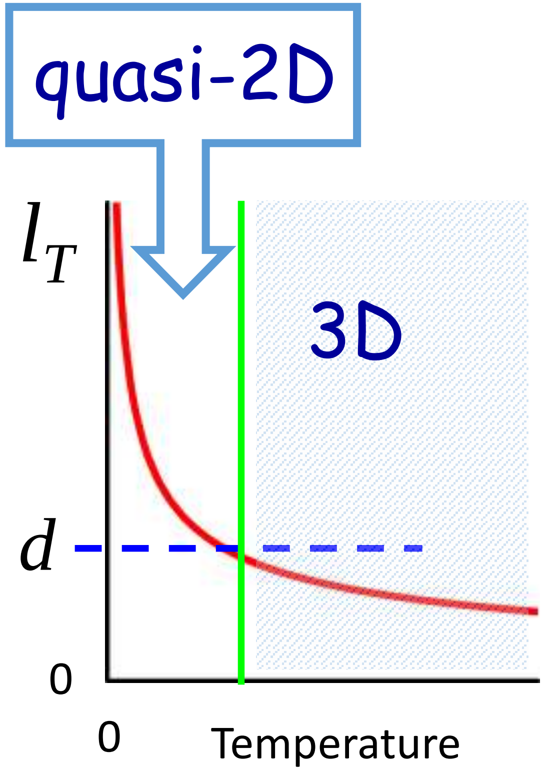
d – the thickness of the film

l – the mean free path

λ_F – Fermi wave length

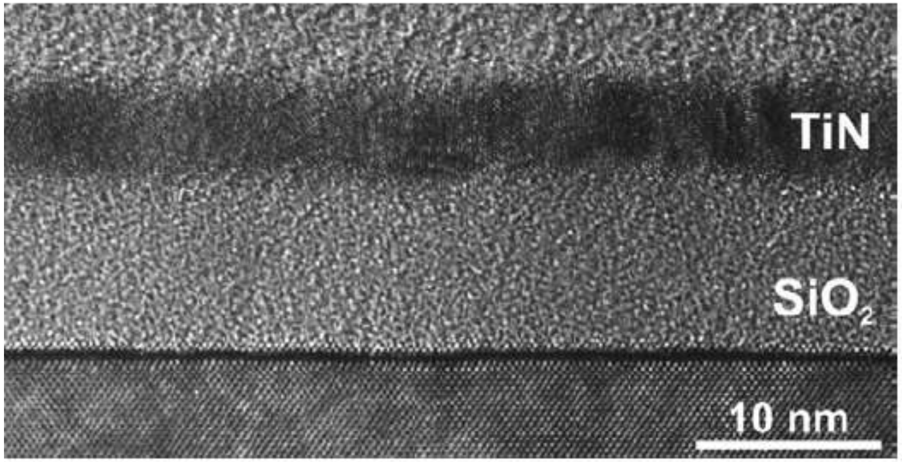
ξ – the superconducting coherence length

l_T – the thermal coherence length

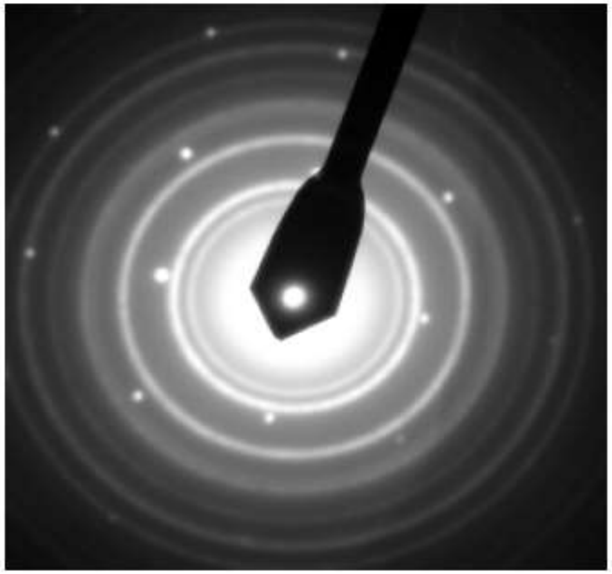


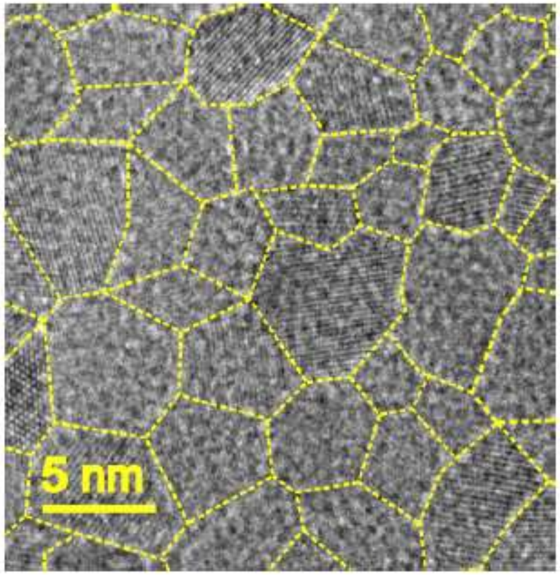
$$l_T = \sqrt{\frac{2\pi\hbar D}{k_B T}}$$

Experiment TiN films



the thickness is 3.6 - 23 nm



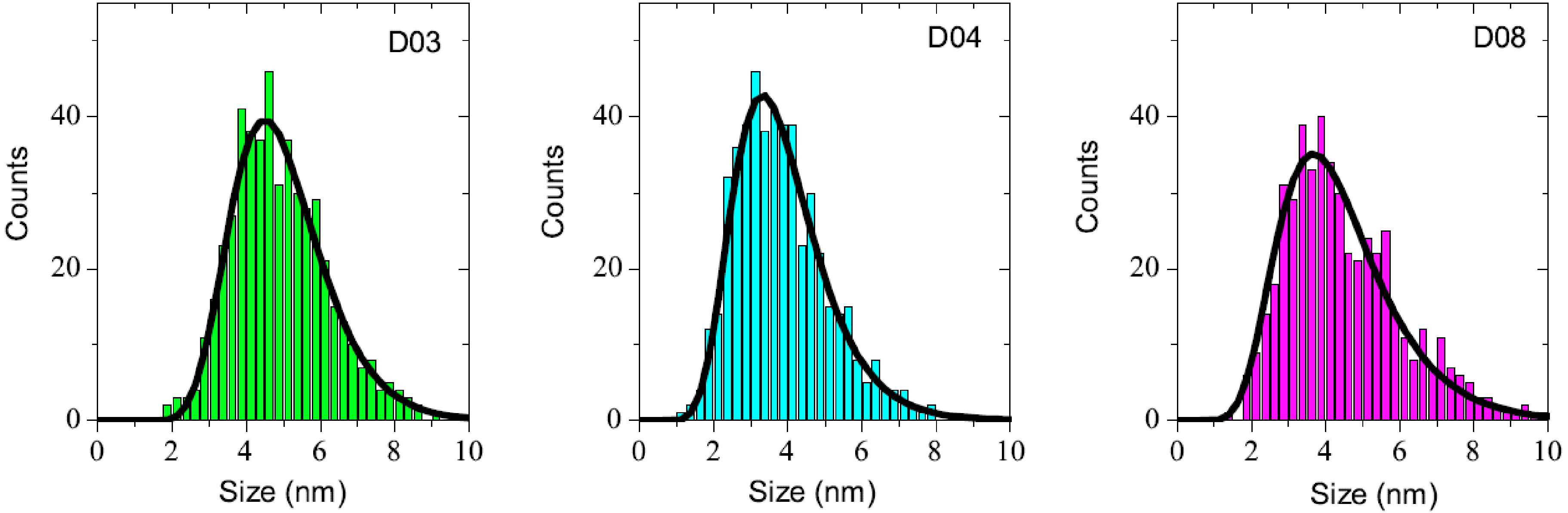


✓ TiN films were formed by atomic layer deposition onto a Si/SiO$_2$ substrate at 400 ^{0}C.

Experiment

TiN films

Crystallites size distribution of the TiN films



The crystallites size distribution of films follows the lognormal distribution:

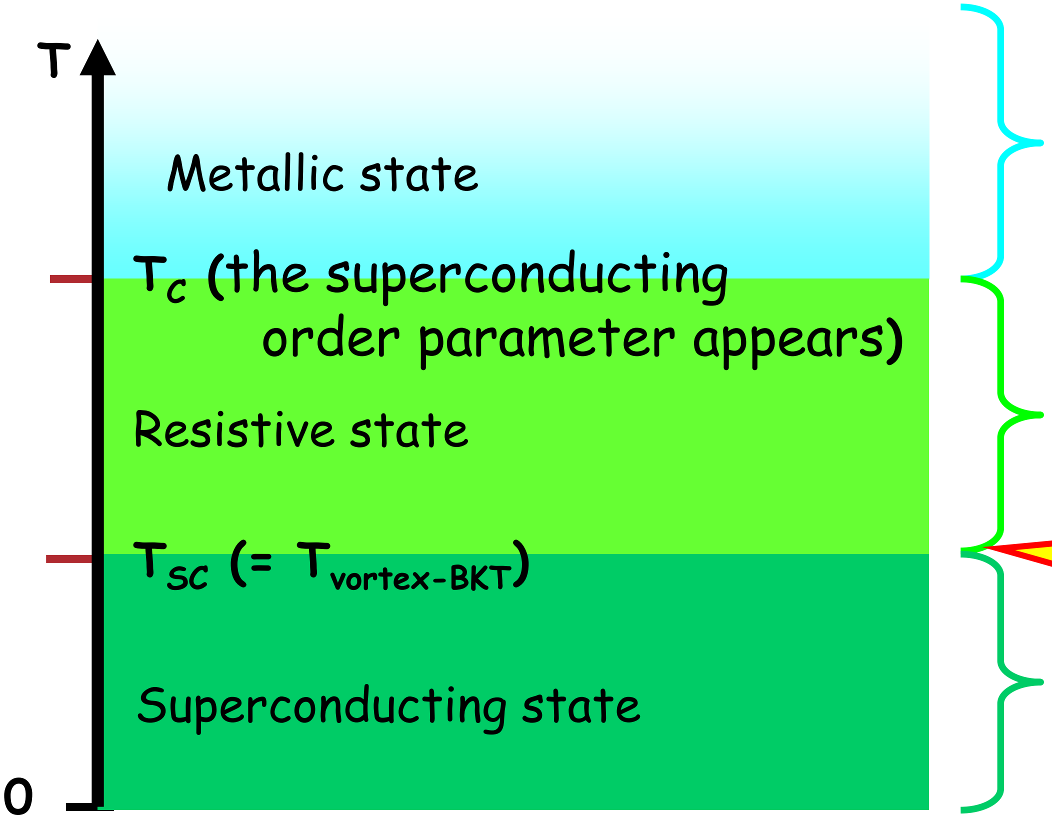
$$f(x) \propto \frac{1}{x\sigma\sqrt{2\pi}} \cdot e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}$$

The object

! Two-dimensional superconducting systems:
2D JJ-array, granular films,
homogeneously disordered films

Superconductor

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



T

Metallic state

T_c (the superconducting order parameter appears)

Resistive state

T_{SC} (= $T_{vortex\text{-}BKT}$)

Superconducting state

0

Drude conductivity
+ quantum corrections:
weak localization, e-e interaction,
superconducting fluctuations

Absence of the global phase coherence: a gas of unbound vortices and antivortices

Berezinskii-Kosterlitz-Thouless transition

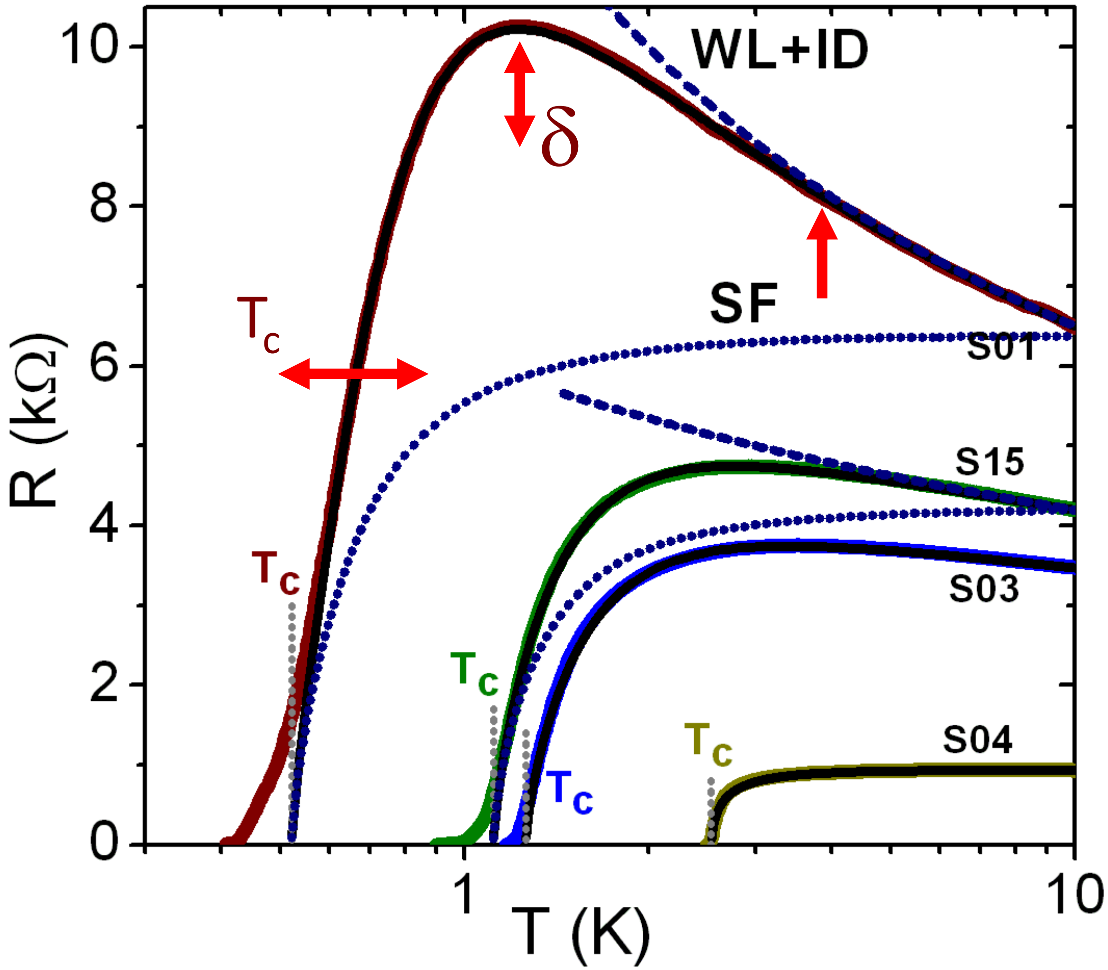
Macroscopic phase coherence: vortices and antivortices are bound in pairs

R (T) fitting

TiN films

The fitting remarkable captures all major features of the observed dependences:
non-monotonic behaviour,
the position and value of R_{max} and T_{max},
the graduate decrease in the resistance.

We find that T_c lies at the foot of the R(T) curves.



The determinations of T_c as the temperature where R(T) drops to 0.9, 0.5 R_N significantly overestimates T_c.

T.I. Baturina, S.V. Postolova, A.Yu. Mironov, A. Glatz, M.R. Baklanov, V.M. Vinokur, EPL 97 (2012) 17012

Determination of T_{BKT}

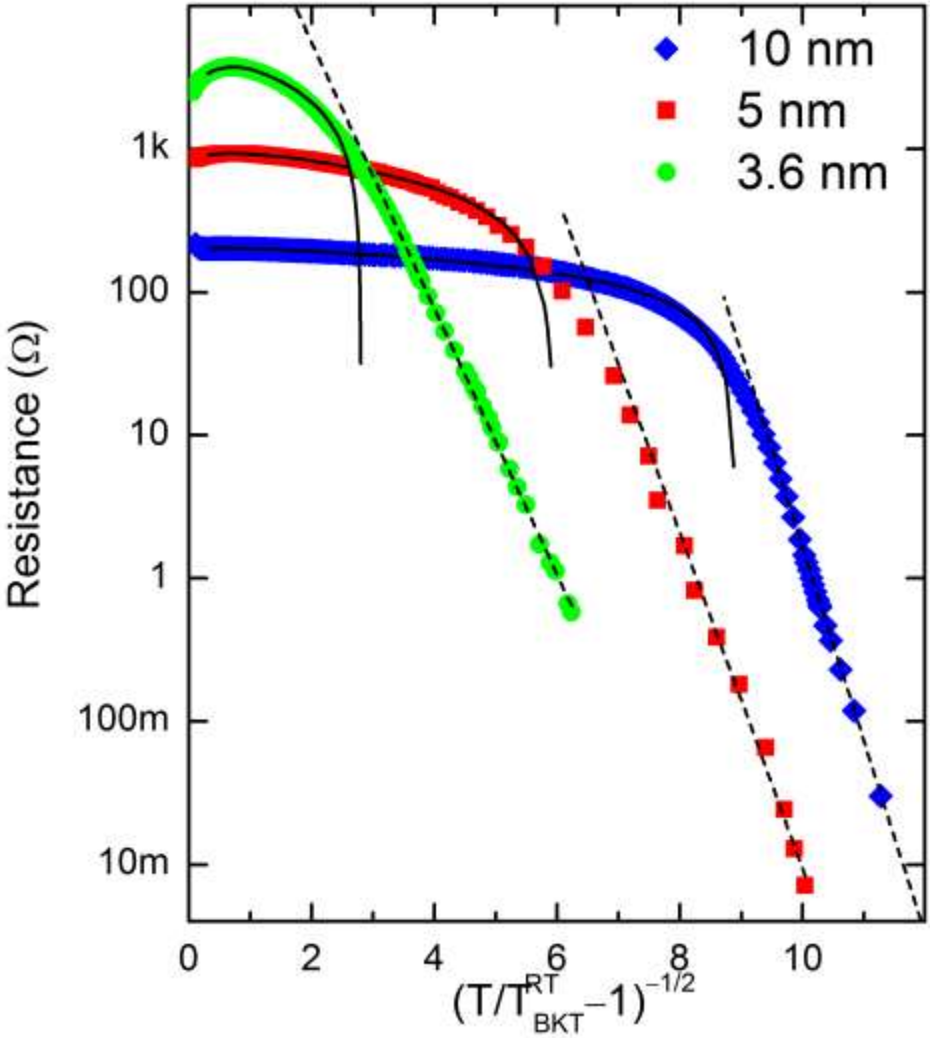
from linear conduction $T_{BKT} < T < T_c$

$$R(T) \propto \exp[-b(T/T_{\mathrm{BKT}} - 1)^{-1/2}]$$

b is a constant of the order of unity

T_{BKT} is the only fitting parameter

d, nm	3.6	5	10
T_c, K	1.290	2.545	3.215
T_{BKT}^{RT}, K	1.145	2.475	3.175
b	2.14	2.7	3.13



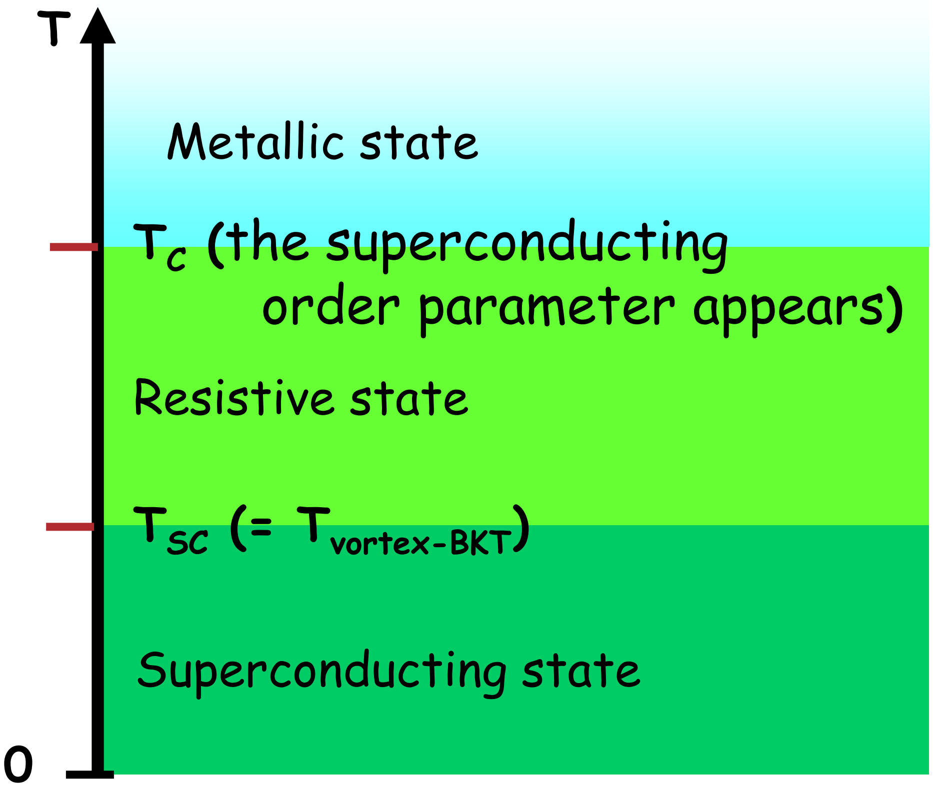
B. I. Halperin and D. R. Nelson,
J. Low. Temp. Phys. **36**, 599 (1979).
S. Doniach and B. A. Huberman,
Phys. Rev. Lett. **42**,1169 (1979).

The object

! **Two-dimensional superconducting systems:**
2D JJ-array, granular films,
homogeneously disordered films

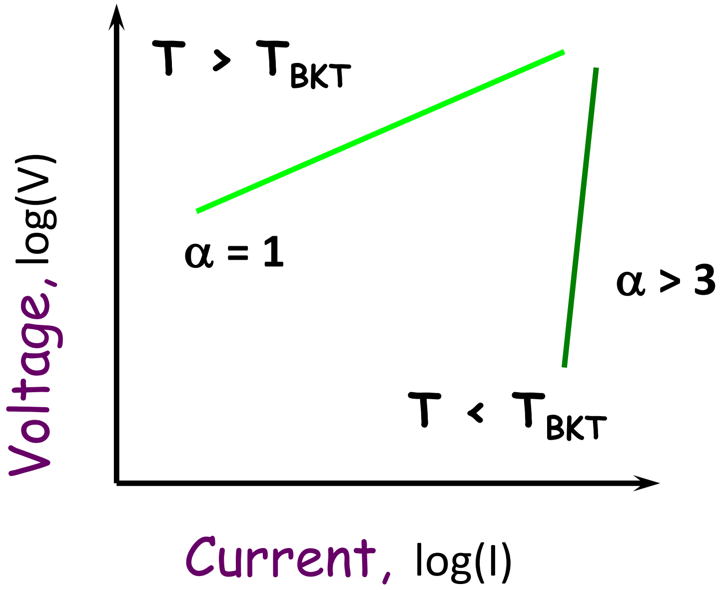
Superconductor

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



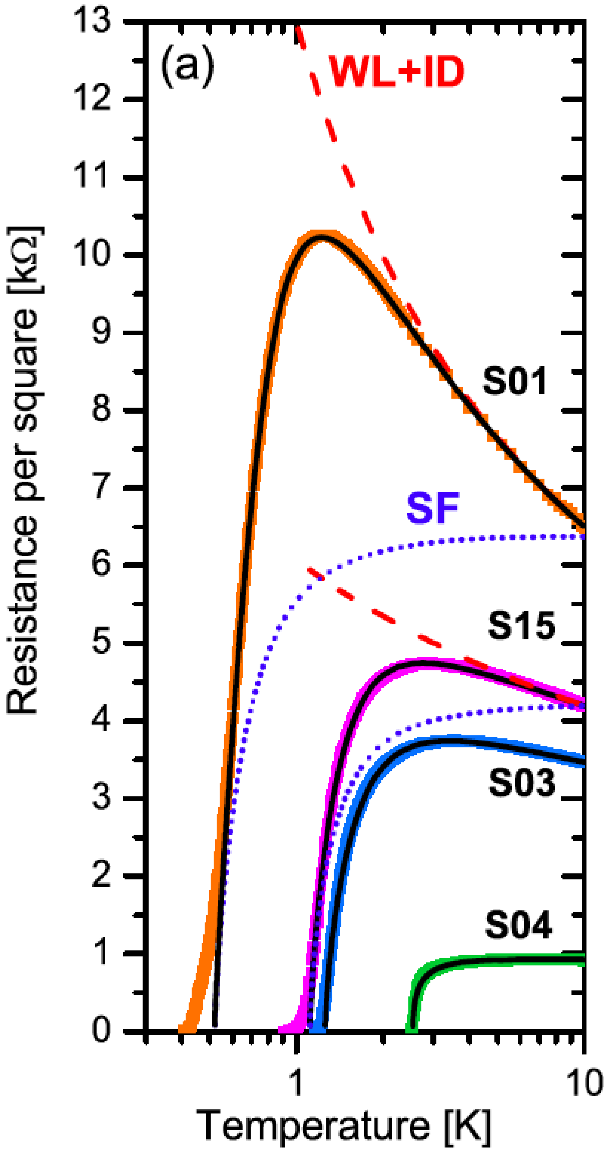
in experiment:

$V \propto I^{\alpha(T)}$

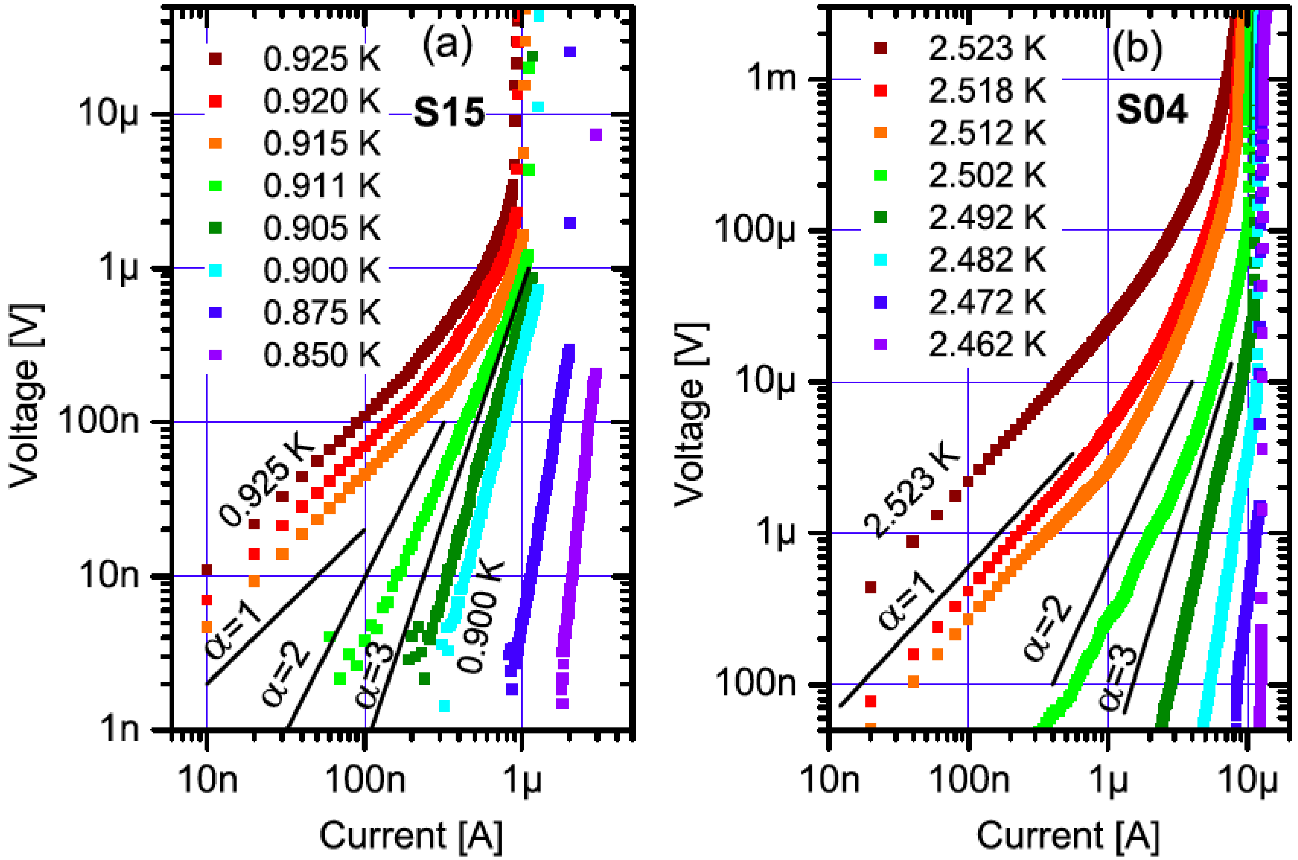


Vortex BKT transition

linear response regime



current - voltage characteristics $V \propto I^{\alpha(T)}$

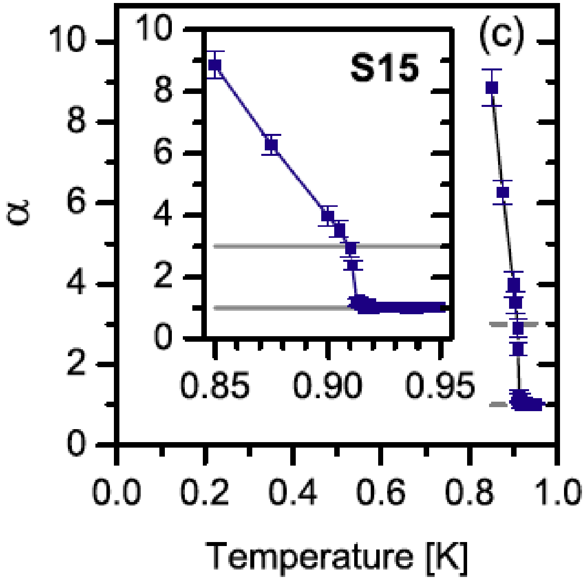


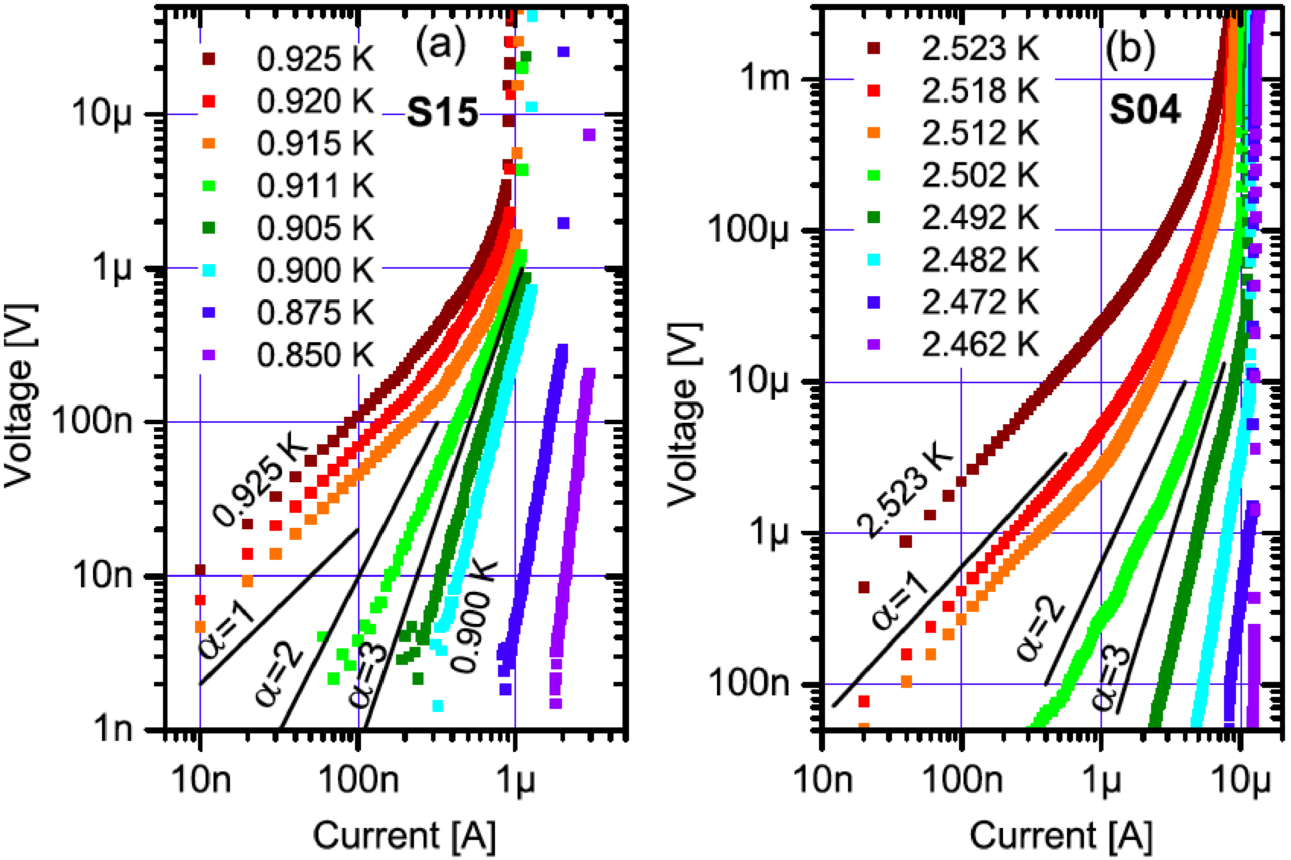
T. I. Baturina, S. V. Postolova, A. Yu. Mironov, A. Glatz, M.R. Baklanov, and V.M. Vinokur, EPL **97**, 17012 (**2012**).

Vortex BKT transition

current - voltage characteristics $V \propto I^{\alpha(T)}$

Characteristic jump in the power exponent at T_{BKT}



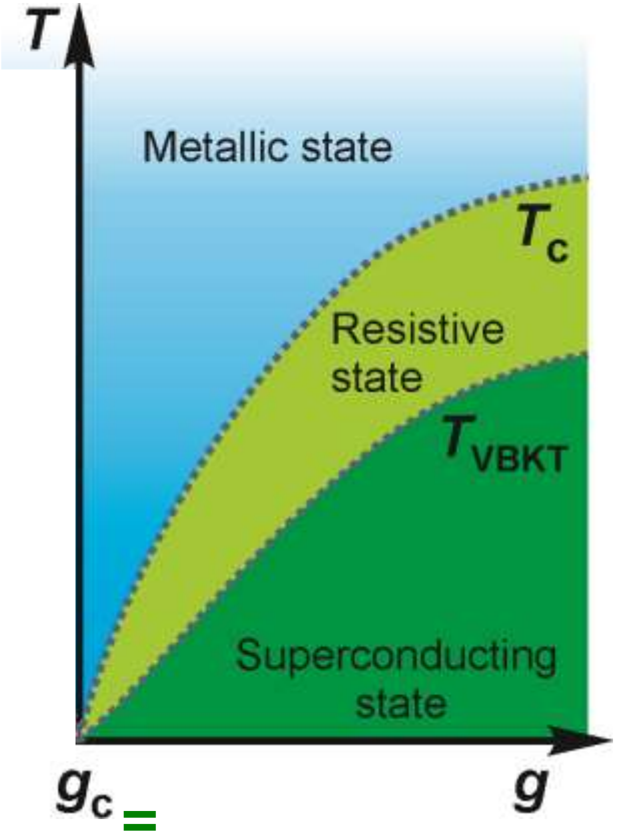


T. I. Baturina, S. V. Postolova, A. Yu. Mironov, A. Glatz, M.R. Baklanov, and V.M. Vinokur, EPL **97**, 17012 (**2012**).

Superconductor - Superinsulator Duality in two dimensions

Thermodynamic phase diagram

$V \to 0,\ I \to 0$



$$\Delta\varphi\Delta N \sim 1$$

$$\Delta\varphi = 0$$

= the low-temperature vortex-BKT phase

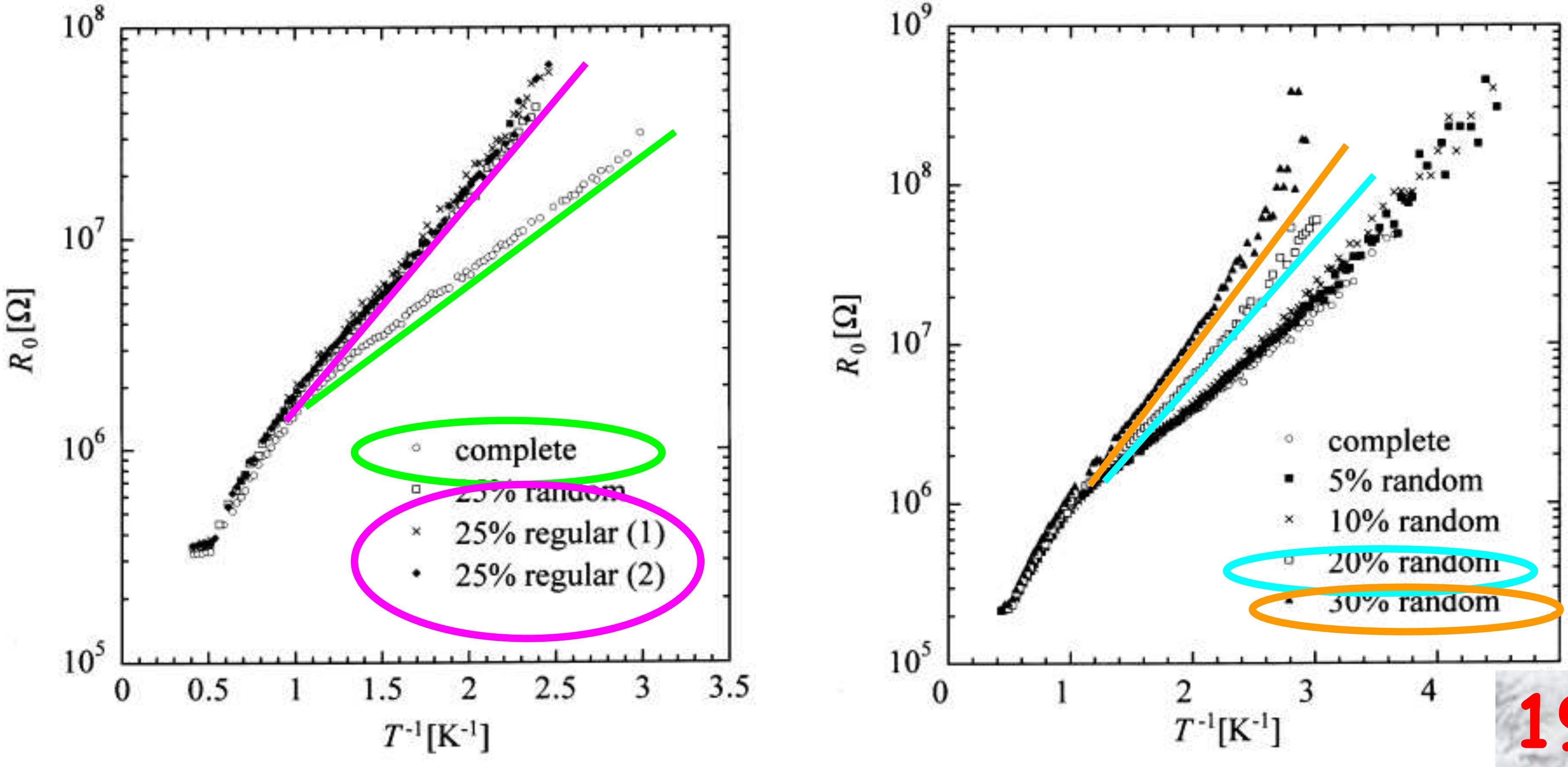
Journal of the Physical Society of Japan
Vol. 67, No. 3, March, 1998, pp. 729-731

More of experiment…

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

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

We investigated the transport properties of two-dimensional arrays of small Josephson junctions of which a number of junctions are removed. We found that the more the number of removed junctions, the more rapidly the array resistance increases with decreasing temperature. The



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

More of experiment…

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

Akinobu KANDA and Shun-ichi KOBAYASHI

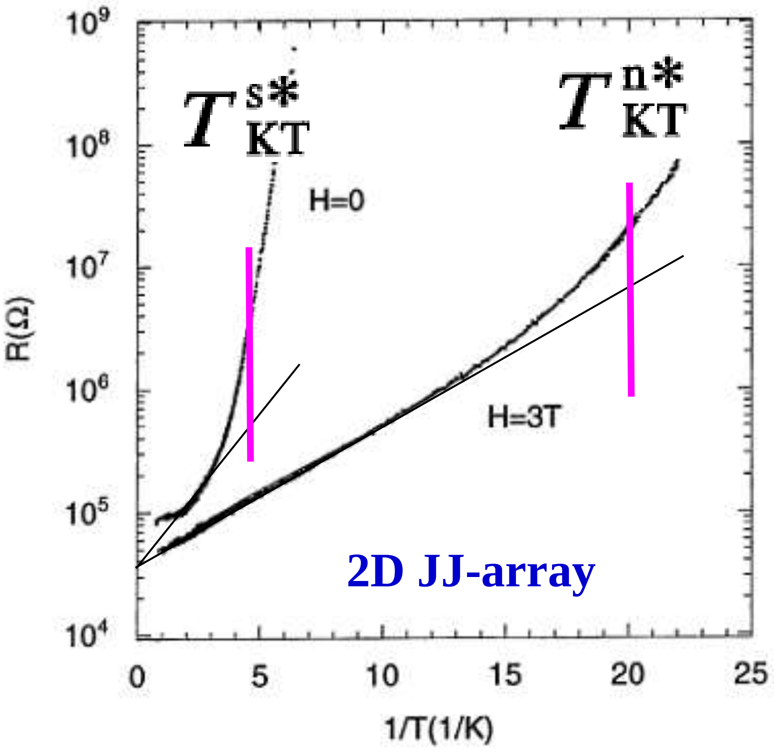


Fig. 1. Resistance at $V=50\ \mu$V as a function of $1/T$ in $H=0$ and 3 T. Solid lines are results of fitting with eq. (1). The values of fitting parameters are $K=1.6$ and $b=1.0$ in $H=0$, and $K=1.6$ and $b=2.2$ in $H=$ 3 T. For the values of T_{KT}, see the text.

The array was 380 junctions in length and 331 junctions in width. Each junction had an area of 0.0072 $(\mu\mathrm{m})^2$, normal-state tunneling resistance $R_N=32\ \mathrm{k\Omega}$ and the capacitance $C=1.1\times10^{-15}$ F. The self-capacitance of the island electrode was 5.1×10^{-17} F.

$T^{s*}_{KT}=(0.19\pm0.01)$ K $\qquad e^*=2e$

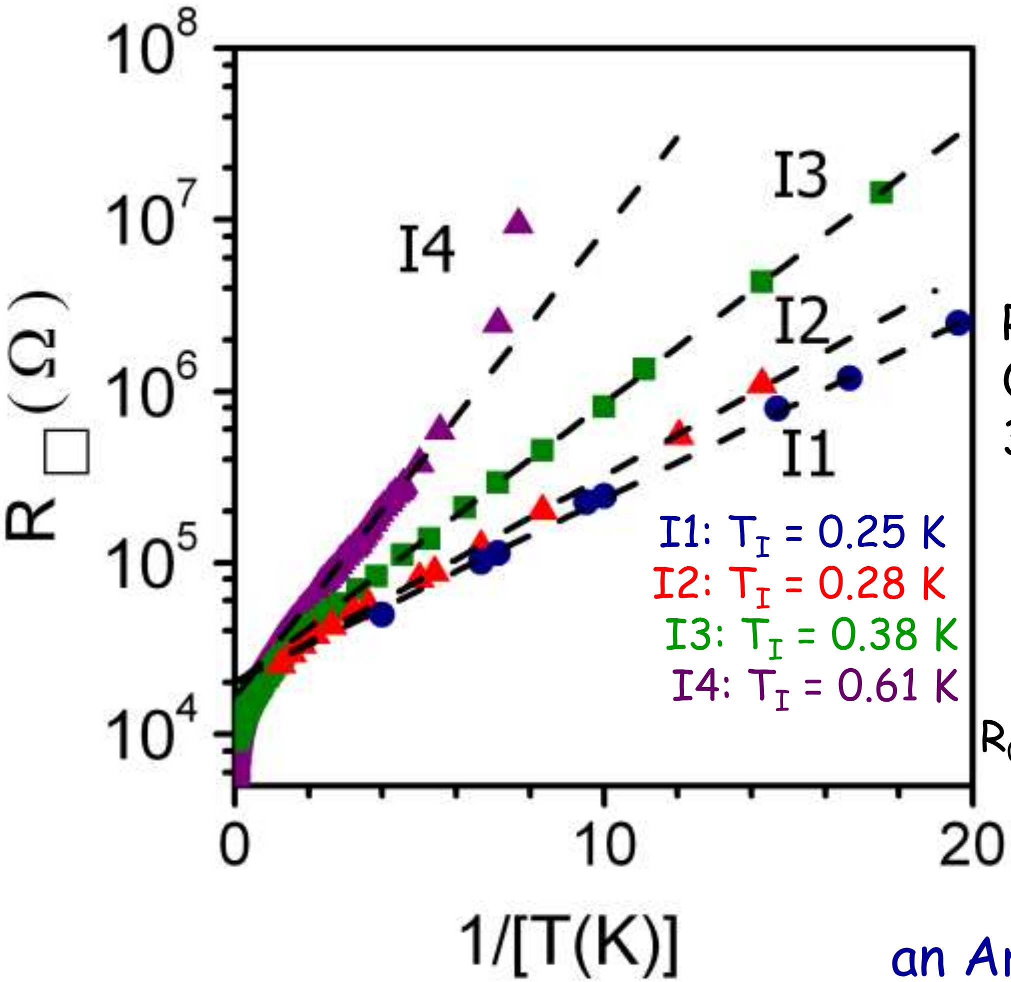
$T^{n*}_{KT}=(0.05\pm0.01)$ K $\qquad e^*=e$

$T^{s*}_{KT}/T^{n*}_{KT}\sim 4$

$$k_B T_{C-BKT}=E_c=\frac{e^*}{2C}$$

Insulating side of the D-SIT in TiN films

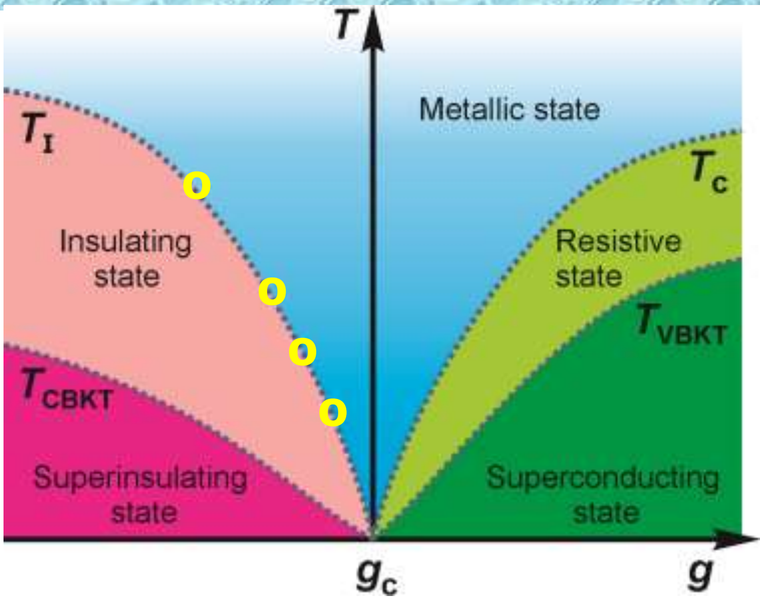
At lower temperatures...



Rsq
@
300 K

I1: T_I = 0.25 K 4.60 kΩ
I2: T_I = 0.28 K 4.68 kΩ
I3: T_I = 0.38 K 4.73 kΩ
I4: T_I = 0.61 K 4.77 kΩ

R_0 = 20 kΩ

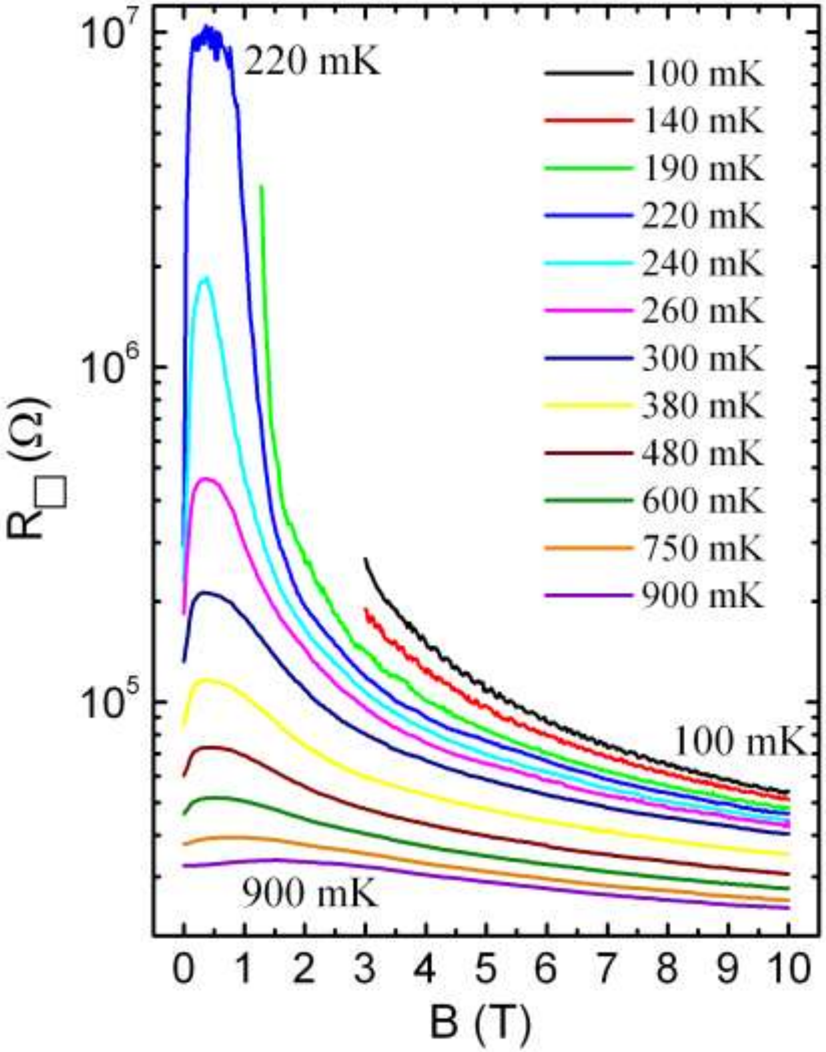


$$R = R_0 exp(T_I/T)$$

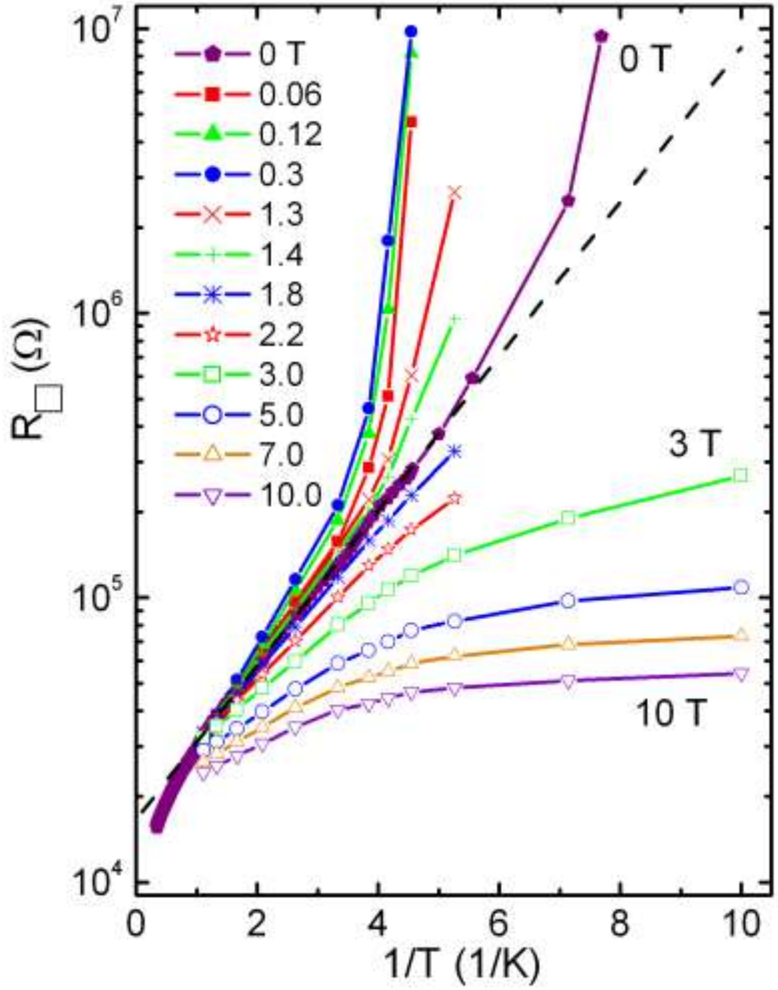
an Arrhenius behavior of the resistance

T. Baturina, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk, PRL 99, 257003 (2007)
T. Baturina, A. Bilušic, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk, Physica C 468, 316 (2008)
T. Baturina, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk, JETP Lett. 88, 752 (2008)

Hyperactivated behavior of the resistance

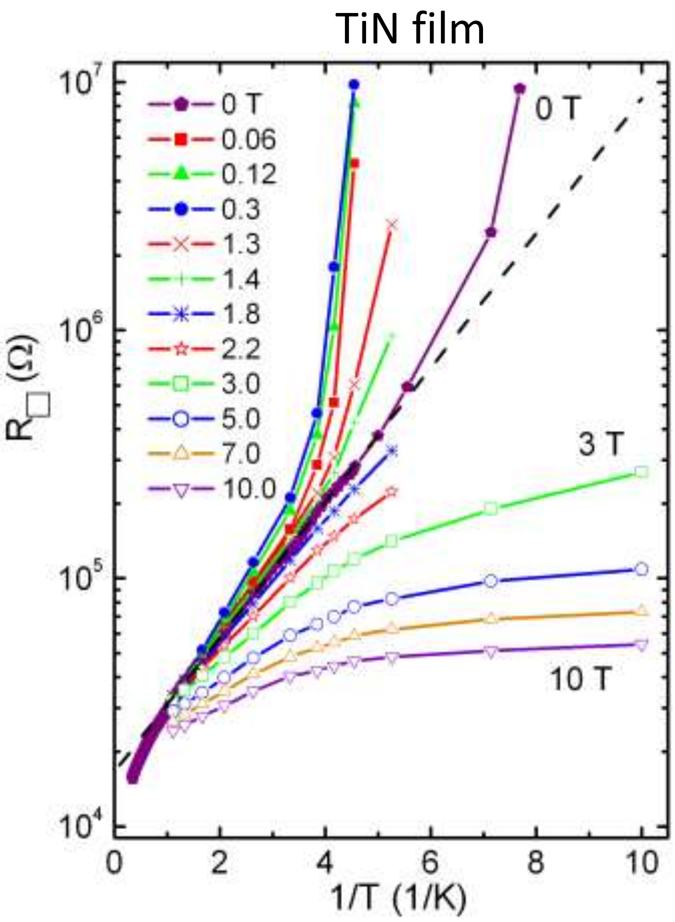


Arrhenius plots of the isomagnetic temperature dependences of the resistance.

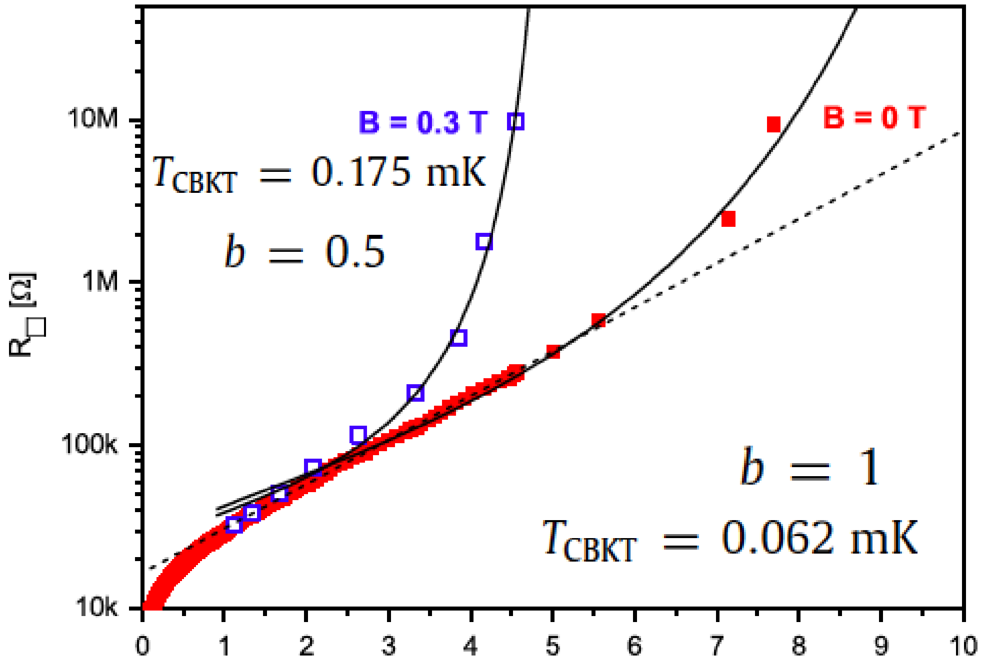


T. Baturina, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk,
JETP Lett. 88, 752 (2008)

Hyperactivated behavior of the resistance


TiN film

T.I. Baturina, V.M. Vinokur / Annals of Physics 331 (2013) 236–257



$$R = R_0 \exp\left(A \exp \sqrt{\frac{b}{(T/T_{\mathrm{CBKT}}) - 1}} \right)$$

$$R_0 = 8\ \mathrm{k}\Omega$$
$$A = 1$$

T. Baturina, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk,
JETP Lett. 88, 752 (2008)

T. Baturina & V. Vinokur, Annals of Physics 331, 236-257 (2013)

Sample NbTiN
d = 10 nm

Arrhenius plot of the isomagnetic temperature dependences of the resistance

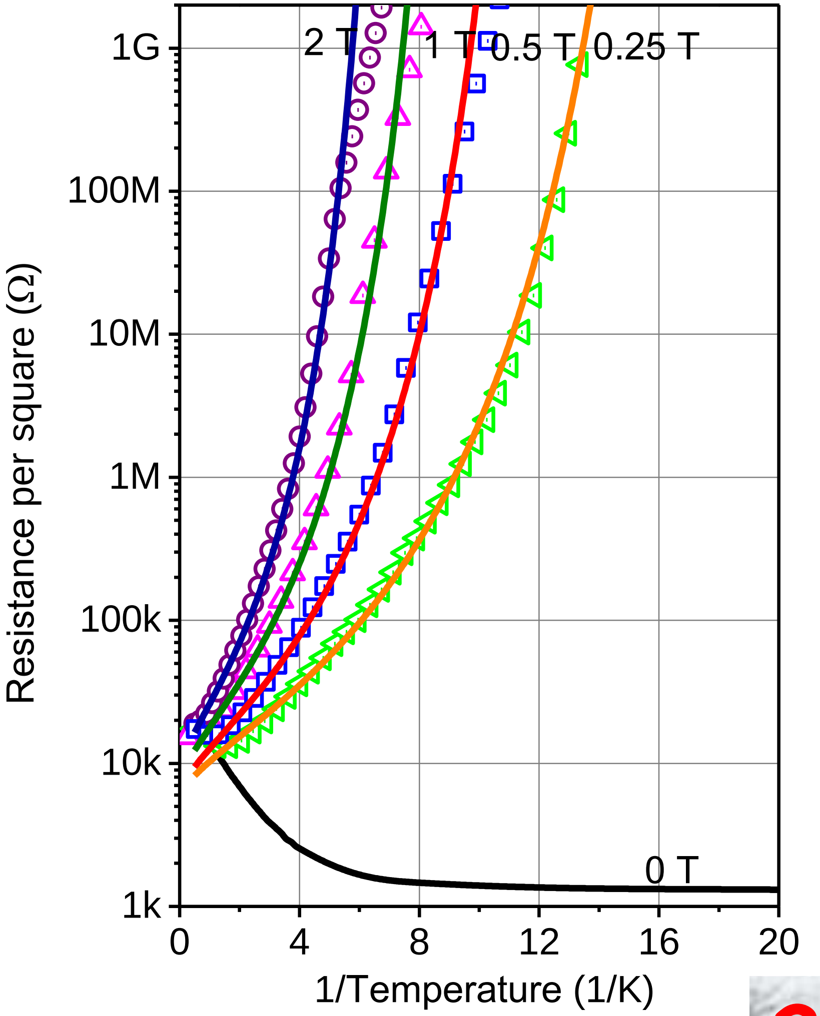
Hyperactivated behavior:
Resistance increases faster than that of the thermally activated type.

This indicates a change of the mechanism of the conductivity.

$$R = R_0 \exp\left(A \exp\sqrt{\frac{b}{(T/T_{\mathrm{CBKT}})-1}}\right)$$

B	R_0	T_{cBKT}
2 T	3000 Ω	90 mK
1 T	2500 Ω	70 mK
0.5 T	2100 Ω	54 mK
0.25 T	2000 Ω	39 mK

$A = 1$
$b = 6$

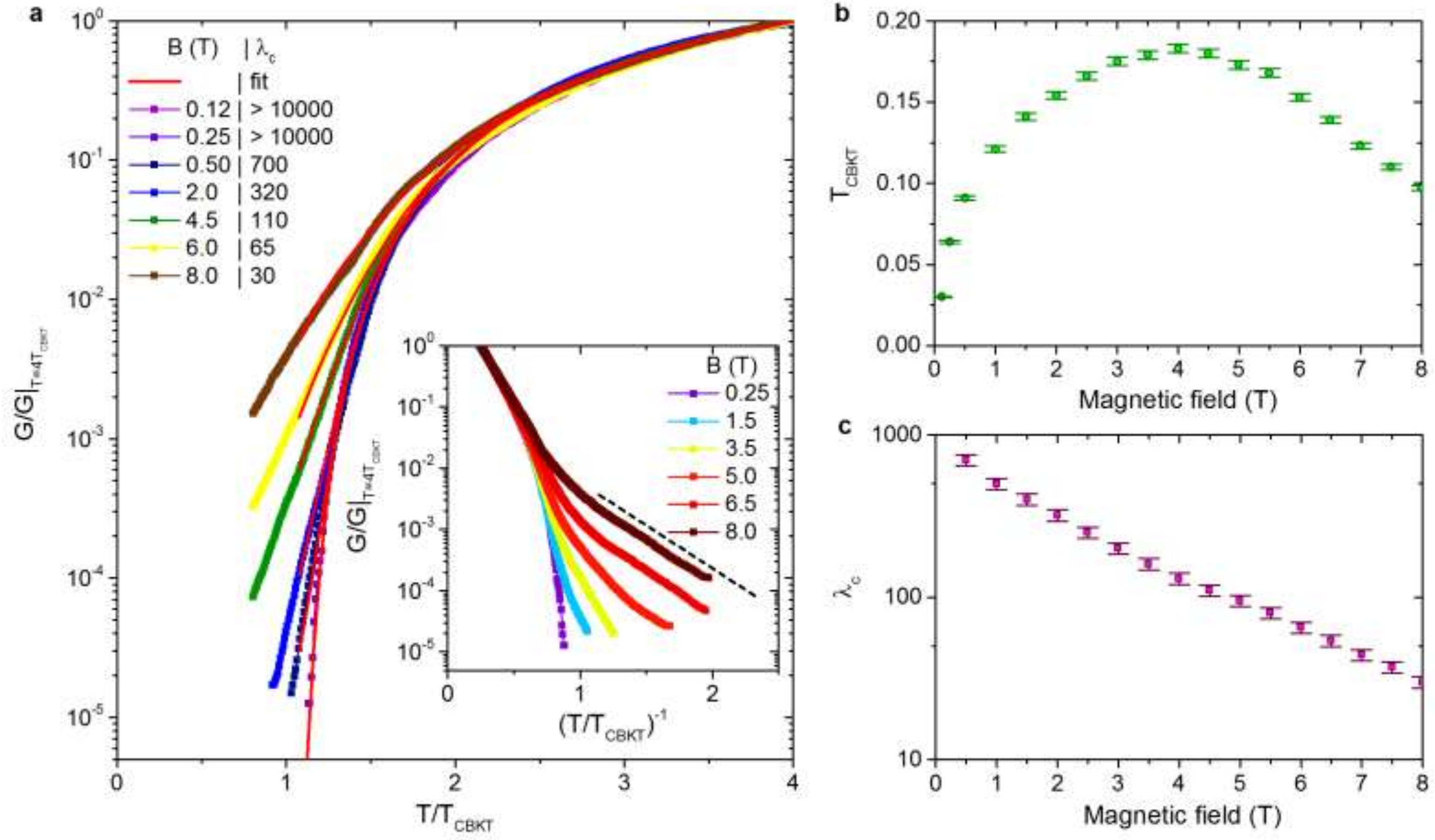


Sample NbTiN
d = 10 nm

CBKT plot of the isomagnetic temperature dependences of the resistance

P. Minnhagen.
The two-dimensional Coulomb gas, vortex unbinding, and superfluid-superconducting films.
Rev. Mod. Phys., 59, 1001-1066 (1987).

$$\frac{2\pi n}{t} = \frac{1}{\lambda^2} - \frac{1}{\lambda_c^2};\qquad \lambda^{\sqrt{4t-1}} = \frac{1}{z}\left(1 - \frac{\lambda^2}{\lambda_c^2}\right);\qquad t = \frac{T}{T_{CBKT}};\qquad n \propto \frac{G}{G|_{T=4T_{CBKT}}}$$

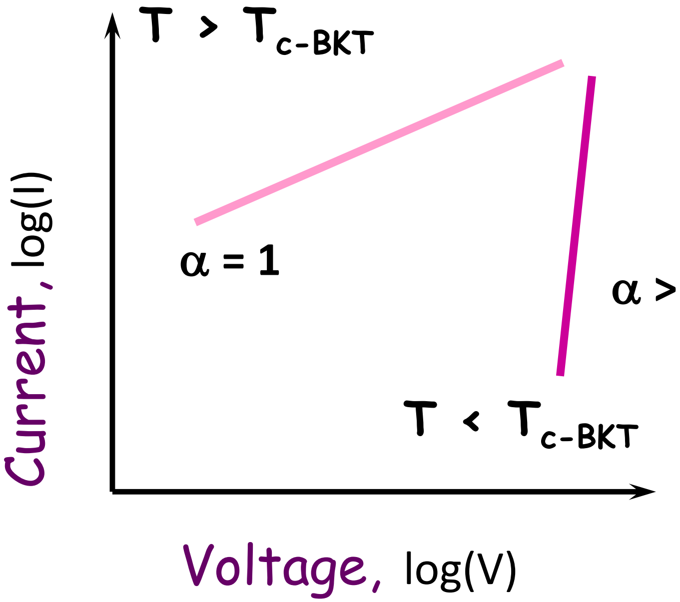


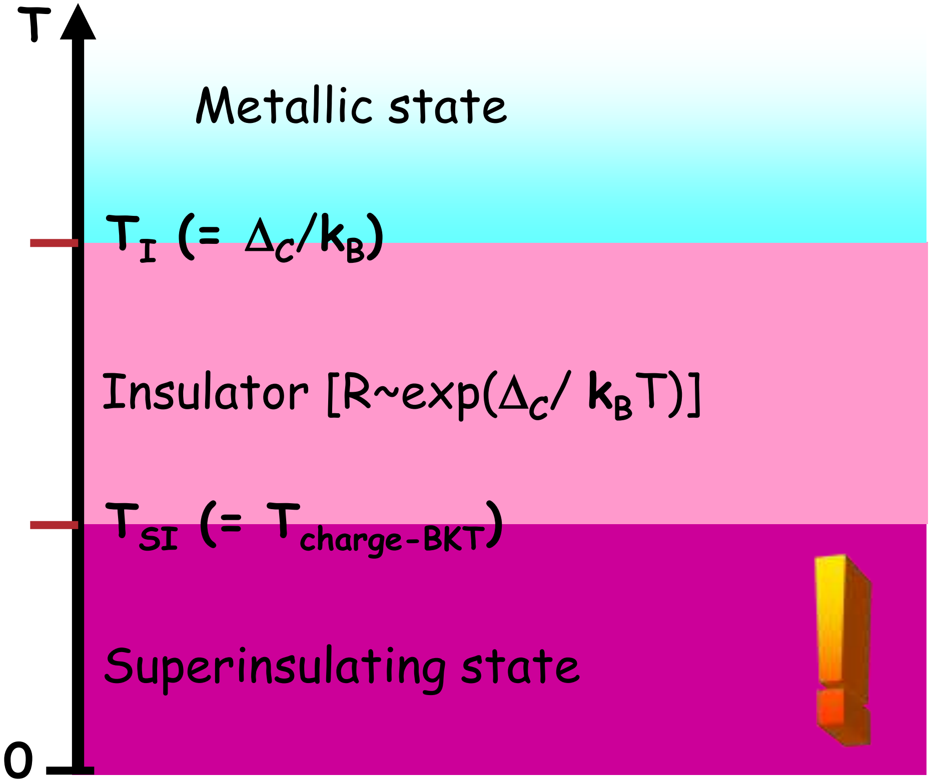
Superinsulator

Current-Voltage Characteristics

in experiment:

$$I \propto V^{\alpha(T)}$$





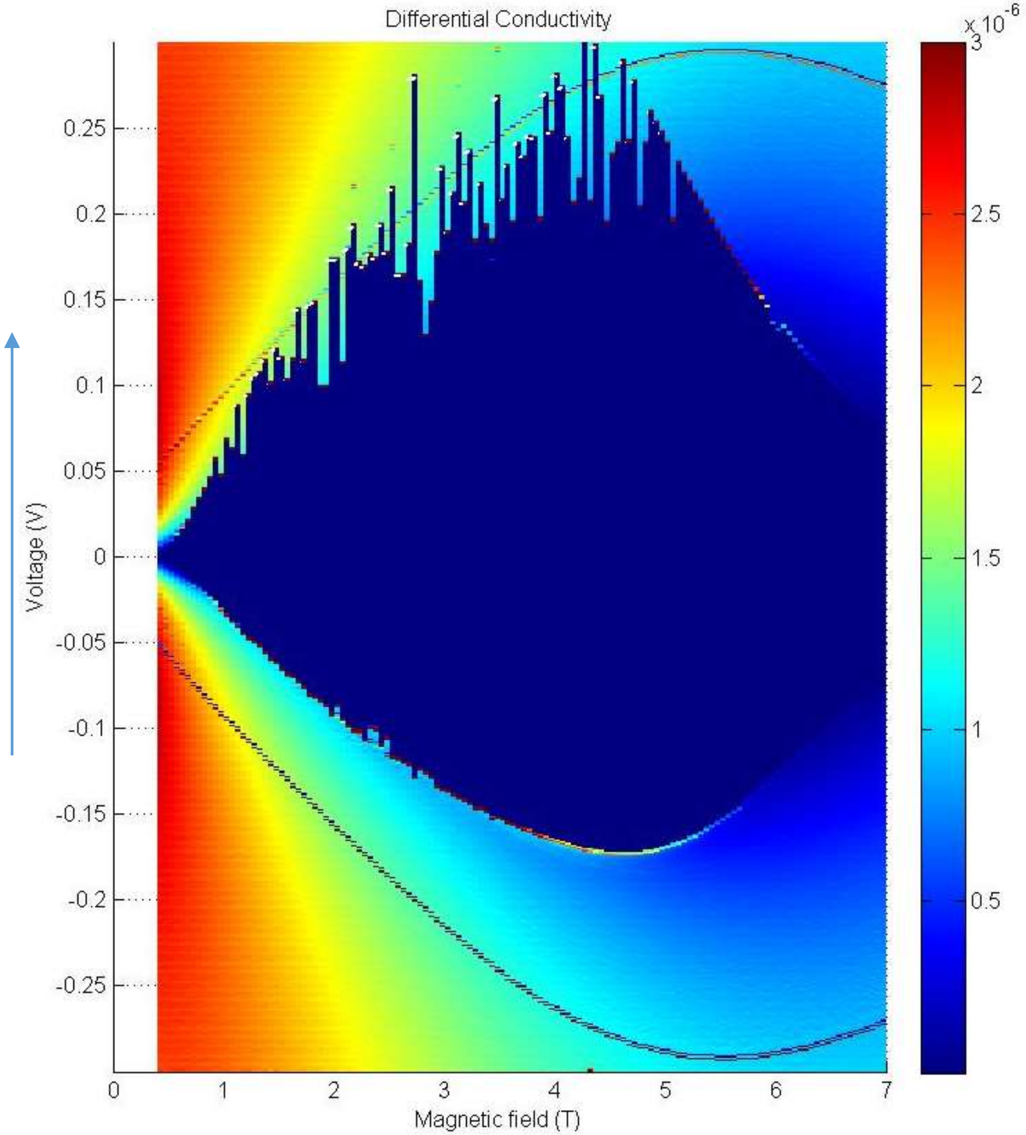
Sample NbTiN
d = 10 nm

Magnetic field evolution of differential conductivity

Temperature T= 40 mK

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

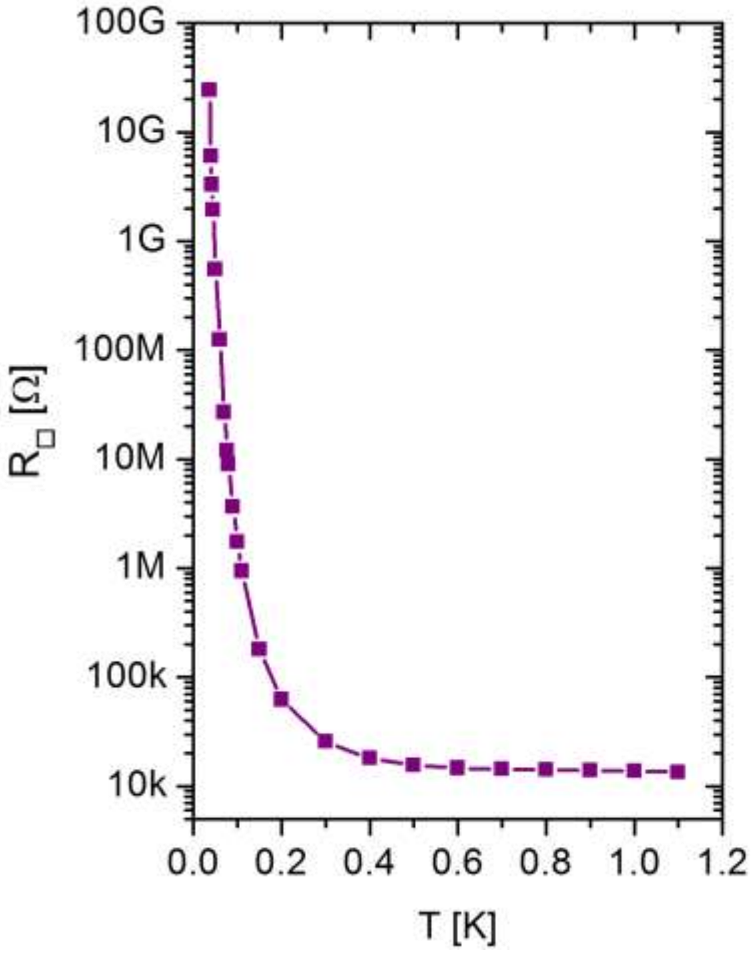
The threshold voltage
changes nonmonotonically
upon magnetic field



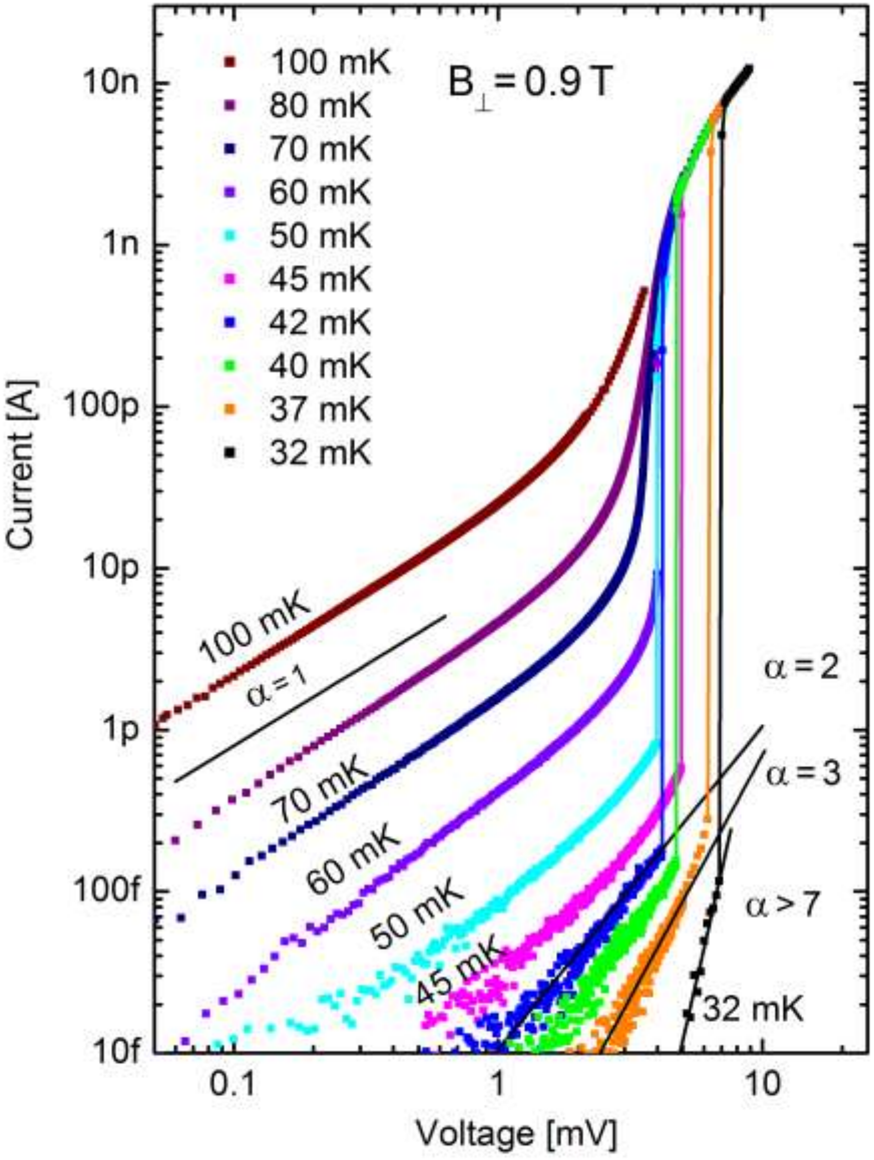
Charge BKT transition

Sample TiN

linear response regime

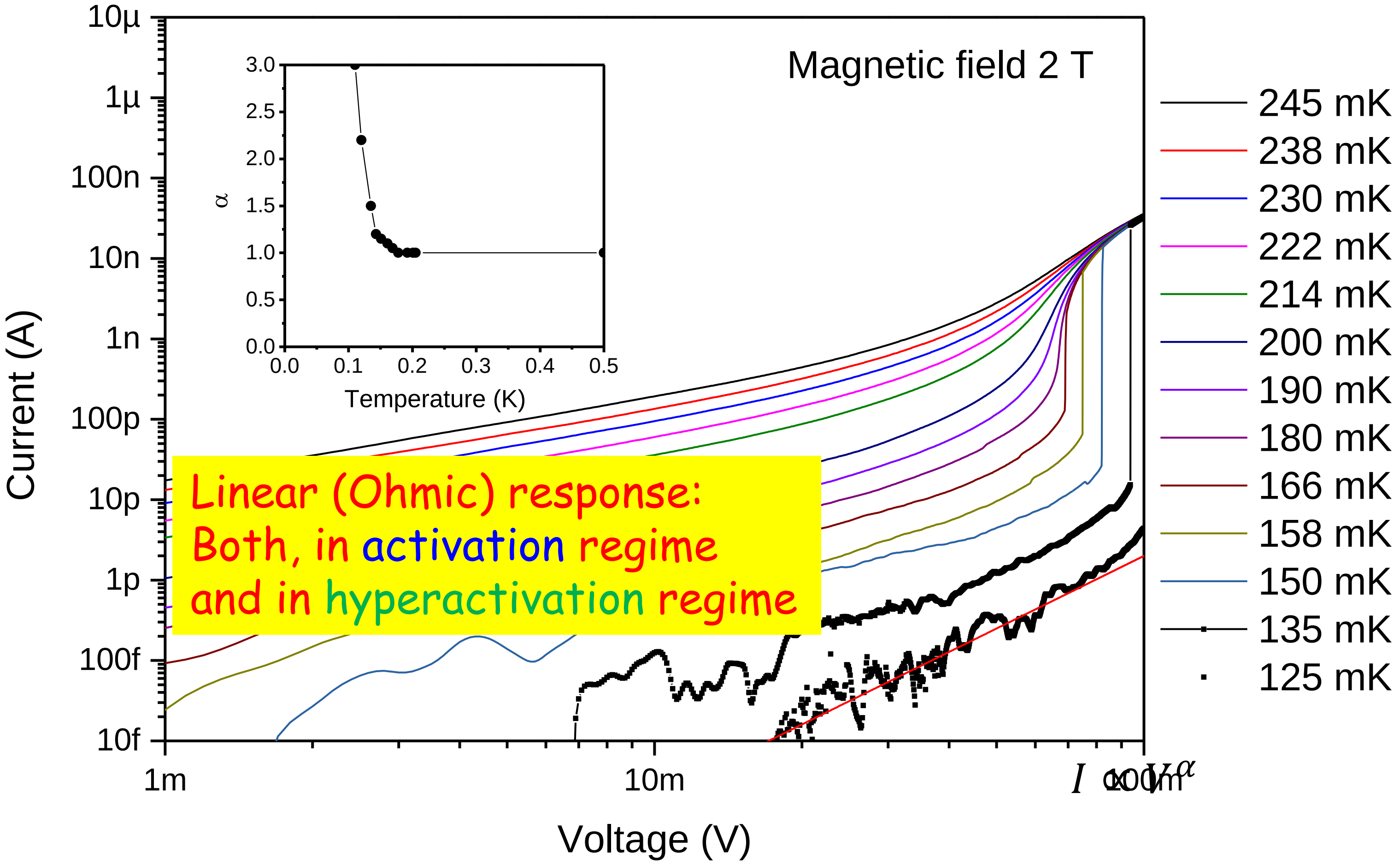


current - voltage characteristics



Charge BKT transition

Sample NbTiN



Linear (Ohmic) response:
Both, in activation regime
and in hyperactivation regime

electron-phonon decoupling overheating

heat balance equation

$$P = I^2 R(T_e) = \Sigma\Omega(T_e^\beta - T_{\mathrm{ph}}^\beta)$$

Σ is the electron-phonon coupling constant

Ω is the volume of the sample

$R(T_e)$ is the sample resistance, which is assumed to depend only on the temperature of the electron subsystem, T_e

$\beta = n+2$, n is the power describing the temperature dependence of the electron-phonon relaxation rate:

$$\tau_{e-\mathrm{ph}}^{-1} \propto T^n$$

The value $n = 3$ ($\beta = 5$) was first calculated by

V. F. Gantmakher [Rep. Prog. Phys. 37, 317 (1974)]

and found in most metals.

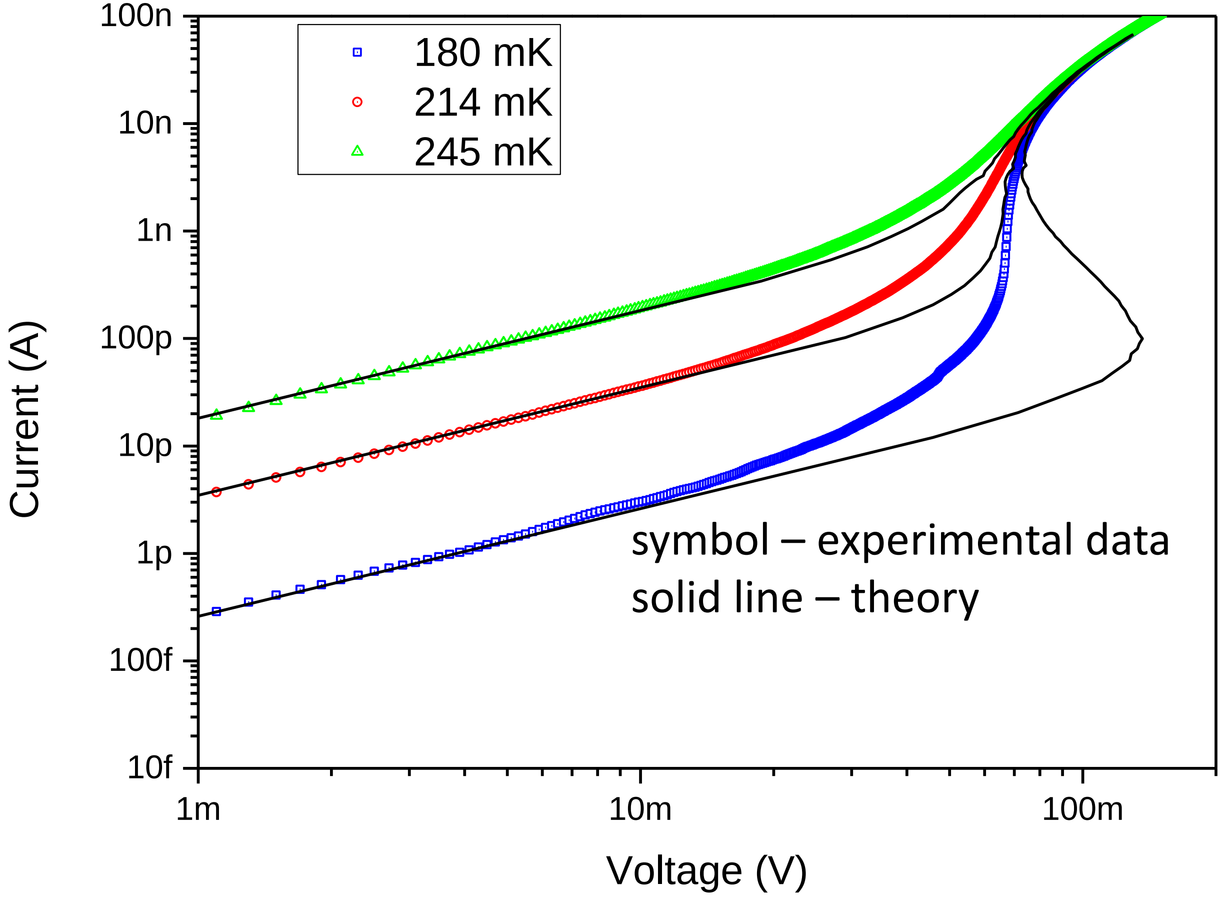
Sample NbTiN
d = 10 nm

Overheating?

the conventional overheating instability model well describes

nonlinear current-voltage characteristics

only in the activation regime



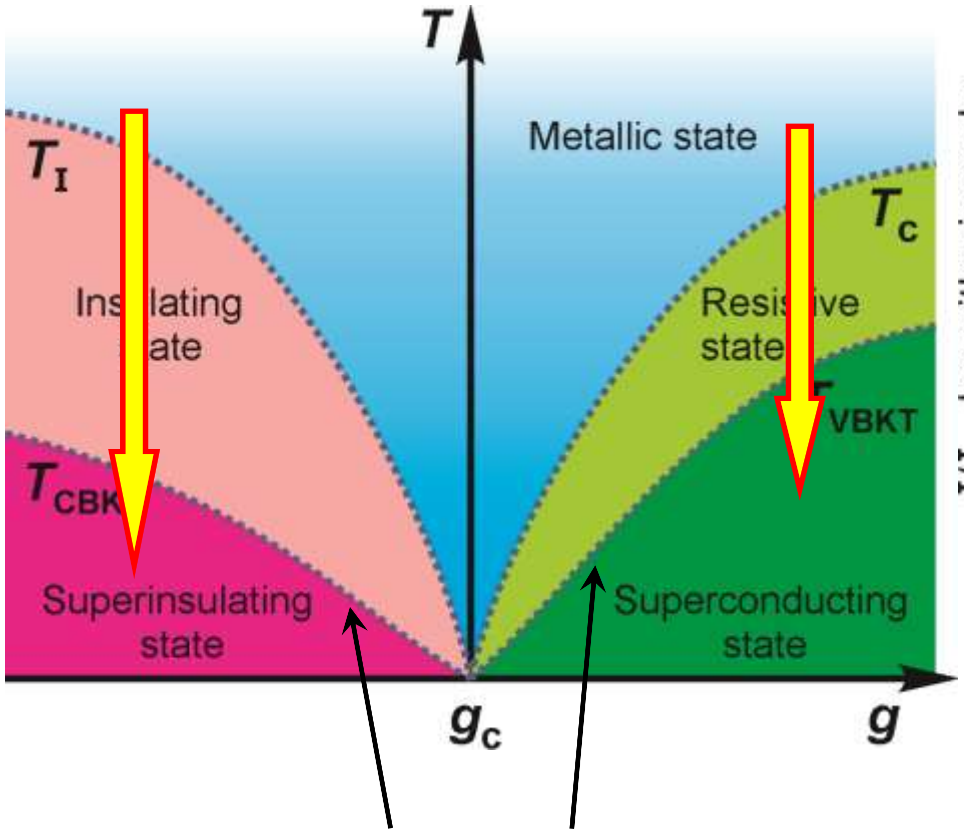
symbol – experimental data
solid line – theory

$$V^2 / R(T_{el}) = \Sigma\Omega\left(T_{el}^6 - T_{ph}^6\right)$$

Superconductor - Superinsulator Duality

Thermodynamic phase diagram

$$V \to 0, \; I \to 0$$



Topological phase transition

Dual current - voltage characteristics