2046-14

Summer College on Nonequilibrium Physics from Classical to Quantum Low Dimensional Systems

6 - 24 July 2009

Does a bad metal become good superinsulator?

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Does a bad metal become good “superinsulator”?

Giant jumps in *I-V* characteristics in 2D films (near a superconductor-insulator transition)

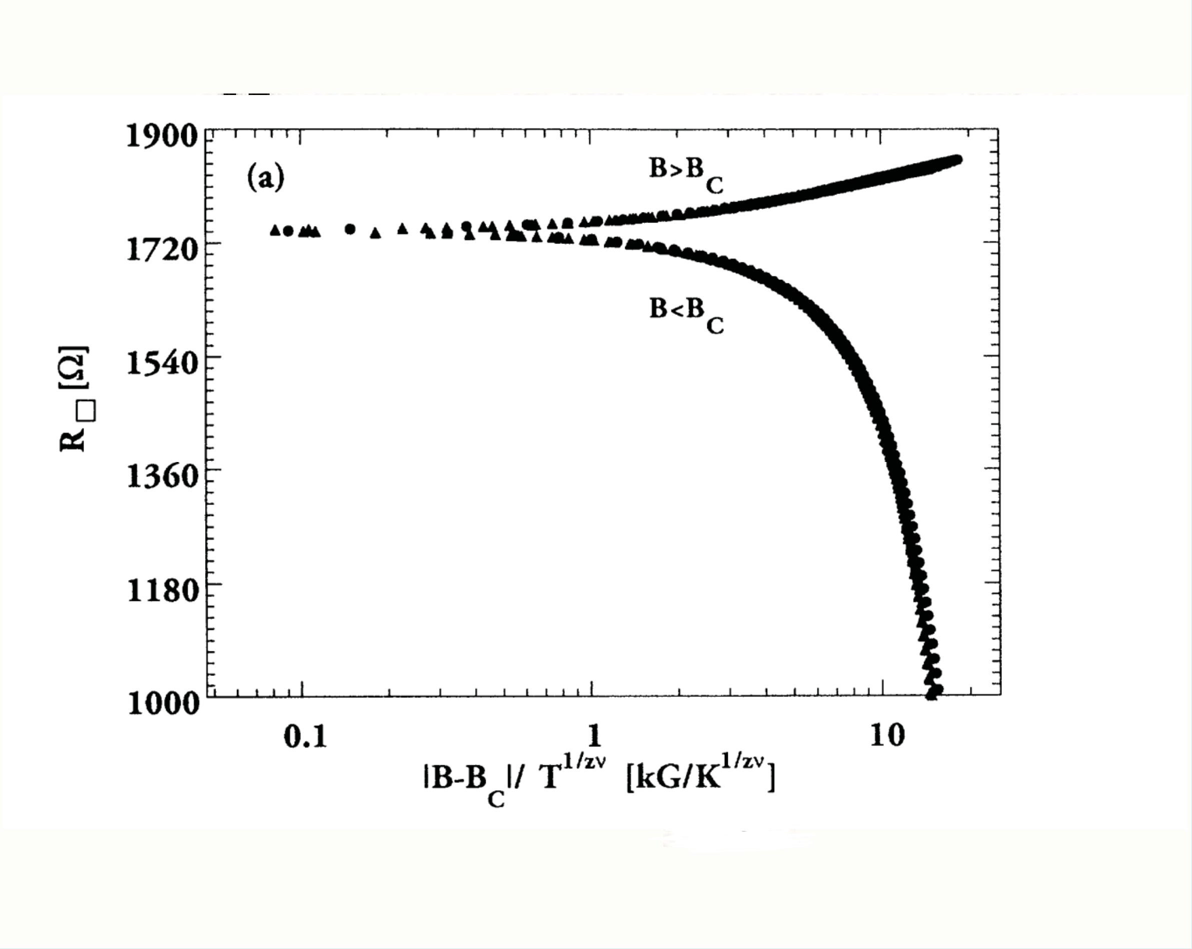
Boris Altshuler, Vladimir Kravtsov, I.L., Igor Aleiner

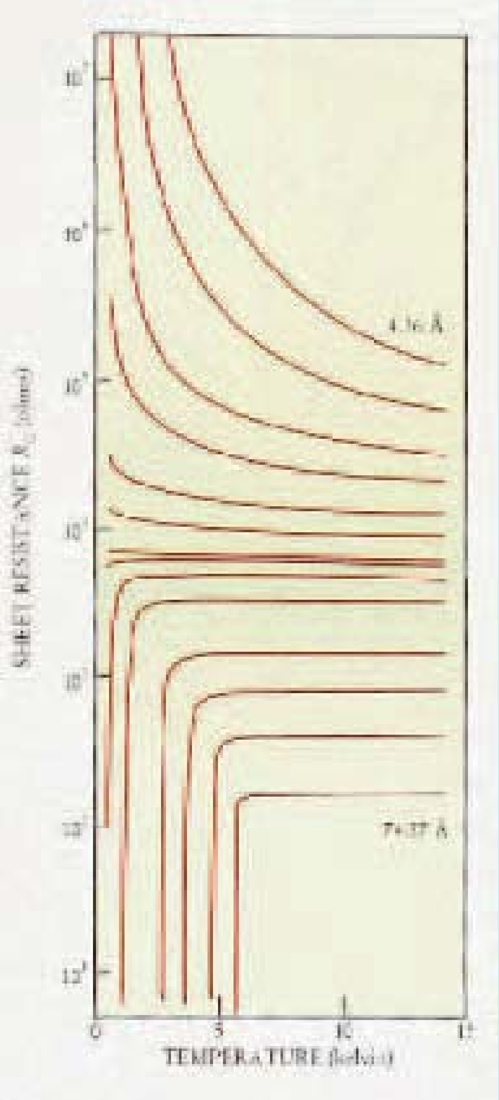
Columbia U., NY

Columbia U., NY

PRL, 102, 176803 (2009) (also Ovadia, Sacepe, Shahar, *ibid*, 176802)

Superconductor-Insulator Transition





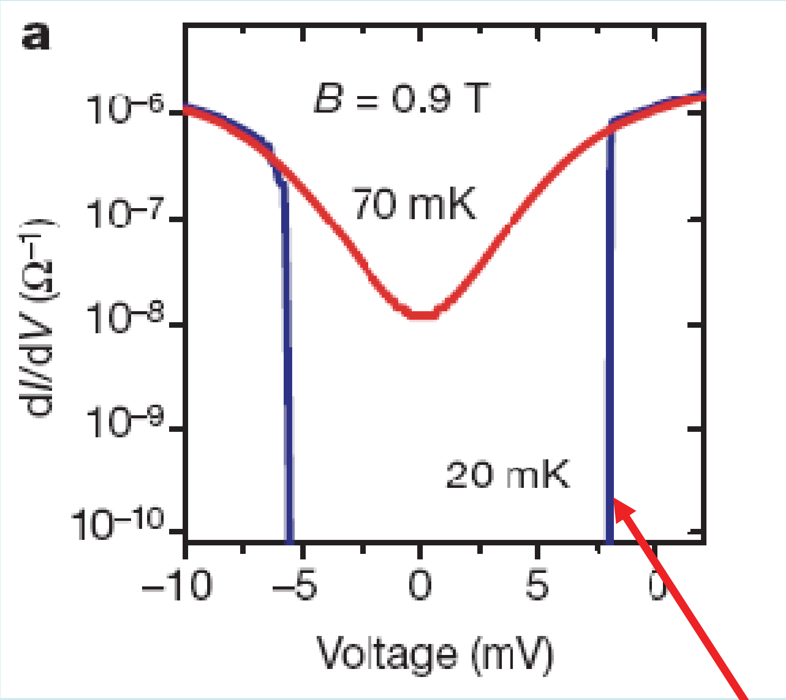
Goldman et al; Kapitulnik et al; Paalanen et al.,
Hsu et al, Ovidiyahu et al, ..., 1989-till now

Subject of the talk:

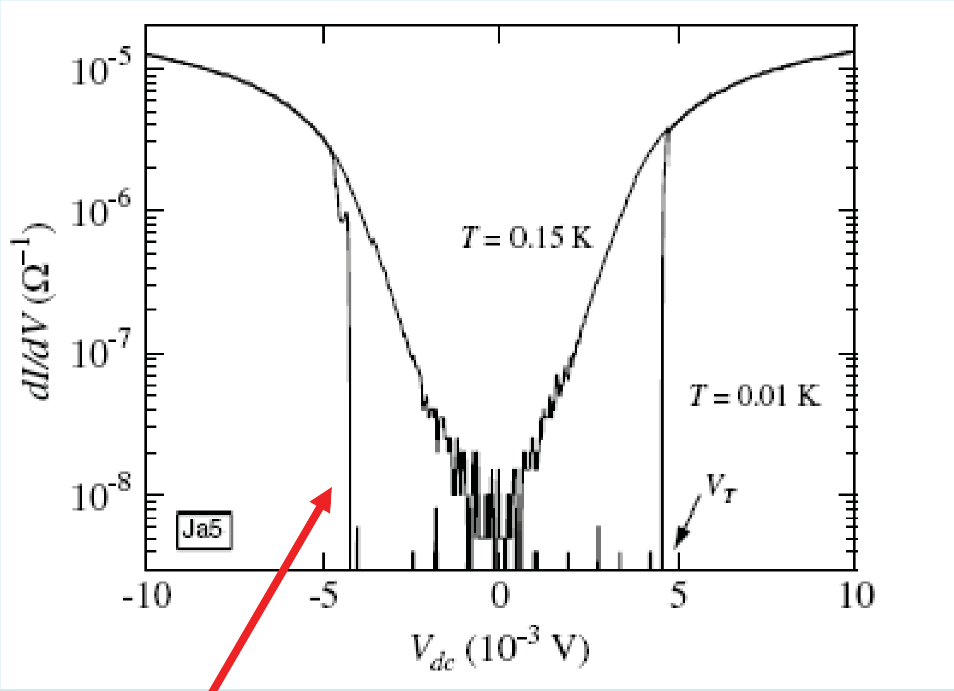
Highly unusual
nonlinear electronic transport
on the insulating side of SIT in
disordered thin films of
InO and TiN,
and also in other materials

Giant jumps in I-V characteristics

TiN films



InO films



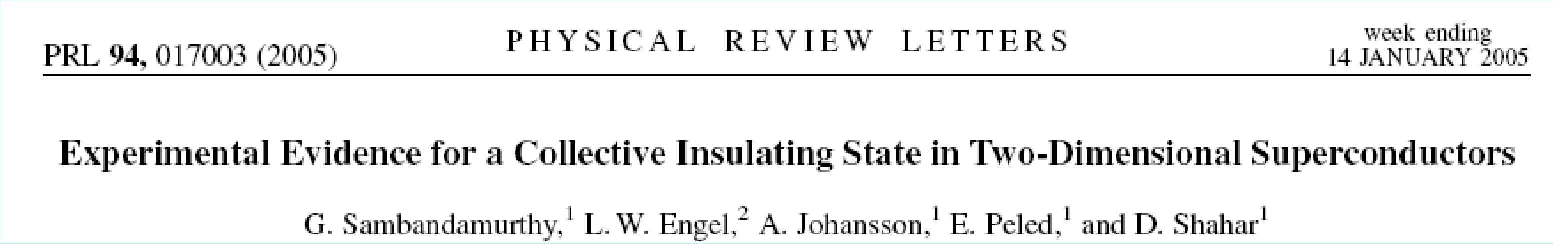
Baturina, Mironov, Vinokur,
Baklanov, Strunk,'07

Sambandamurthy, Engel, Johansson,
Peled, Shahar, '05

Giant jumps in resistance
from kΩ to GΩ regime

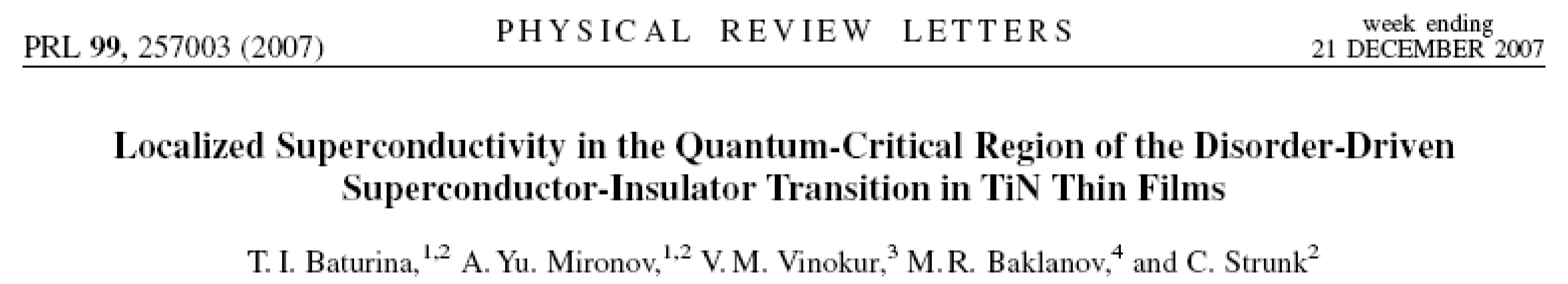
in systems tantalizingly
close to superconductors

From a superconductor to a super-insulator?


PRL **94,** 017003 (2005) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2005

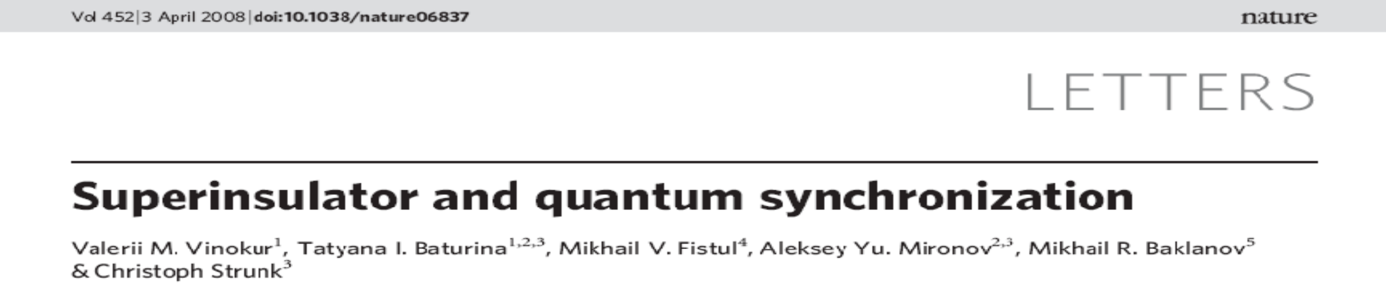
Experimental Evidence for a Collective Insulating State in Two-Dimensional Superconductors

G. Sambandamurthy,[1] L. W. Engel,[2] A. Johansson,[1] E. Peled,[1] and D. Shahar[1]


PRL **99,** 257003 (2007) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2007

Localized Superconductivity in the Quantum-Critical Region of the Disorder-Driven Superconductor-Insulator Transition in TiN Thin Films

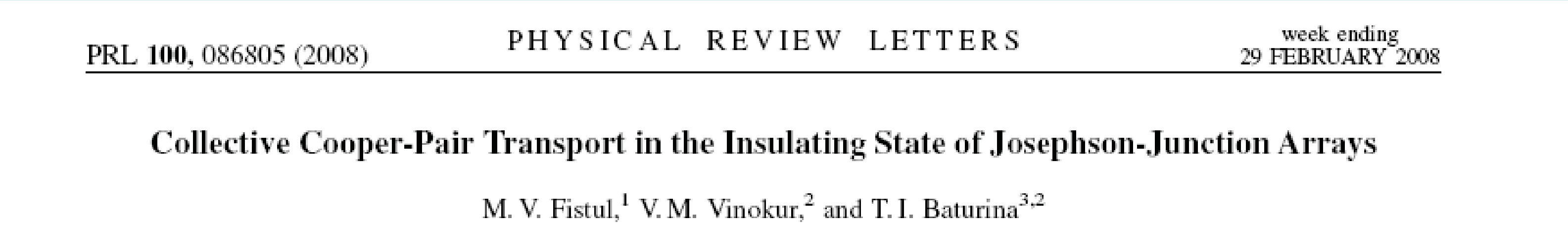
T. I. Baturina,[1,2] A. Yu. Mironov,[1,2] V. M. Vinokur,[3] M. R. Baklanov,[4] and C. Strunk[2]


Vol 452 | 3 April 2008 | **doi:10.1038/nature06837** nature

LETTERS

Superinsulator and quantum synchronization

Valerii M. Vinokur[1], Tatyana I. Baturina[1,2,3], Mikhail V. Fistul[4], Aleksey Yu. Mironov[2,3], Mikhail R. Baklanov[5] & Christoph Strunk[3]


PRL **100,** 086805 (2008) PHYSICAL REVIEW LETTERS week ending 29 FEBRUARY 2008

Collective Cooper-Pair Transport in the Insulating State of Josephson-Junction Arrays

M. V. Fistul,[1] V. M. Vinokur,[2] and T. I. Baturina[3,2]

Is this resistance so super large?

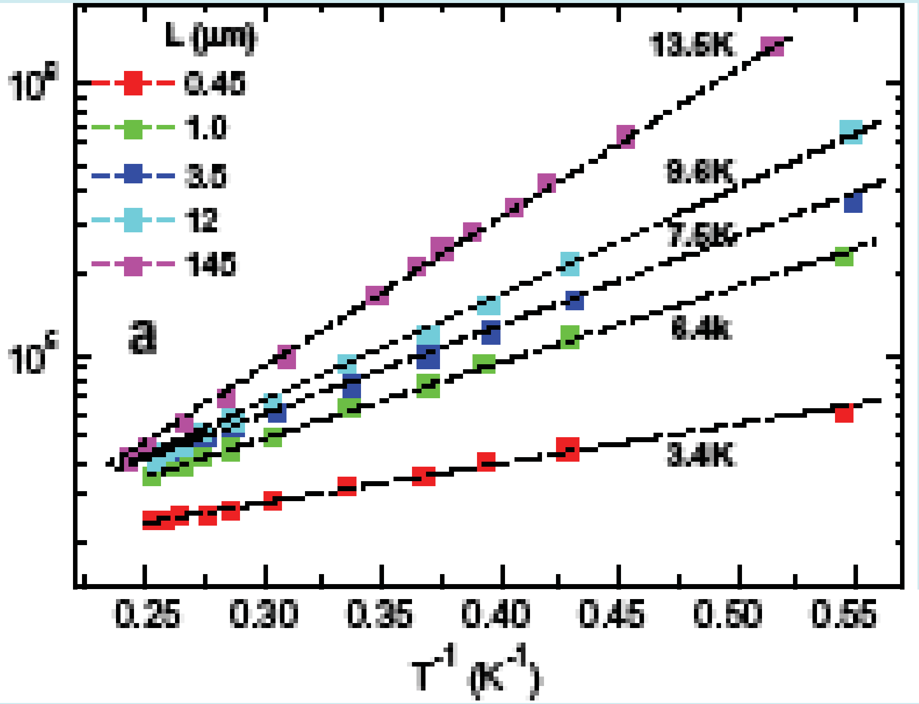
Linear regime: Arrhenius law at low T was observed in numerous experiments in InO amorphous films and elsewhere but is also **rather strange**

$$R(T) = R_0 e^{(\Delta/T)^\gamma}$$

$$\gamma \approx 1\,, \Delta \sim 1 \div 10\text{K}$$

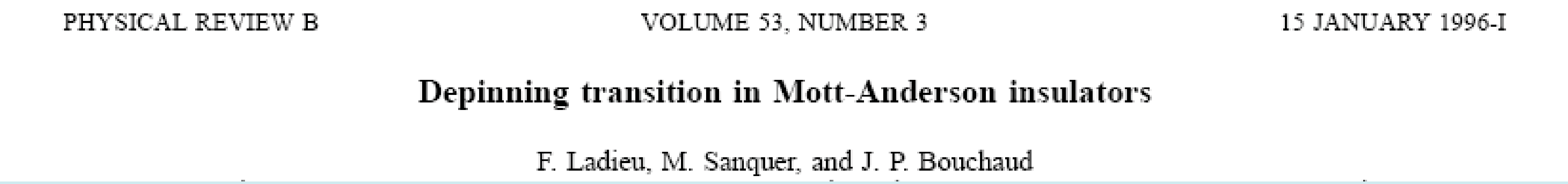
One expects Mott's VRH, $\gamma=1/(d+1)$, or Efros-Shklovskii $\gamma=½$

This was always considered as a puzzle and still doesn't have a fully satisfactory theoretical explanation



If we extrapolate this down to T~100mK, then R~$R_q e^{10}$~10^8 Ω: one should wonder why SMALL values of R were also observed in this range of T.

Is the closeness to superconducting transition so important?

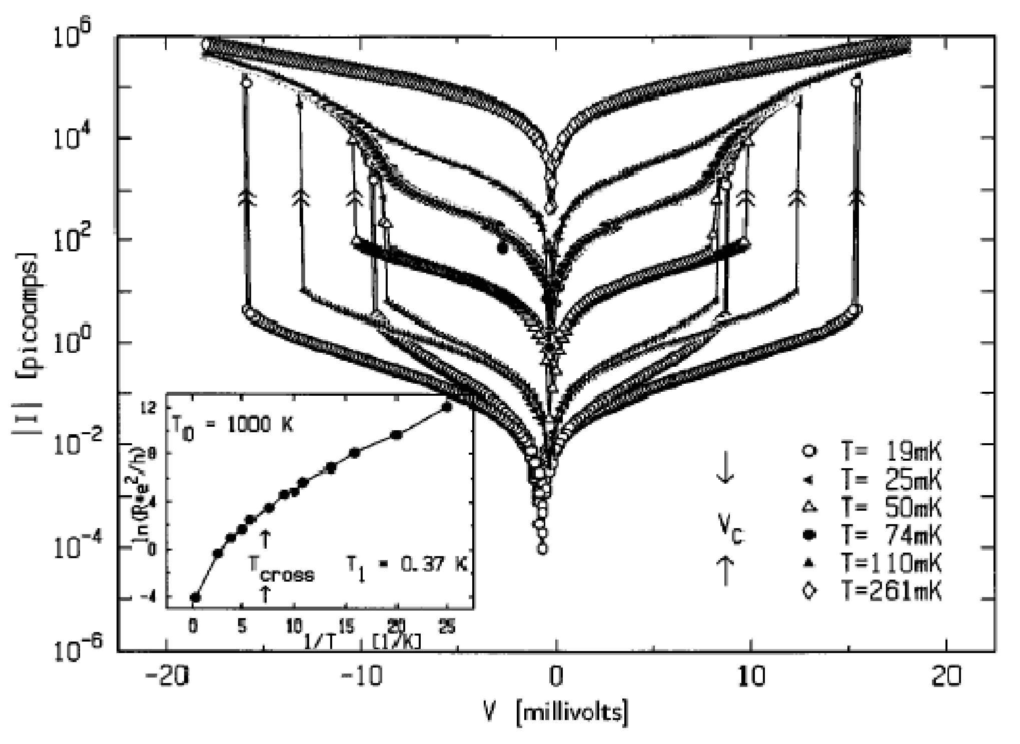


PHYSICAL REVIEW B VOLUME 53, NUMBER 3 15 JANUARY 1996-I

Depinning transition in Mott-Anderson insulators

F. Ladieu, M. Sanquer, and J. P. Bouchaud

A few orders in magnitude current jumps increasing with lowering temperature **not in the vicinity of the SIT transition**



Something else?

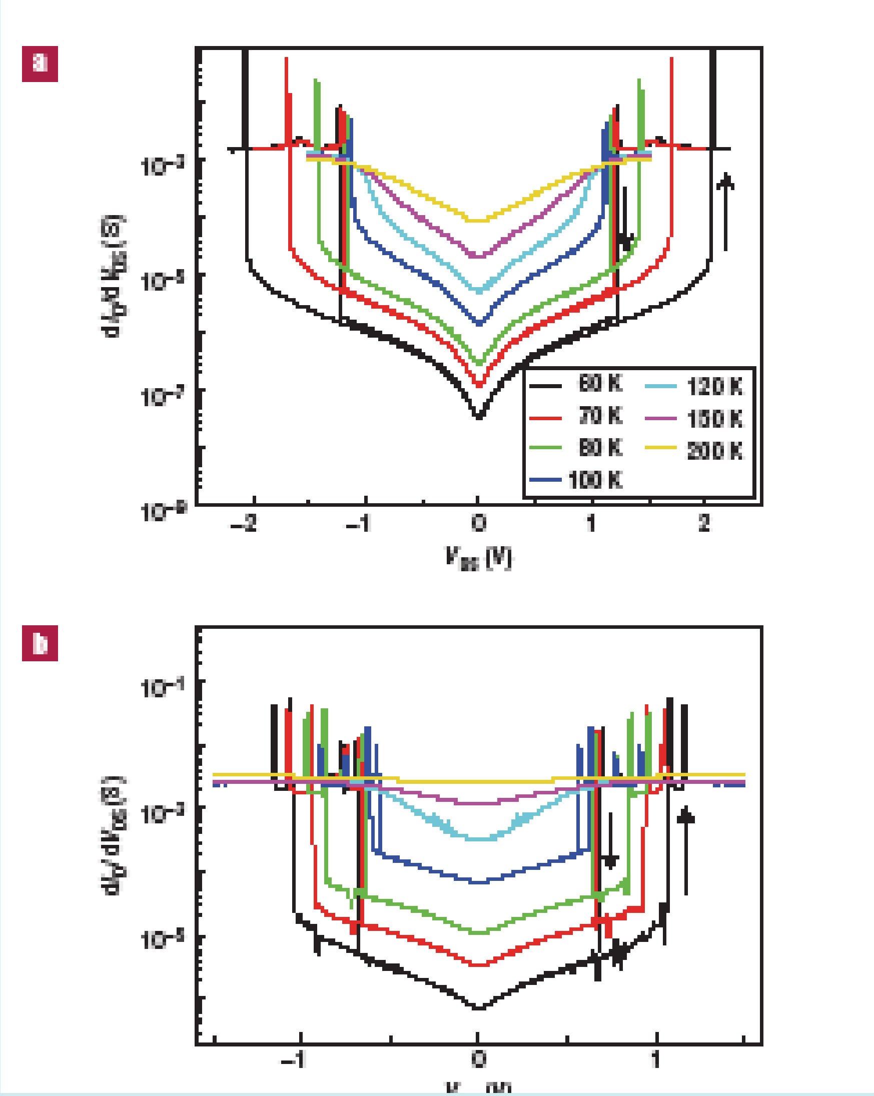
LETTERS

Electrically driven phase transition in magnetite nanostructures

SUNGBAE LEE[1], ALEXANDRA FURSINA[2], JOHN T. MAYO[2], CAFER T. YAVUZ[2], VICKI L. COLVIN[2], R. G. SUMESH SOFIN[3], IGOR V. SHVETS[3] AND DOUGLAS NATELSON[1,4]*

nature materials | VOL 7 | FEBRUARY 2008 |

Magnetite (Fe_3O_4) nanostructures



Common features

- Strong disorder: $R_0 \sim R_q \equiv \dfrac{2h}{e^2} \sim 50\kappa\Omega$ in low-R state

- Arrhenius law for linear (V→0) resistance at low T - *pseudo-gap*

$$\boxed{R(T) = R_0 \mathrm{e}^{\Delta/T}}$$

- VRH ($\gamma \leq \frac{1}{2}$) is not observed at low T – no electron-phonon thermalization?

$$\xcancel{R(T) \propto e^{(\Delta/T)^\gamma}}$$

- Voltage threshold eV (at which jumps occurs) increases with increasing Δ much faster than Δ itself

Phenomenological explanation?

No single microscopic approach can possibly explain so similar behaviour in so different systems...

Our main idea: bi-stability due to (over)heating is the main cause of giant resistance jumps

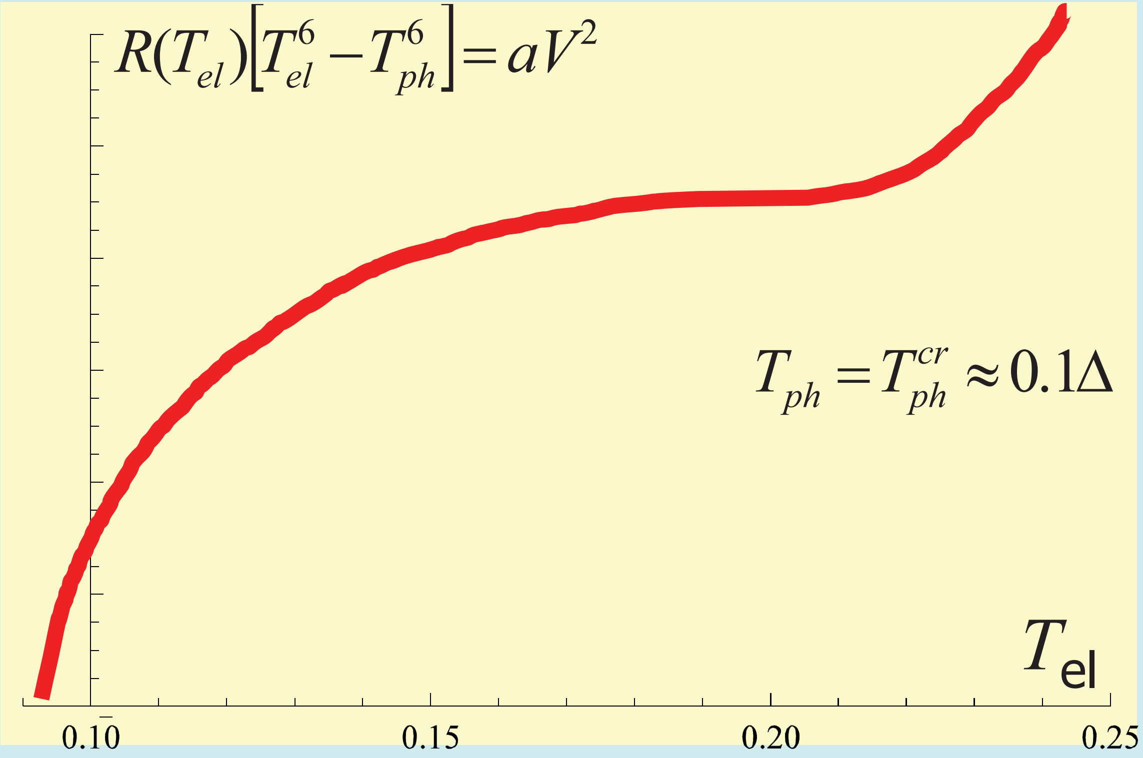
Not normally expected for hopping conductivity in the insulating regime – in contrast to the metallic one...

Stepping Stones

- Electron-electron interaction is strong enough: electrons are mutually thermalized with T_{el}
- Cooling is mainly due to electron-phonon interaction which is, however, inefficient: electrons can be joule –heated to temperature $T_{\text{el}} > T_{\text{bath}} \equiv T_{\text{ph}}$
- Linear (Ohmic) $R(T)$ has steep (Arrhenius-like) T -dependence which remains valid at a finite voltage with $T \to T_{\text{el}}$
- T_{el} should be found from the balance of Joule heating (by electric field) and phonon cooling

Bi-stability in a nutshell

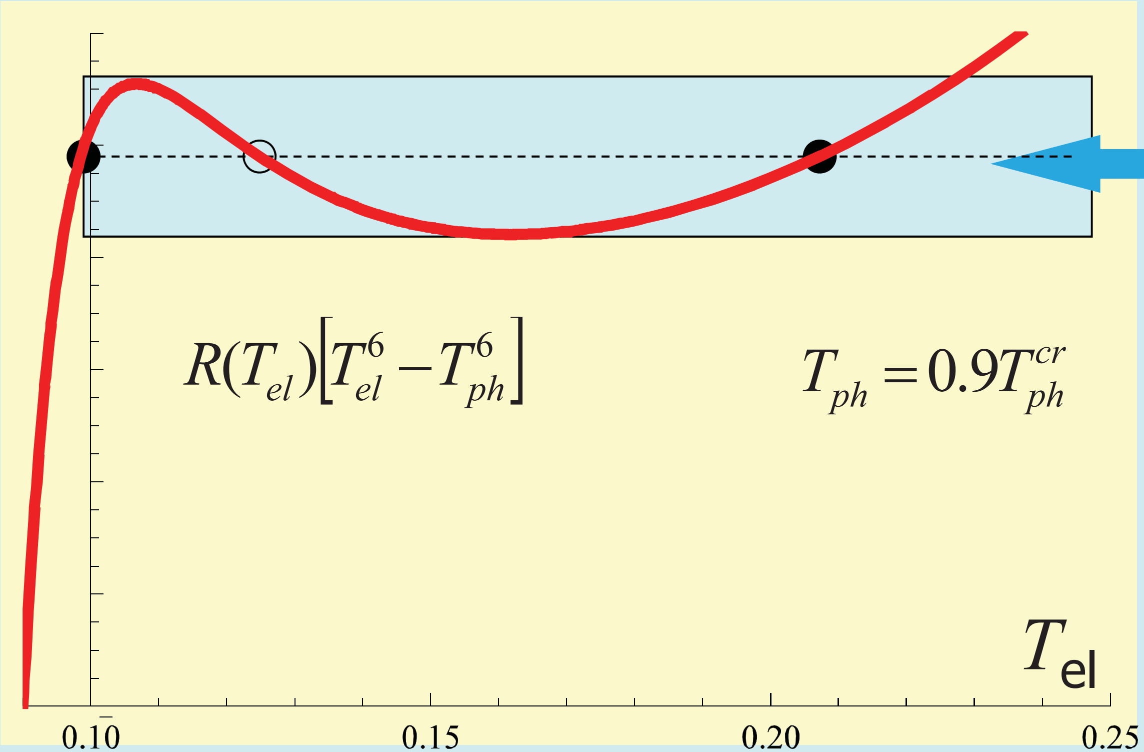
Heat balance: $$\frac{V^2}{R(T_{\text{el}})} = \frac{\mathcal{E}(T_{\text{el}})}{\tau_{\text{e-ph}}(T_{\text{el}})} - \frac{\mathcal{E}(T_{\text{ph}})}{\tau_{\text{e-ph}}(T_{\text{ph}})} \propto T_{\text{el}}^{\beta} - T_{\text{ph}}^{\beta}$$



For each voltage there is a unique T_{el} provided that $T_{\text{ph}} < T^{\text{cr}} \cong 0.1\Delta$

Bi-stability in a nutshell

Heat balance: $$\frac{V^2}{R(T_{\rm el})} = \frac{\mathcal{E}(T_{\rm el})}{\tau_{\text{e-ph}}(T_{\rm el})} - \frac{\mathcal{E}(T_{\rm ph})}{\tau_{\text{e-ph}}(T_{\rm ph})} \propto T_{\rm el}^{\beta} - T_{\rm ph}^{\beta}$$



Bi-stable region

Two stable electron temperatures at the same voltage

Suppression of cooling by disorder

$$\frac{\hbar}{\tau_{\text{e-ph}}} = \frac{T^3}{T_D^2}$$

electron-phonon scattering rate in a clean metal:

T_{D} – Debye temperature;
assumed that $p_F \sim \hbar/a$ (dense metal)

$$\frac{\hbar}{\tau_{\text{e-ph}}} = n^* \frac{T^3}{T_D^2}$$

in a clean semiconductor with $p_F \ll \hbar/a$

n^*= # of electrons per unit cell

Energy relaxation (cooling) from the kinetic equation:

$$\frac{\dot{\mathcal{E}}}{\mathcal{V}} = \nu_0 \int \varepsilon \dot{f}(\varepsilon, T_{\text{el}}) \mathrm{d}\varepsilon \sim \frac{T_{\text{el}}^2}{\tau_{\text{e-ph}}(T_{\text{el}})} - \frac{T_{\text{ph}}^2}{\tau_{\text{e-ph}}(T_{\text{ph}})} \propto T_{\text{el}}^5 - T_{\text{ph}}^5$$

$$\frac{\hbar}{\tau_{\text{e-ph}}} \sim \underbrace{n^* \frac{q_T \ell}{\hbar}}_{\sim 10^{-4} \text{ in InO and TiN}} \frac{T^3}{T_D^2} \propto T^4$$

Dirty-metal (or low T) limit:

$$q_T \ell / \hbar \ll 1 \quad \Leftrightarrow \quad T\,\ell \ll \hbar v_{\mathrm{s}}$$

ℓ – electron mean free path
v_{s} – transverse sound velocity
q_{T} – thermal phonon momentum

Disorder-independent heat balance

Substituting the exact solution of the kinetic equation in the model results in the disorder-independent equation for heat balance in proper dimensionless variables:

$$\frac{V^2}{R} = \frac{\mathrm{d}\mathcal{E}}{\mathrm{d}t} \qquad \mapsto \qquad v^2 \mathrm{e}^{-1/t_{\mathrm{el}}} = t_{\mathrm{el}}^6 - t_{\mathrm{ph}}^6 \,,$$

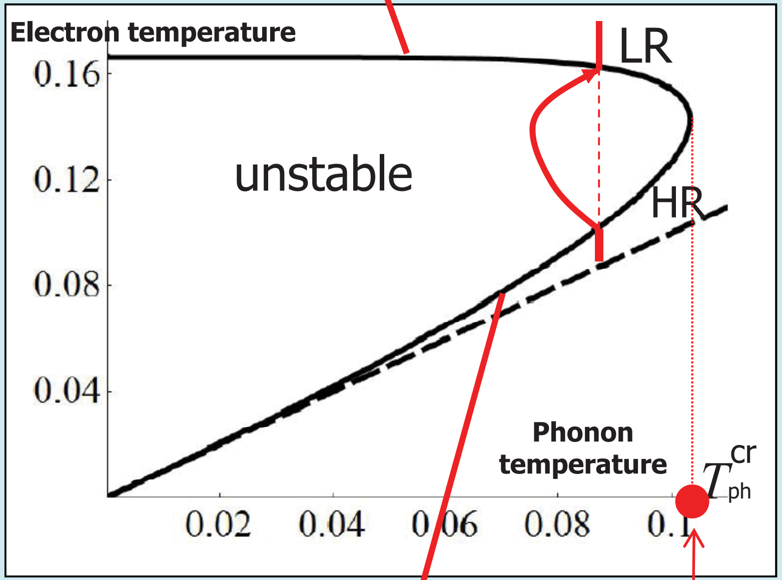
$$t \equiv \frac{T}{\Delta}\,, \qquad v \equiv \frac{V}{V_0}\,,$$

$$\frac{eV_0}{L} \equiv \frac{\alpha k_{\mathrm{F}} \Delta^3}{\Delta_0^2}\,, \qquad \Delta_0 \equiv (\rho v_{\mathrm{s}}^5 \hbar^3)^{1/4}\,, \qquad \alpha \equiv \frac{2\pi^2}{\sqrt{315}} \approx 1.1$$

Heat balance depends ONLY on electron density (k_F), the Arrhenius pseudo-gap Δ and the `material' energy Δ_0

Critical temperature and voltage

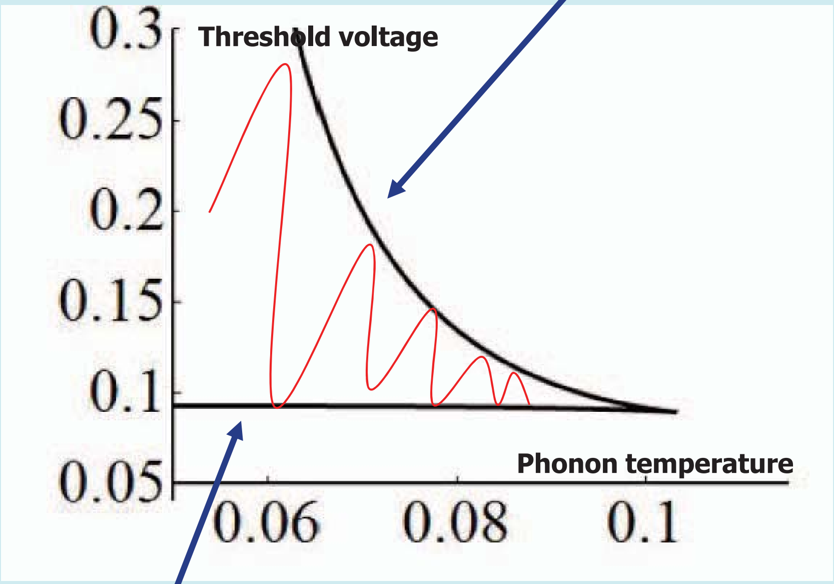
Minimal temperature of the hot (LR) state is 0.14 Δ



Maximal temperature of the cold (HR) state is close to the bath temperature

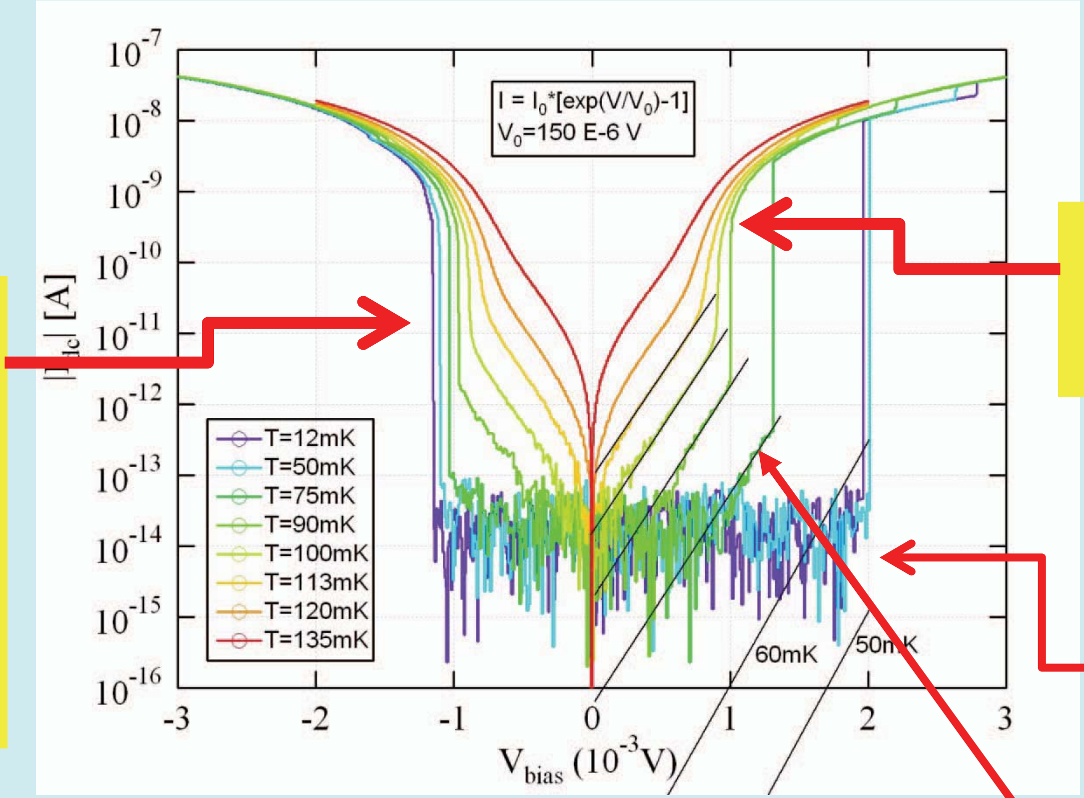
Critical bath temperature T_{ph} depends only on Δ

Threshold voltage of the cold (HR) state is strongly *T*-dependent



Threshold voltage for the hot (LR) state is almost independent of T_{bath}

Compare to the newest data



Threshold voltage for the hot (LR) state is almost independent of T_{bath}

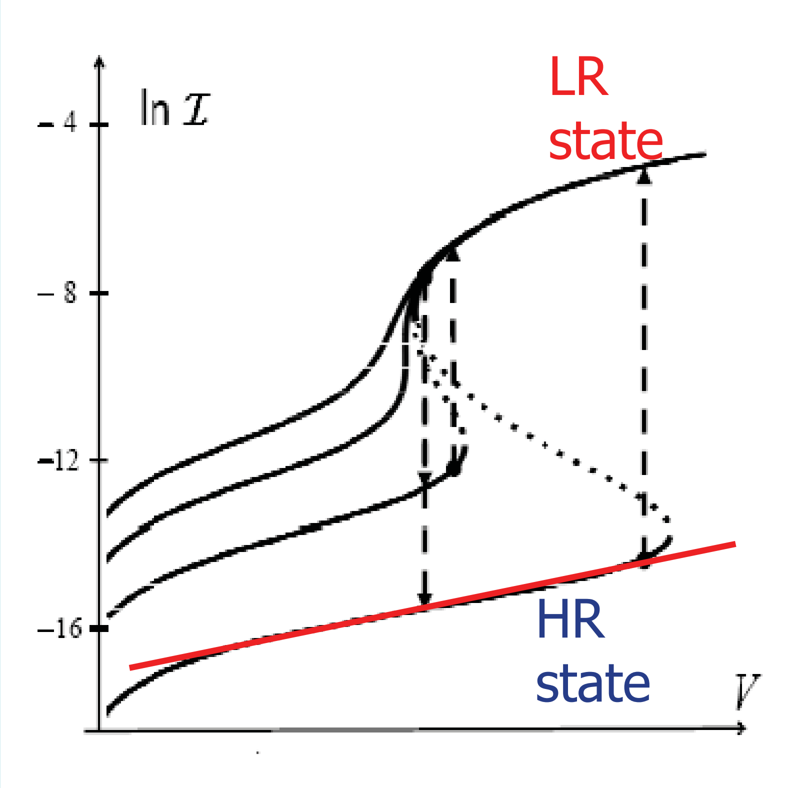
Threshold voltage of the cold (HR) state is strongly T-dependent

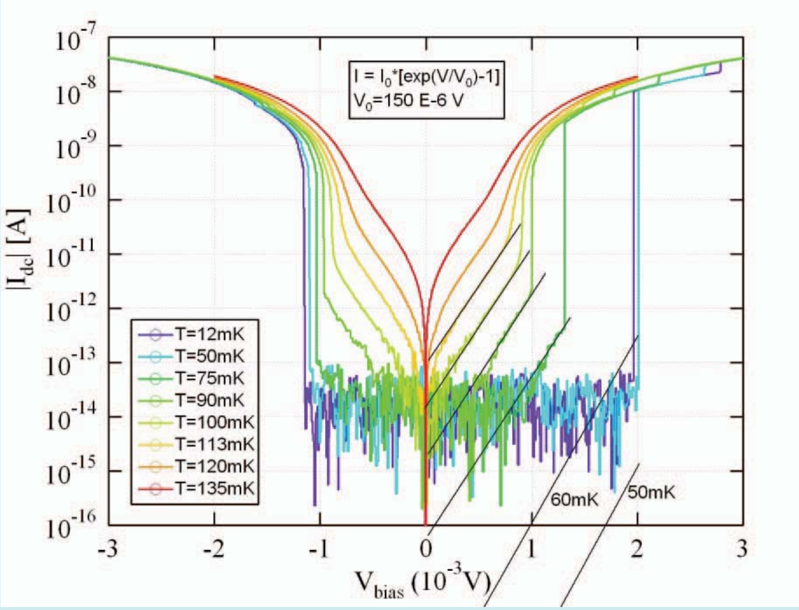
Higher R are unmeasurable due to noise

M.Ovadia, B.Sacepe, D.Shahar,
InO film (PRL,'09)

Non-zero almost exponential conductance: the insulator is not ideal

Nonlinear I-V characteristics

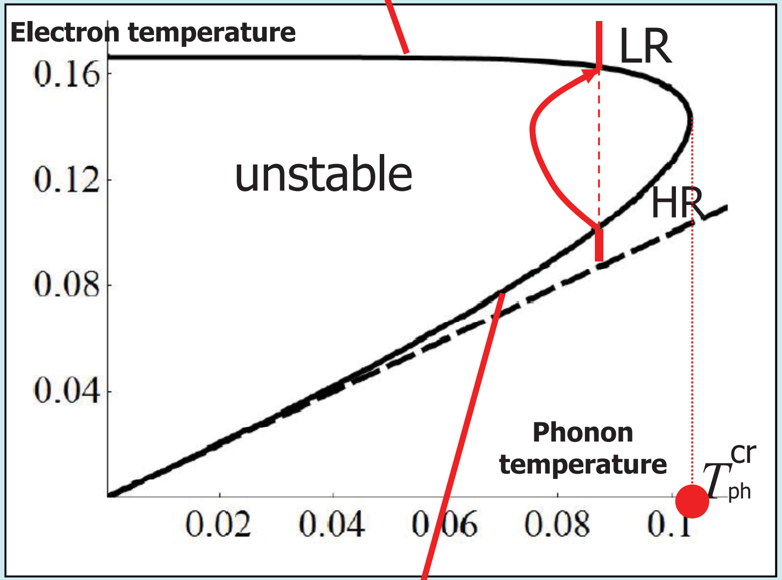




- ❖ Current jumps of several orders of magnitude
- ❖ Wide range of almost exp behavior in the HR state

Bistability temperature

Minimal temperature of the hot (LR) state is 0.14 Δ



Maximal temperature of the cold (HR) state is close to the bath temperature

Experimental bistability diagram (Ovadia, Sasepe, Shahar, 2009)

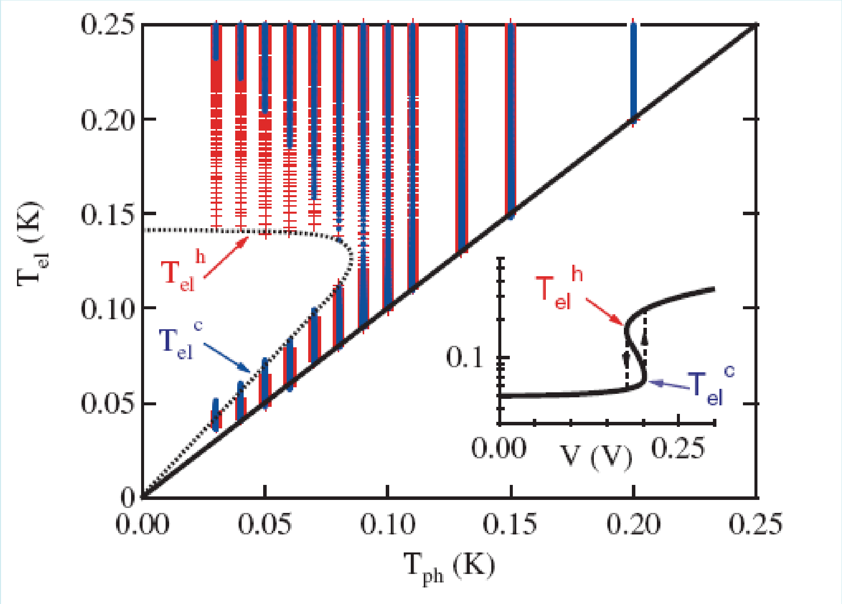


FIG. 3 (color online). T_{el} versus T_{ph}, showing the excluded region of temperatures which appears below $T_{ph} = 0.1$ K, and the accompanying hysteresis. Blue (dark gray) circles correspond to data measured while increasing $|V|$ and red (gray) crosses represent data taken while decreasing $|V|$. Inset:

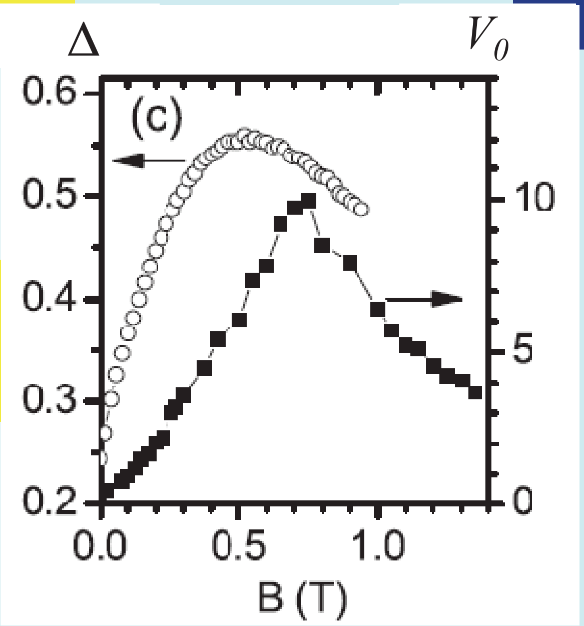
Quantitative comparison

$$\frac{eV_{\rm hot}^{\rm cr}}{L} \equiv \frac{0.1k_{\rm F}\Delta^3}{\Delta_0^2}, \quad T_{\rm ph}^{\rm cr} = 0.1\Delta\,, \quad \Delta_0 \equiv (\rho v_{\rm s}^5 \hbar^3)^{1/4}$$

Theoretical estimates:
V=0.8 mV & T_{ph}^{cr}=190mK
for Δ=1.9K

Experimental data:
V=1.0 mV & T_{ph}^{cr}=120mK
for Δ=1.9K

Reasonable agreement in a wider range of Δ for TiN



Baturina et al, 2007

Beyond Arrhenius and $\tau_{\text{e-ph}}$

$$R(T) = R_0 \exp\left[(\Delta/T)^\gamma\right], \qquad \frac{V^2}{R(T_{\mathrm{el}})} \propto T_{\mathrm{el}}^\beta - T_{\mathrm{ph}}^\beta$$

Critical phonon temperature $t_{\text{ph}}^{\text{cr}} = T_{\text{ph}}^{\text{cr}}/\Delta$

$$t_{\mathrm{ph}}^{\mathrm{cr}} = (1+\beta/\gamma)^{-\frac{\beta+\gamma}{\gamma\beta}} = \begin{cases} 0.1 & \gamma = 1,\ \beta = 6 \\ 0.004 & \gamma = \frac{1}{2},\ \beta = 6 \\ 1.5 \cdot 10^{-6} & \gamma = \frac{1}{4},\ \beta = 6 \end{cases}$$

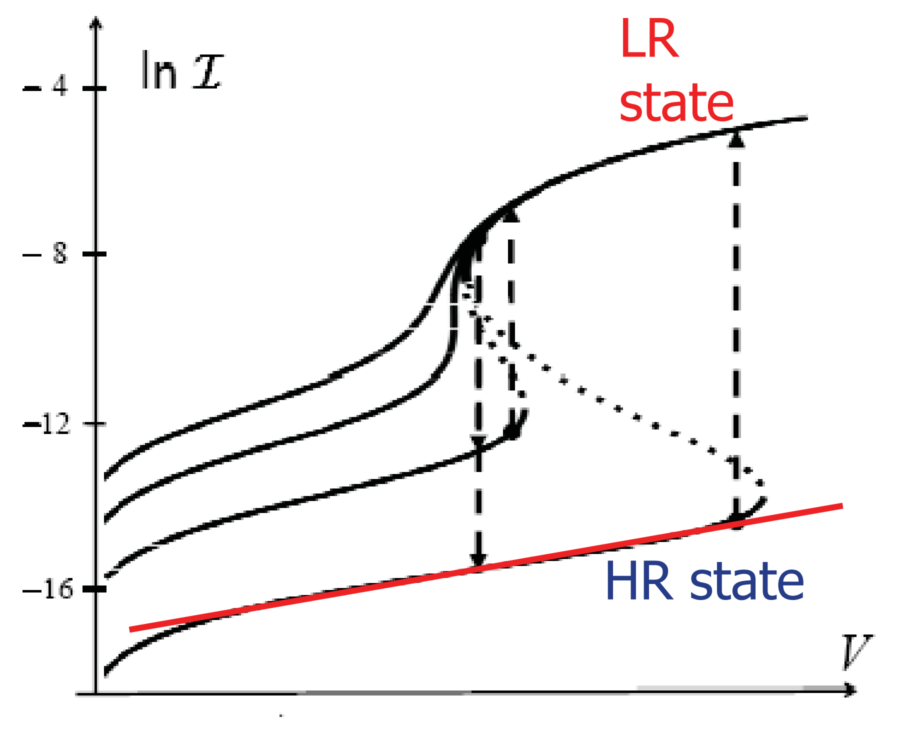
Scaling of the threshold voltage:

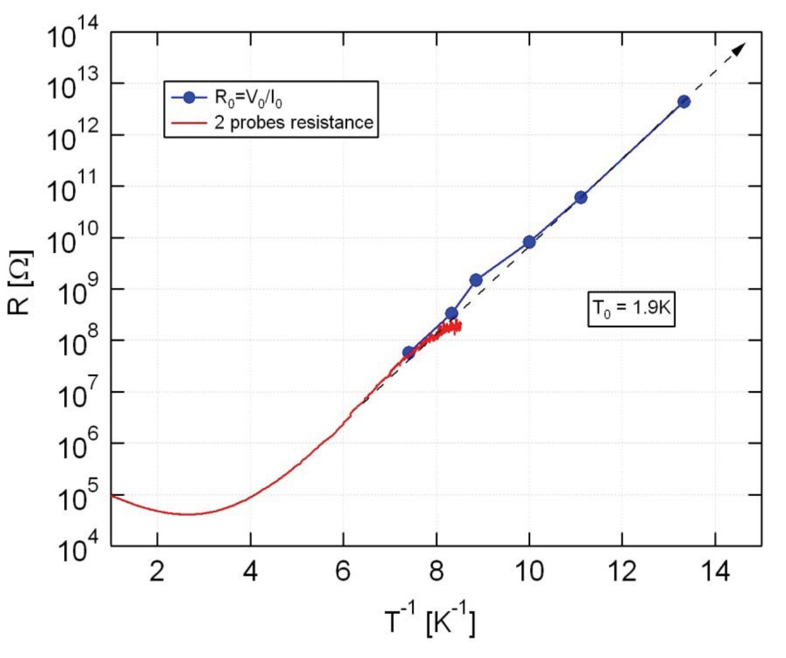
$$V_{\mathrm{LH}}/\Delta^\beta = f(T_{\mathrm{ph}}/\Delta)\,.$$

Not all experimental features captured

What is not quantitatively good: $I_{max}/I_{min}<e$ in the HR state;

Experimentally this ratio is $10 \div 20$; cannot be cured by any γ or β





$$\ln\frac{I}{I_0} = \frac{V}{V_0}, \qquad \frac{V_0}{I_0} \approx 2R_0$$

Kapitza resistance?

- *A priori,* it is possible that a disordered film is overheated with respect to a substrate due to ***Kapitza resistance*** caused by acoustic or diffusive mismatch of phonons in the film and in the bulk

$$\frac{V^2}{R(T_{\rm el})} = \frac{\Omega(T_{\rm el}) - \Omega(T_{\rm ph})}{\tau_{\rm K}}, \quad \Omega \simeq \frac{\mathcal{V}T^3}{\hbar^3 v_s^3} \times \max\left(T, \frac{\hbar v_s}{d}\right), \quad \tau_K = \frac{d}{v_s D}$$

- However, this would give wrong (compared to experiment) T-dependence, no dependence on magnetic field, and requires the boundary transparency D to be unrealistically low: $D<10^{-5}$, whereas

$$D = \frac{4Z_1 Z_2}{(Z_1+Z_2)^2} > 10^{-2}$$ even for artificially mismatched solids

($Z=v_s\rho$ is the acoustic impedance)

Is e-ph overheating too mundane?

- ❑ Not usually happens on the insulating side, i.e. at $R \ll h/e^2$
- ❑ Never was looked after as it is in contradiction to the picture of phonon-assisted hopping
- ❑ “Checked for” and vigorously denied in YSi and magnetite
- ❑ Signals new physics and requires a new approach to electron-assisted hopping at low T

Summary

- Electrons overheating due to inefficient cooling and the resulting current bistability leads to giant current jumps
- Good qualitative agreement with experiment without fitting parameters
- A microscopic description of hopping electron transport in the absence of thermalization with phonons is wanted
- Good super-insulator? – this particular hypothesis is not required for explaining experimental data…