Сверхпроводимость и квантовые явления в нанопроволоках

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Acknowledgments

Experiment:

A. T. Bollinger – PhD 2005; now at BNL
A. Rogachev – former postdoc; now at Utah Univ.
M.-Ho Bae – postdoc at UIUC
T. Aref – PhD 2010; now postdoc in Pekola group, Finland
D. Hopkins – PhD 2006; now at LAM research
R. Dinsmore – PhD 2009; now at Intel
M. Sahu – PhD 2009; now at Intel
M. Brenner – grad student
A. Belkin – postdoc

Theory:

P. Goldbart; A. Levchenko; N. Shah; T. C. Wei; D. Pekker; V. Vakaryuk

Outline

- Motivation:

(a) Understanding the origins of the dissipation in nanowires

(b) Little's phase slips

(c) Macroscopic quantum tunneling (MQT)

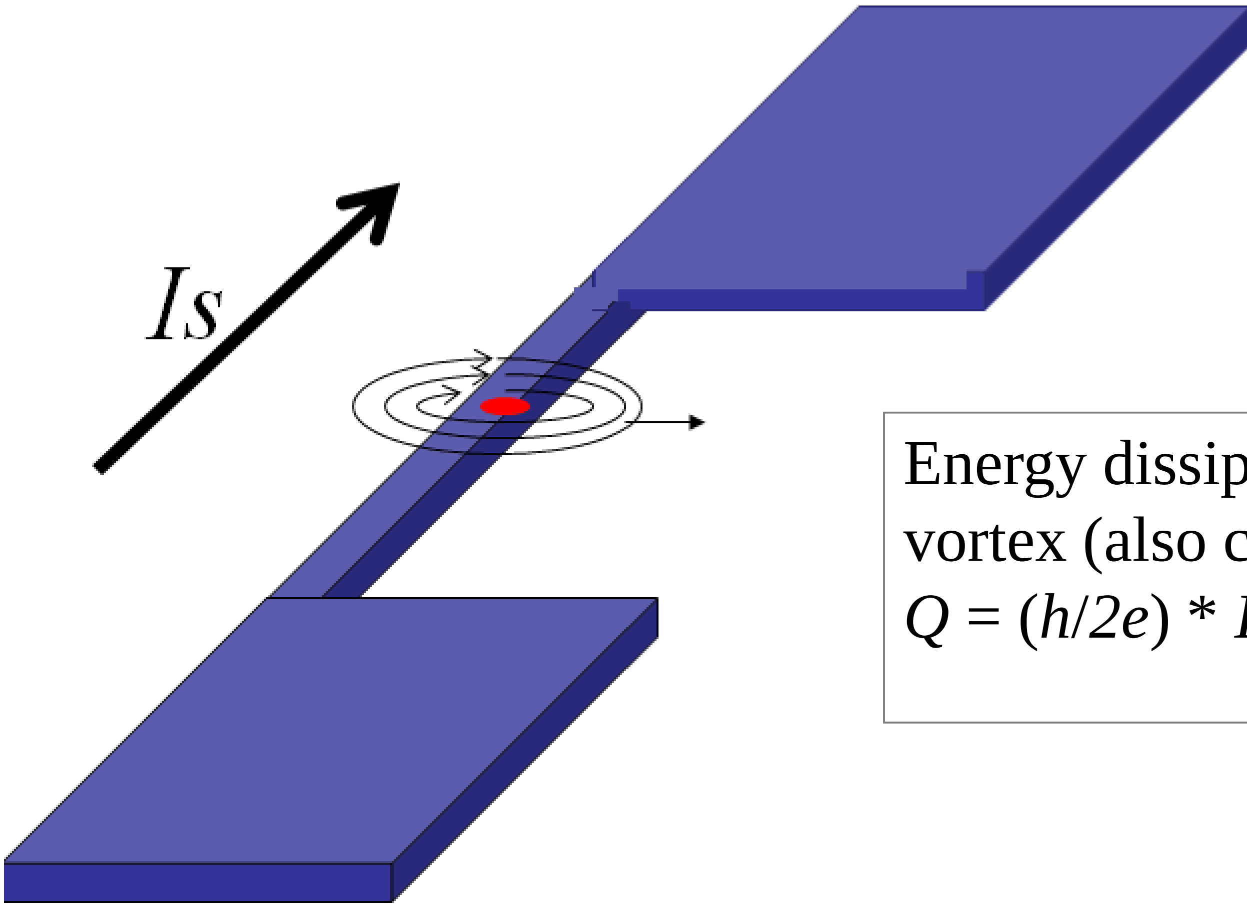
(d) Kurkijarvi process and the switching dispersion power law dependence of temperature

(e) Switching current as a probe for the phase slip effect

(f) Conclusions

Our nanowire sample schematic.

-Vortices can cross the thin wire.
-Vortices are powered by fluctuation, either thermal or quantum.
-Vortices disrupt the flow of the supercurrent *Is* and generate nonzero resistance.

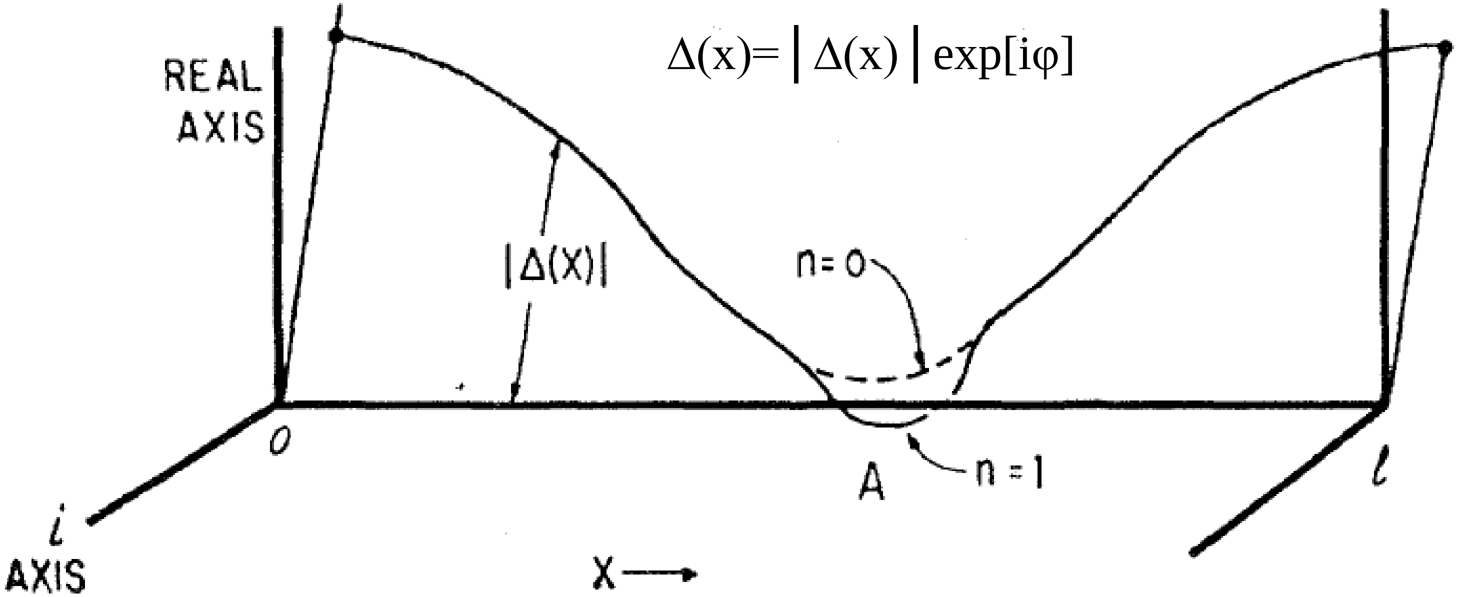


Energy dissipated by one crossing vortex (also called phase slip) is
$Q = (h/2e) * Is$

Little's Phase Slip (LPS)

LPS is the only intrinsic mechanism for the dc supercurrent decay in quasi-1D superconducting wires

$$\Delta(x) = |\Delta(x)| \exp[i\varphi]$$



William A. Little,
"Decay of persistent currents in small superconductors",
Phys. Rev., **156**, 396 (1967).

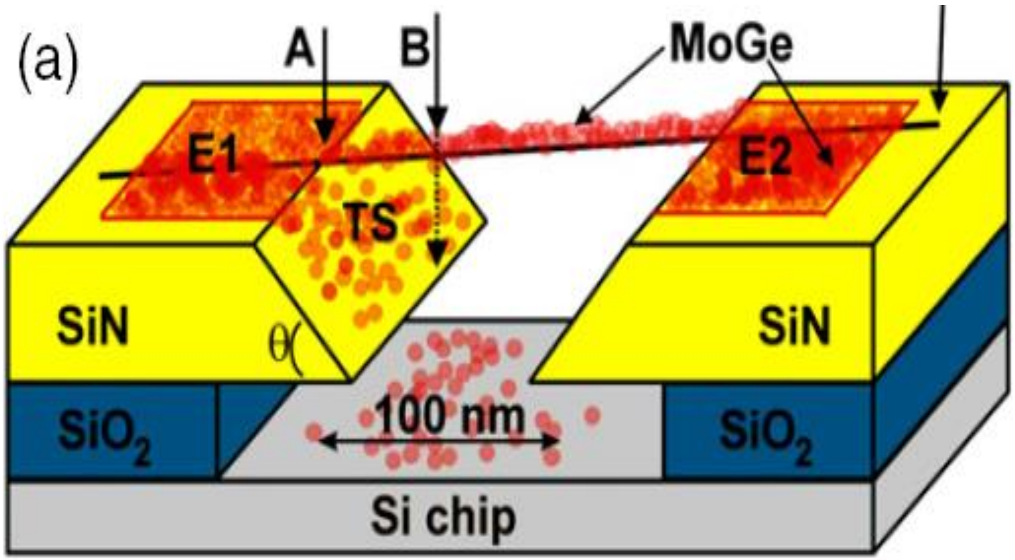
Energy barrier for phase slip: $\Delta F = (8\sqrt{2}/3)(H_c(T)^2/8\pi)(A\xi(T))$

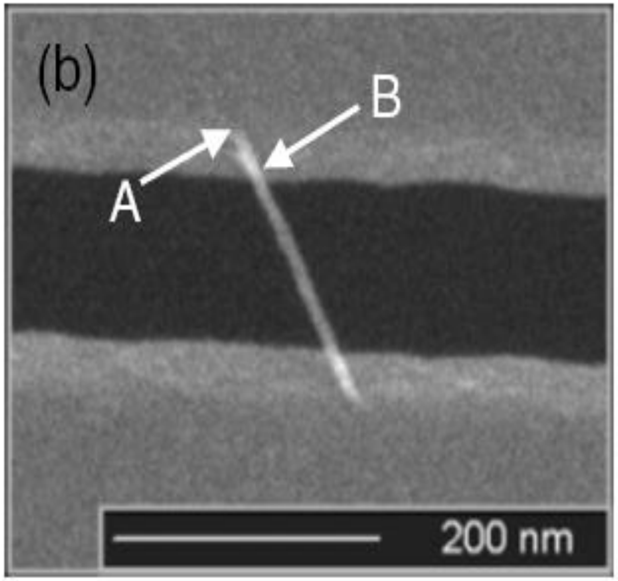
Rate of phase slips: $\Gamma \sim \exp(-\Delta F/kT)$

QPS=MQT

Fabrication of nanowires

Method of Molecular Templating





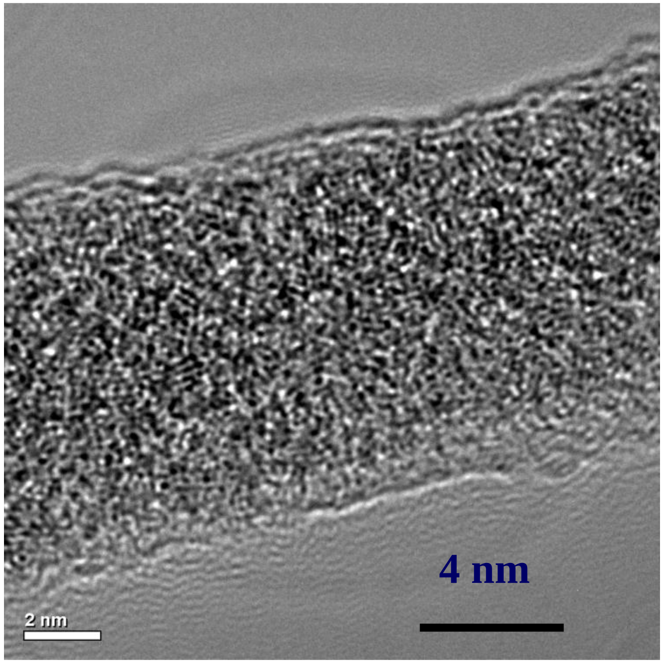
Si/ SiO_2/SiN substrate with undercut

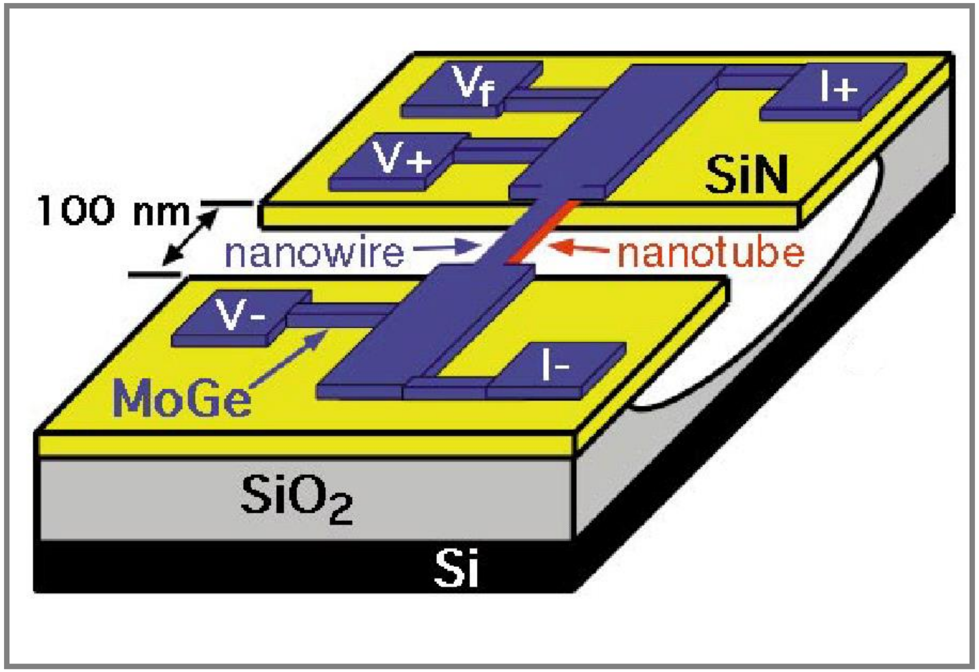
~ 0.5 mm Si wafer
500 nm SiO_2
60 nm SiN
Width of the trenches ~ 50 - 500 nm

HF wet etch for ~10 seconds to form undercut

Bezryadin, Lau, Tinkham, *Nature* **404**, 971 (2000)

Sample Fabrication





TEM image of a wire shows amorphous morphology.
Nominal MoGe thickness = 3 nm

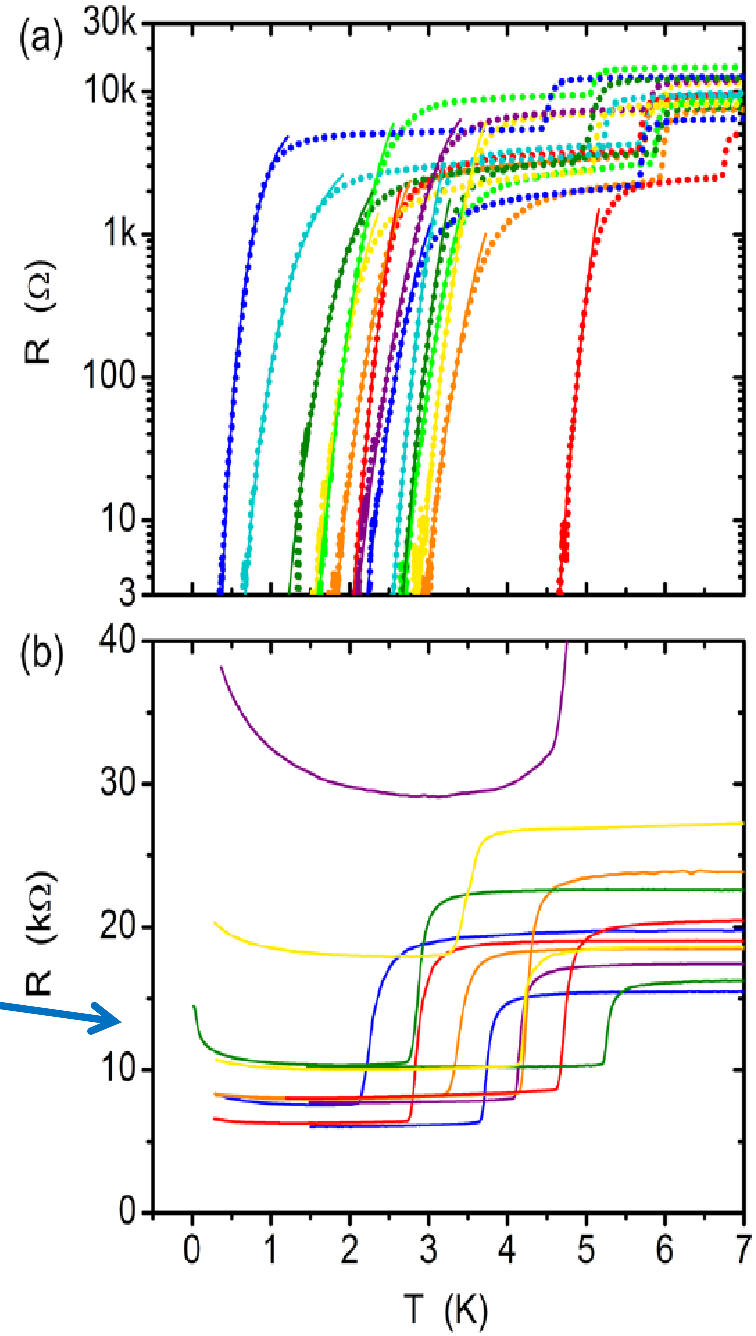
Schematic picture of the pattern
Nanowire + Film Electrodes used in
transport measurements

Dichotomy in nanowires: Evidence for superconductor-insulator transition (SIT)

R=V/I I~3 nA

The difference between samples is the amount of the deposited Mo79Ge21.

$$R_{\text{square}} = 100 - 400\,\Omega$$

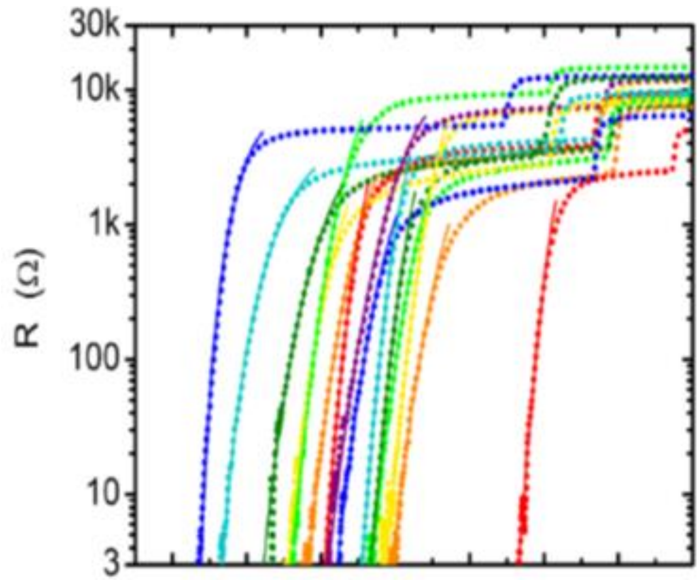


Bollinger, Dinsmore, Rogachev, Bezryadin,
Phys. Rev. Lett. **101**, 227003 (2008)

Useful Expression for the Free Energy of a Phase Slip

Arrhenius-type activation-law formula for the wire resistance:

$$R_{AL} \approx R_N \, exp[-\Delta F(T)/k_B T]$$



$$\Delta F = (8\sqrt{2}/3)(H_c(T)^2/8\pi)(A\xi(T))$$

$$\frac{\Delta F(0)}{k_B T_c} = \sqrt{6}\,\frac{\hbar I_c(0)}{2ek_B T_c} = 0.83\,\frac{R_q L}{R_n \xi(0)} = 0.83\,\frac{R_q}{R_{\xi(0)}}$$

APPLIED PHYSICS LETTERS VOLUME 80, NUMBER 16 22 APRIL 2002

Quantum limit to phase coherence in thin superconducting wires

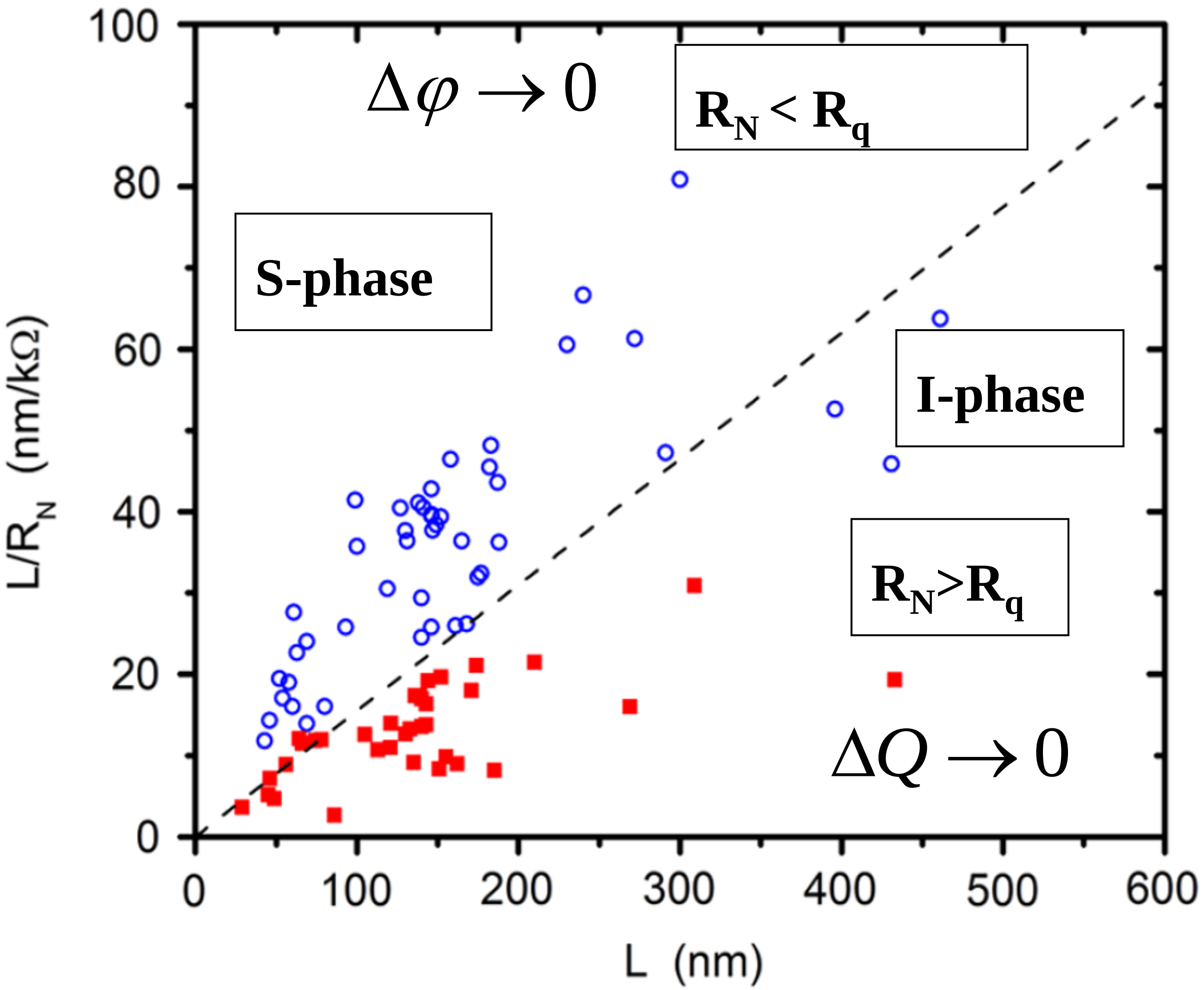
M. Tinkham[a)] and C. N. Lau

Physics Department, Harvard University, Cambridge, Massachusetts 02138

Superconductor-Insulator Transition (SIT)

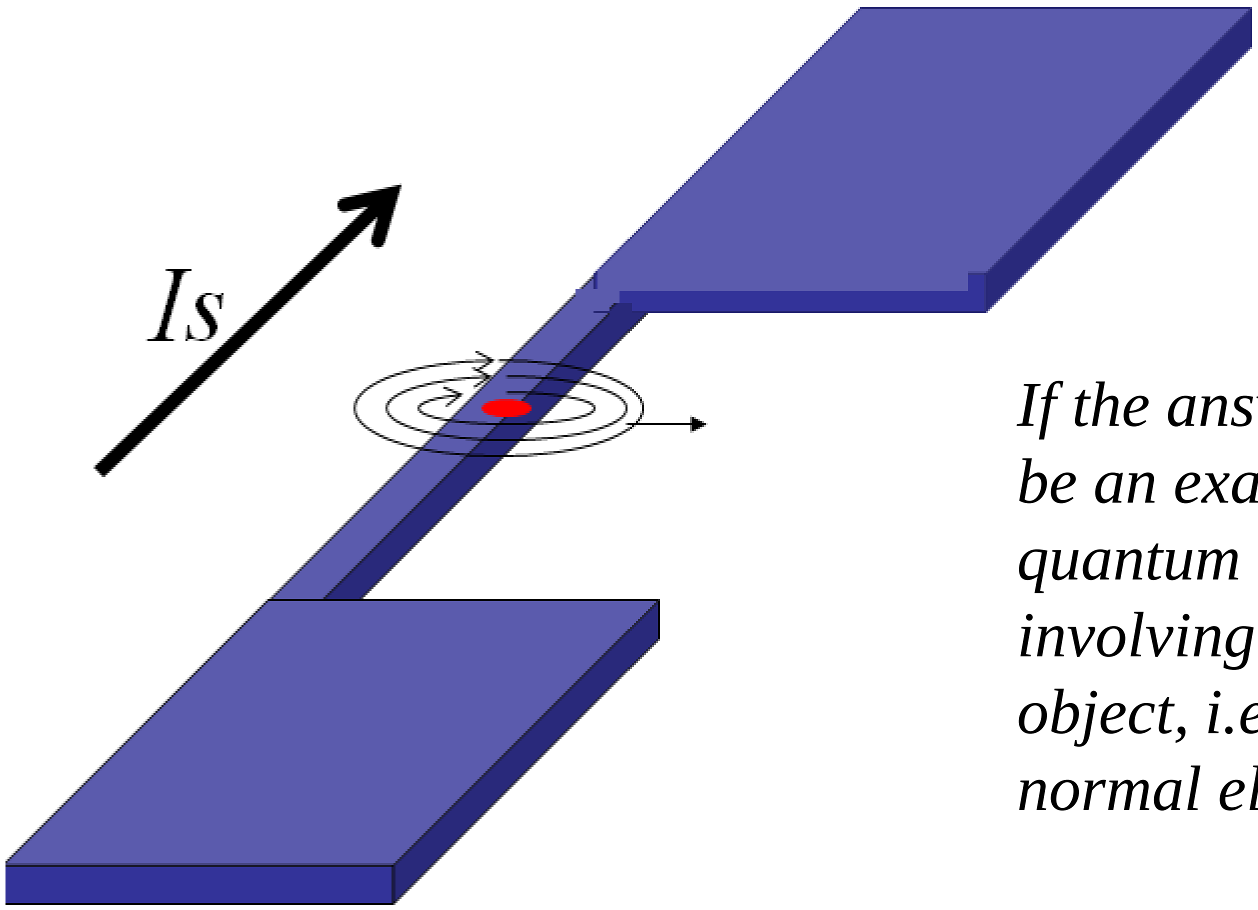
$R_q = (h/4e^2) = 6.45\ k\Omega$

Possible qualitative origin of the SIT is the Heisenberg uncertainty principle: $\Delta\varphi\Delta Q \sim e$



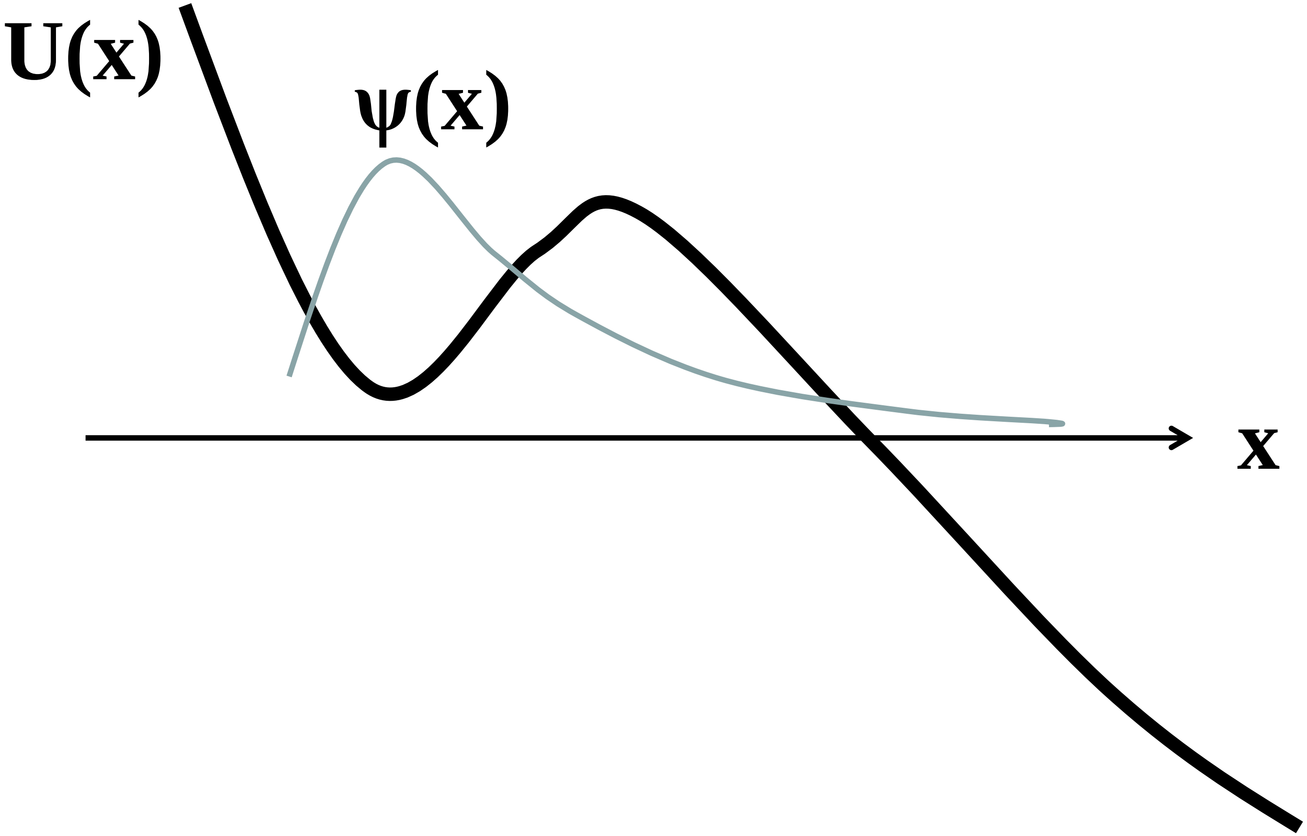
A. Bollinger, R. Dinsmore, A. Rogachev and A. Bezryadin, *Phys. Rev. Lett.* **101**, 227003 (2008)

Each crossing vortex transitions the wire from a state with a higher supercurrent to a state with a lower supercurrent.
Can such transition be accomplished by means of quantum tunneling?



If the answer is yes, this would be an example of macroscopic quantum tunneling (MQT), involving a rather large object, i.e., a vortex with many normal electrons in the core

Quantum tunneling requires quantum superposition of states localized at various locations



Leggett's prediction for macroscopic quantum tunneling (MQT) in SQUIDs

80 Supplement of the Progress of Theoretical Physics, No. 69, 1980

Macroscopic Quantum Systems and the Quantum Theory of Measurement

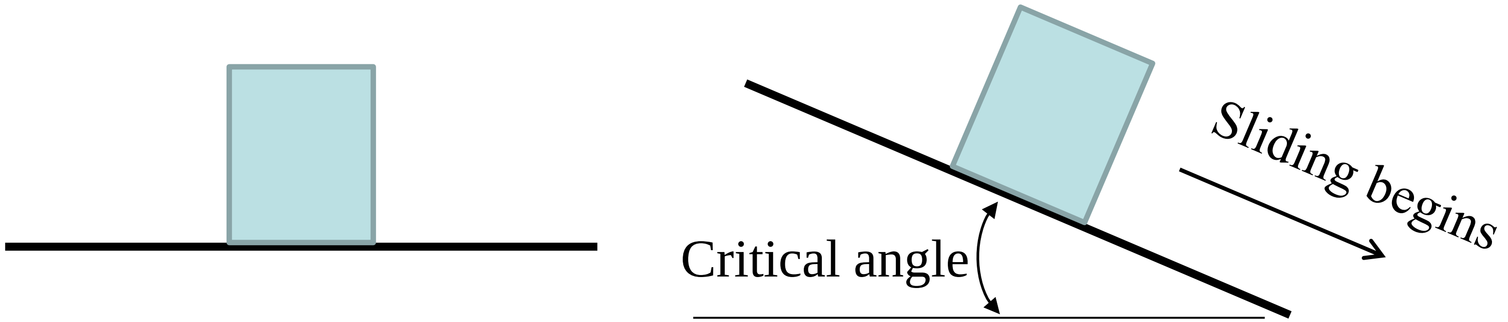
A. J. LEGGETT

School of Mathematical and Physical Sciences
University of Sussex, Brighton BN1 9QH

It is this property which makes a SQUID the most promising candidate to date for observing macroscopic quantum tunnelling; if it should ever become possible to observe macroscopic quantum *coherence*, the low entropy and consequent lack of dissipation will be absolutely essential.[21)]

Kurkijärvi approach provides means to study MQT

Tilt the plane slow and measure the critical sliding angle. Repeat the measurement many times and determine the standard deviation (sigma) of the critical sliding angle. The distribution of the critical angles can be converted into the switching rate.



PHYSICAL REVIEW B VOLUME 6, NUMBER 3 1 AUGUST 1972

Intrinsic Fluctuations in a Superconducting Ring Closed with a Josephson Junction

Juhani Kurkijärvi

Laboratory of Atomic and Solid State Physics, School of Applied and Engineering Physics, Cornell University, Ithaca, New York

(Received 22 March 1972)

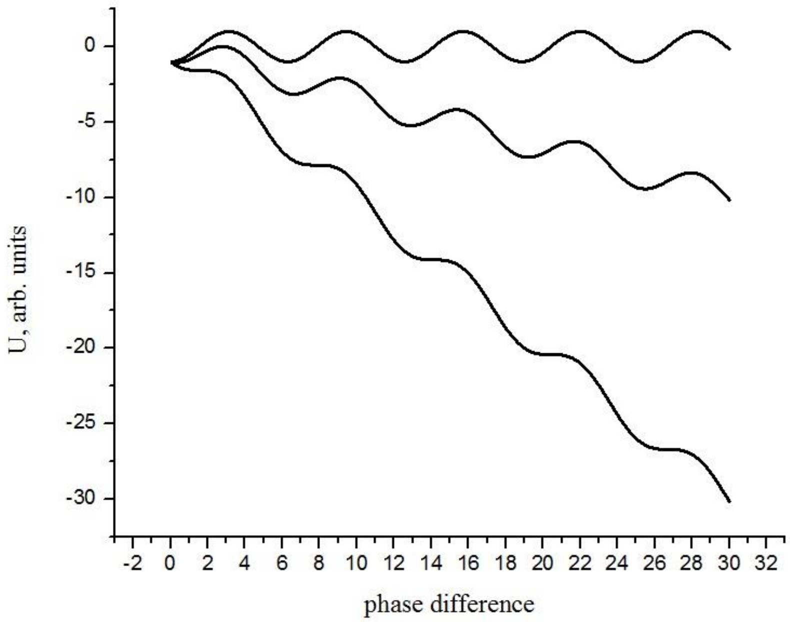
The distribution in the external flux at which a superconducting ring closed with a weak link admits a quantum of flux is determined assuming that the weak link can be treated as a Josephson junction. We find that this transition occurs at an appreciable fraction of the flux quantum from the theoretical critical external flux. To a first approximation the width of the distribution is proportional to the inductance of the ring and varies as $T^{2/3}i_c^{-1/3}$, where T is the temperature and i_c the critical current.

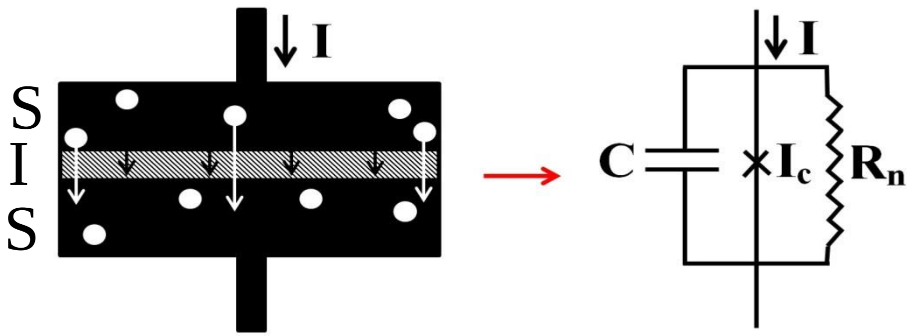
McCumber-Stewart model of a Josephson junction

$$C\left[\frac{\Phi_0}{2\pi}\right]^2\ddot{\delta}+\frac{1}{R}\left[\frac{\Phi_0}{2\pi}\right]^2\dot{\delta}+\frac{\partial}{\partial\delta}\left[-\frac{I_0\Phi_0}{2\pi}\cos\delta-\frac{I\Phi_0}{2\pi}\delta\right]-\frac{\Phi_0}{2\pi}I_N(t)=0\ , \qquad (2.1)$$

Equation (2.1) is also the equation of motion of particle of mass $C(\Phi_0/2\pi)^2$ moving in the one-dimensional (1D) potential

$$U(\delta)=-(I_0\Phi_0/2\pi)[\cos\delta+(I/I_0)\delta]\ .$$





Zoom-in on one minimum. The phase particle needs to escape "prematurely" in order to give nonzero fluctuations of the switching current

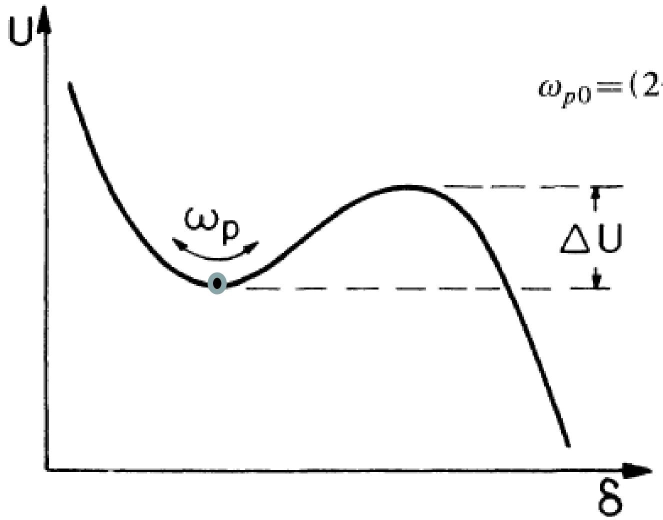


FIG. 2. Potential well from which particle escapes.

$\omega_{p0}=(2\pi I_0/\Phi_0 C)^{1/2}$ $\omega_p=\omega_{p0}[1-(I/I_0)^2]^{1/4}$ $Q=\omega_p RC$

Thermal escape- Arrhenius Law:

$$\Gamma_t=a_t(\omega_p/2\pi)\exp(-\Delta U/k_B T) \ ,$$

the presence of a moderate level of dissipation, Caldeira and Leggett[4] have shown that for a cubic potential[24]

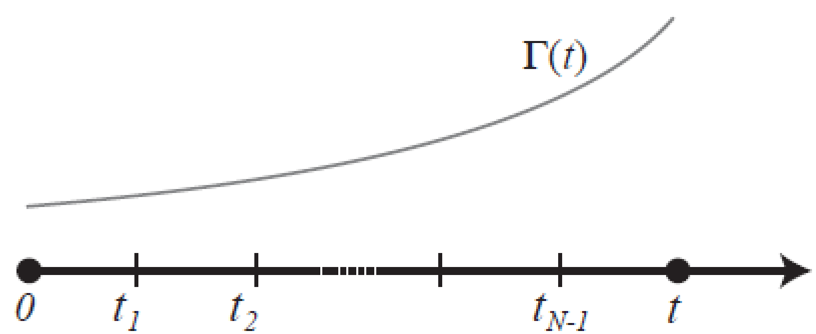
$$\Gamma_q=a_q\frac{\omega_p}{2\pi}\exp\left[-7.2\frac{\Delta U}{\hbar\omega_p}\left[1+\frac{0.87}{Q}+\cdots\right]\right] , \qquad (2.8)$$

where

$$a_q\approx[120\pi(7.2\Delta U/\hbar\omega_p)]^{1/2} . \qquad (2.9)$$

Characterization of the decay probabilities

- Probability of a decay in unit time (decay rate) is $\Gamma(t)$
- Probability w that the system hasn't decayed by time t is found by slicing the time interval:



$$w = (1 - \Gamma(t_1)dt)\,(1 - \Gamma(t_2)dt)\ldots(1 - \Gamma(t_N)dt)$$

$$w(t) = e^{-\int_0^t dt'\,\Gamma(t')}$$

- Probability of a decay between t and $t+dt$ (distribution function):

$$p(t) = \Gamma(t)\,e^{-\int_0^t dt'\,\Gamma(t')}$$

Experimentally measurable

Kurkijärvi theory for the switching current distribution width (1972)

PHYSICAL REVIEW B VOLUME 6, NUMBER 3 1 AUGUST 1972

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$$\Delta U = 2U_0\{[1-(I/I_0)^2]^{1/2} - (I/I_0)\cos^{-1}(I/I_0)\} \quad (I < I_0) \tag{2.2}$$

$$\simeq (4\sqrt{2}U_0/3)(1-I/I_0)^{3/2}, \quad [(I_0-I)/I_0 \ll 1]\,. \tag{2.3}$$

Kurkijarvi Power Law: $\sigma \sim T^{2/3}$

$$\sigma \propto (T/\Phi_0)^{2/3} I_c^{1/3}(T)$$

MQT report by Kurkijarvi and collaborators (1981)

VOLUME 47, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1981

Decay of the Zero-Voltage State in Small-Area, High-Current-Density Josephson Junctions

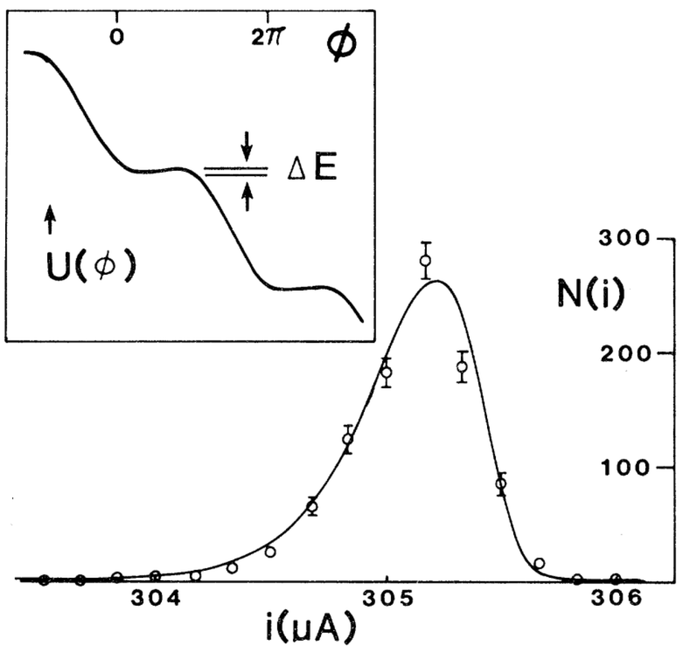


FIG. 1. Measured distribution for $T = 1.6$ K for small high-current-density junction. The solid line is a fit by the CL theory for $R = 20\ \Omega$, $C = 8$ fF, and $i_{cFF} = 310.5\ \mu$A. The inset is $U(\varphi)$ for $x = 0.8$ with barrier ΔE.

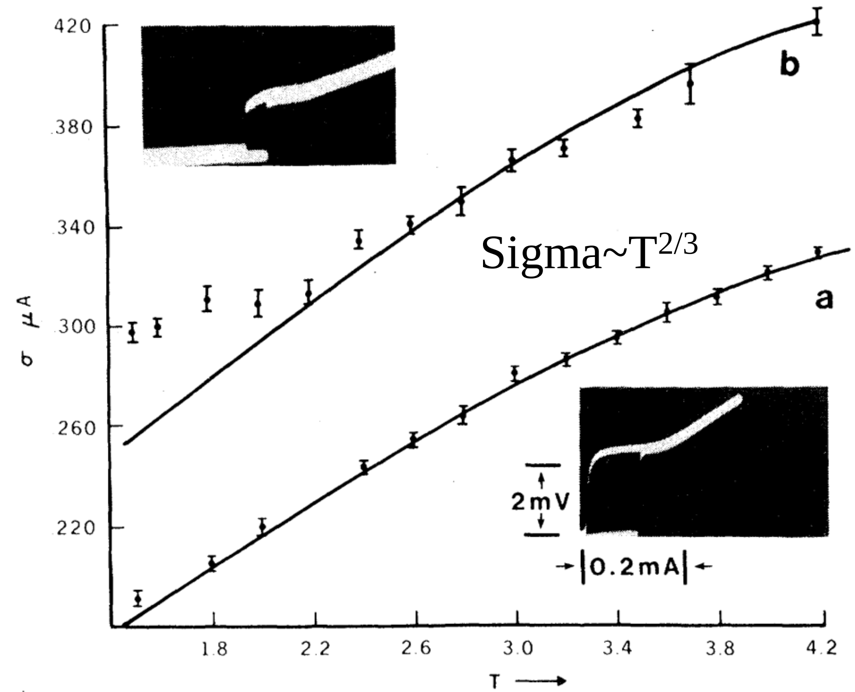
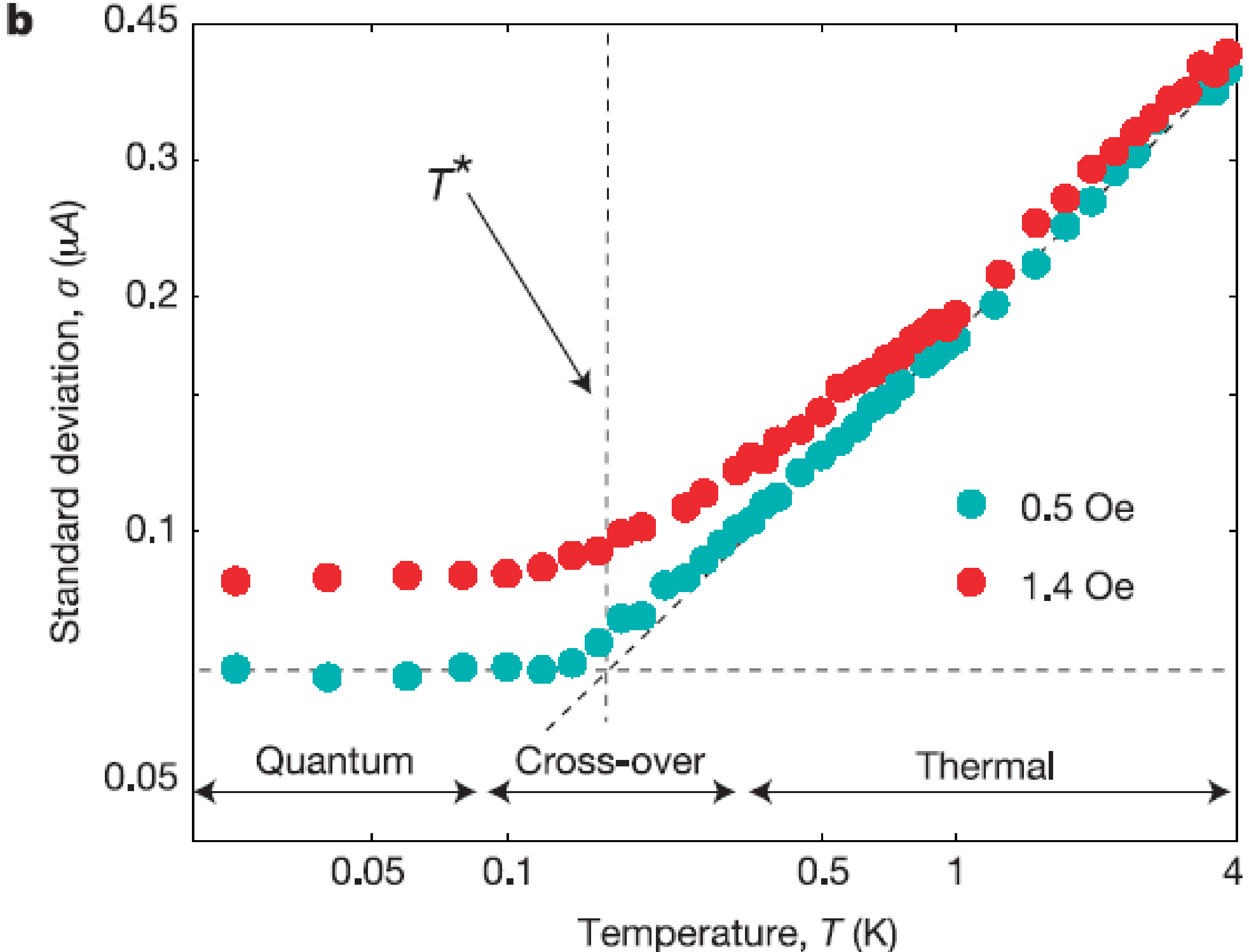


FIG. 2. Measured distribution widths σ vs T for two junctions with current sweep of ~400 μA/sec. Curve a is lower current density junction data and curve b is higher density junction data. The traces adjacent to the plots are the corresponding $I-V$ characteristics at 4.2 K. The scales are the same for both traces.

Kurkijarvi 2/3 power law for pinned versus moving vortex transition

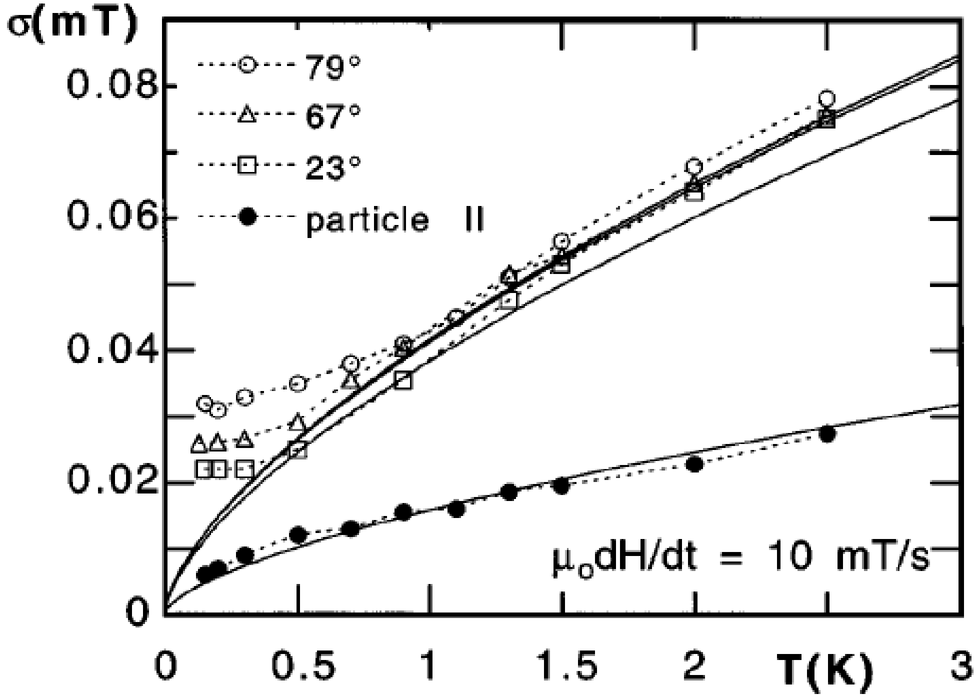
(Vortex escape experiments)



Power exponent = 0.66

A. Wallraff et al., *Nature* V.425, p.155 (2003)

Kurkijärvi 2/3 power law was confirmed also for the magnetic moment switching in nanoparticles

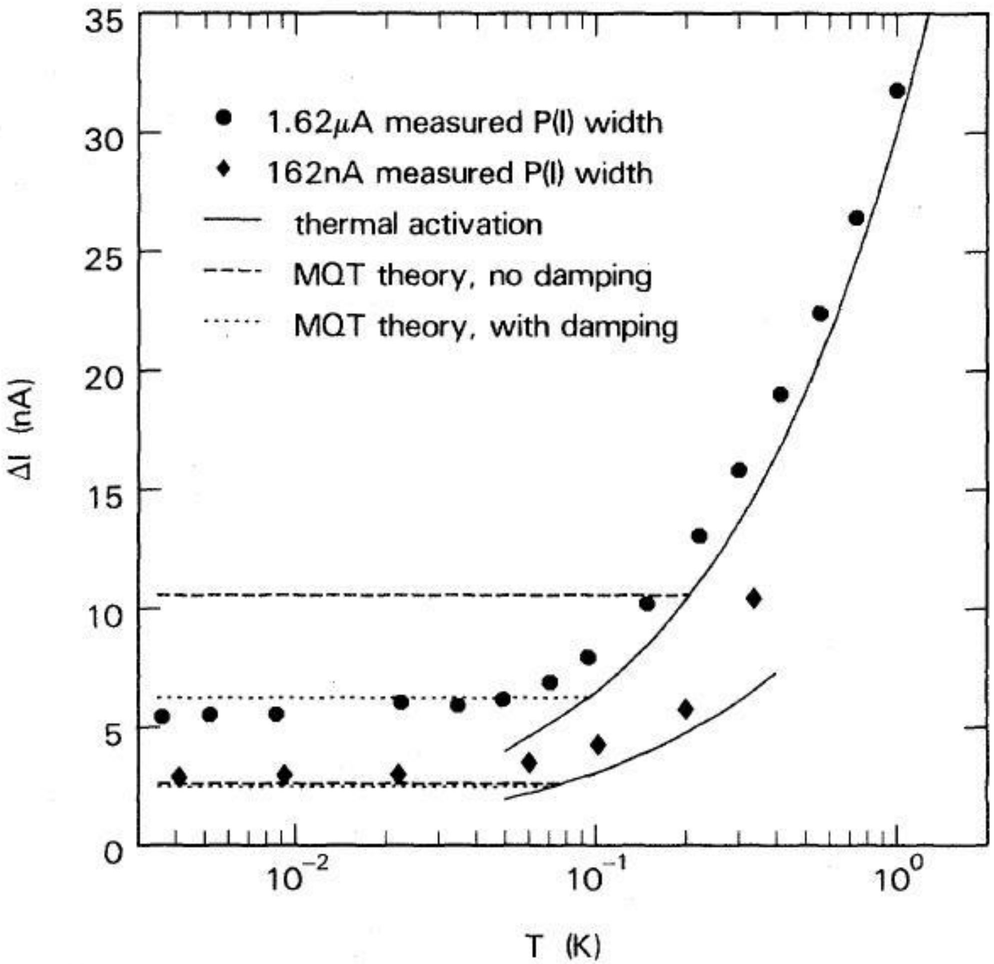


Power exponent = 0.66

FIG. 3. Temperature dependence of the width of the switching field distribution σ for $\mu_0 dH/dt = 10$ mT/s and at three different angles of the applied field for particle I of about $10^5 \mu_B$. Full points were measured on particle II of about $10^6 \mu_B$ at $\theta \approx 20°$. Lines: prediction of the Kurkijärvi model.

A. Wallraff et al., *Nature* V.425, p.155 (2003)

Voss and Webb: width of the switching current distribution vs. T

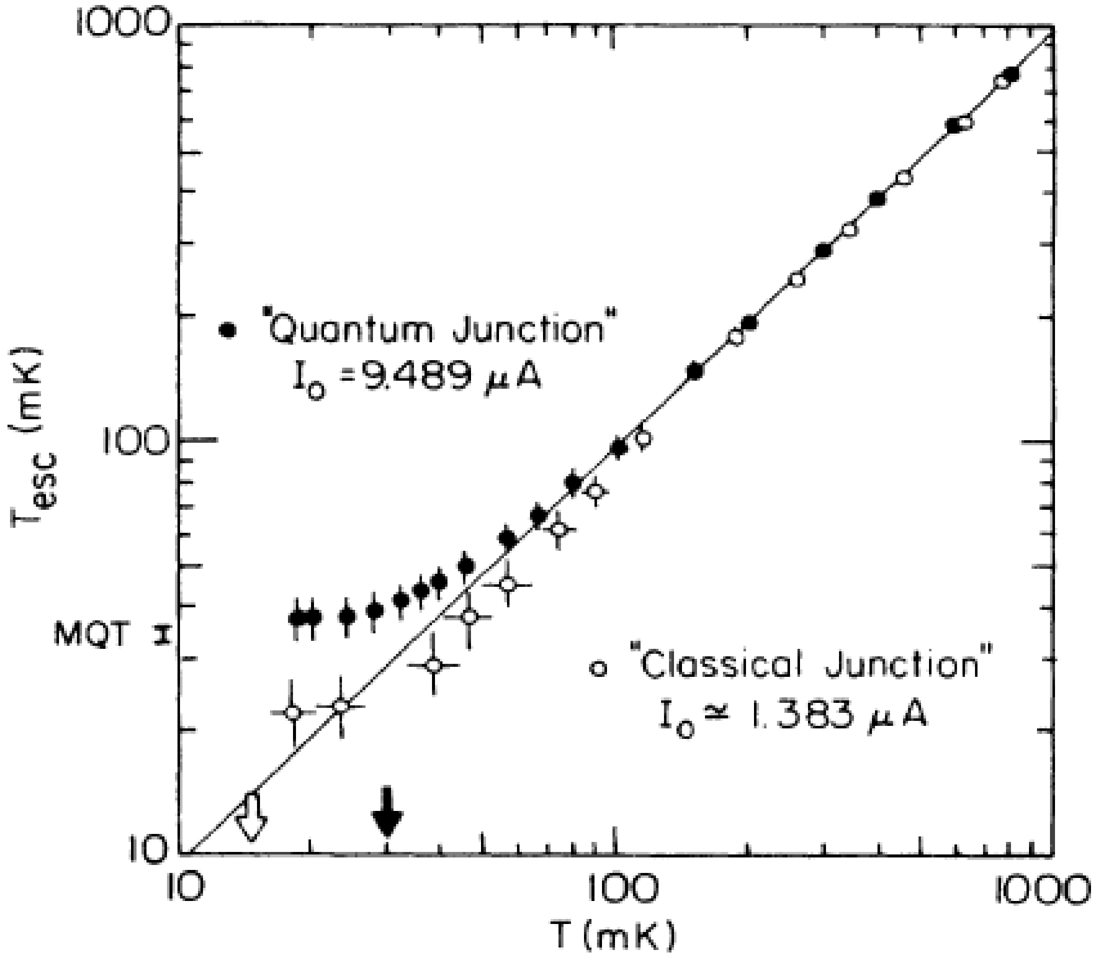


R. Voss and R. Webb
PRL **47**, 265 (1981)

Std. Dev. = σ =ΔI=
="width of the distribution"

FIG. 3. Measured $P(I)$ widths $\Delta I = \langle (I - \langle I \rangle)^2 \rangle^{1/2}$ vs T for the two junctions. Theoretical predictions for thermal activation and MQT rates with and without damping are also shown.

MQT observation by Martinis, Devoret and Clarke



$$\Gamma = (\omega_p/2\pi)\exp(-\Delta U/k_B T_{\mathrm{esc}})$$

Just for thermal escape:

$$\Gamma_t = a_t(\omega_p/2\pi)\exp(-\Delta U/k_B T) \;,$$

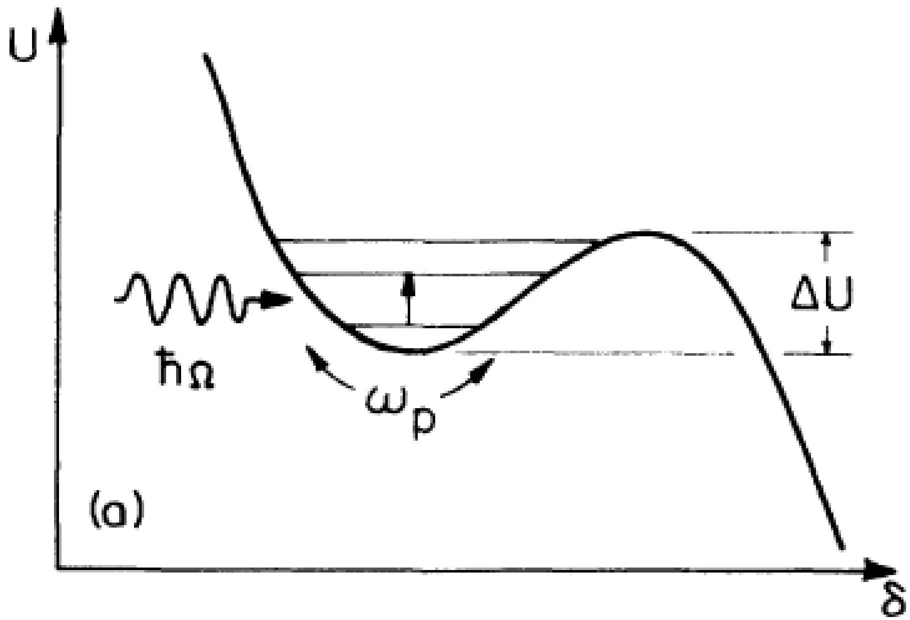
PHYSICAL REVIEW B VOLUME 35, NUMBER 10 1 APRIL 1987

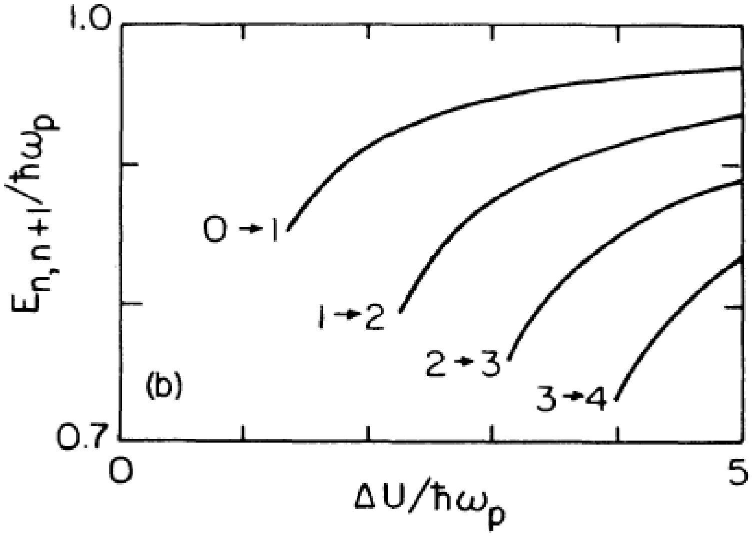
Martinis-Devoret-Clarke: definitive proof of MQT using microwaves

PHYSICAL REVIEW B VOLUME 35, NUMBER 10 1 APRIL 1987

Experimental tests for the quantum behavior of a macroscopic degree of freedom: The phase difference across a Josephson junction

John M. Martinis,* Michel H. Devoret,* and John Clarke





$$\omega_p = \omega_{p0}[1-(I/I_0)^2]^{1/4} \,, \tag{2.4}$$

and

$$\omega_{p0} = (2\pi I_0/\Phi_0 C)^{1/2} \,.$$

Martinis-Devoret-Clarke: results supporting MQT

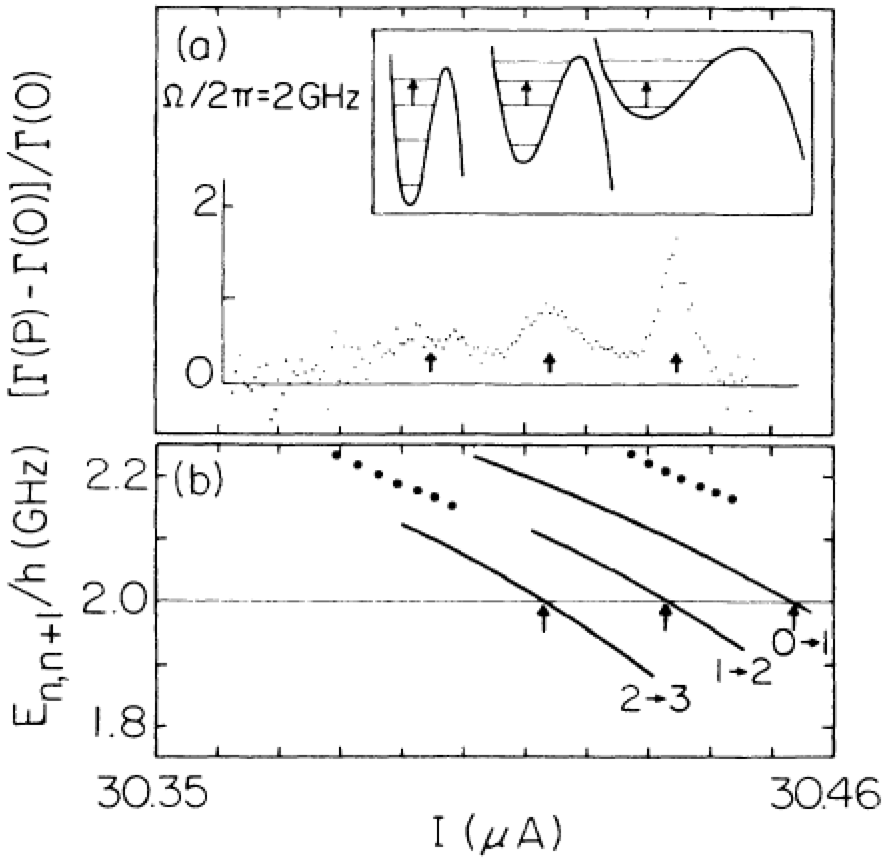
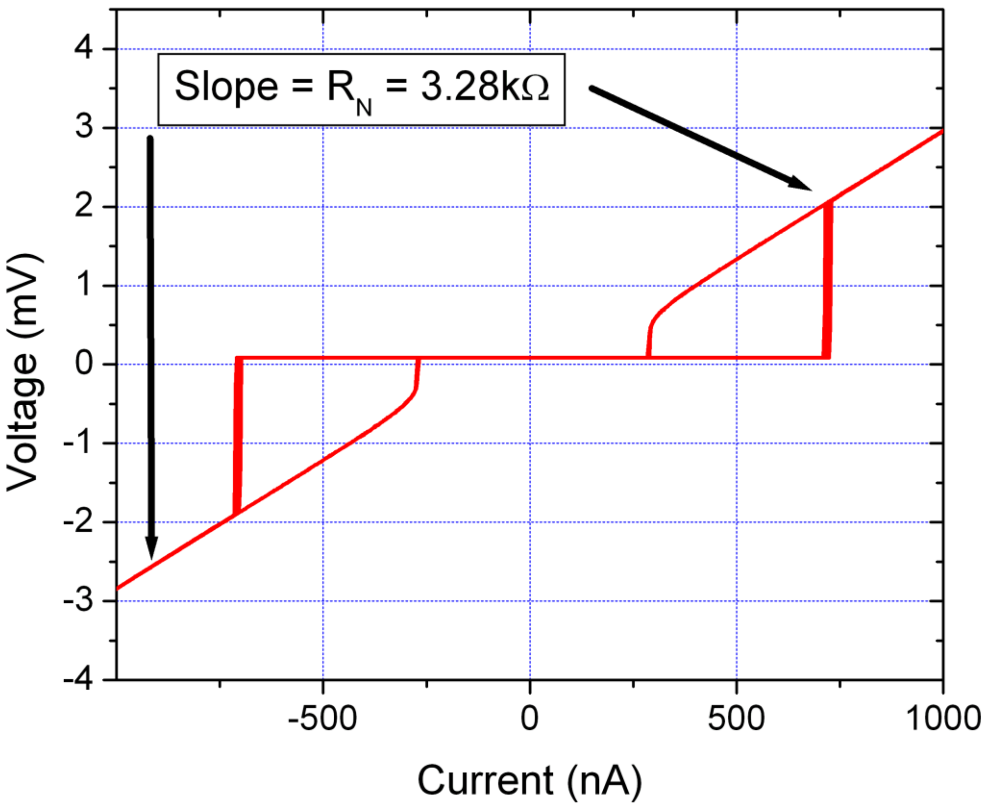
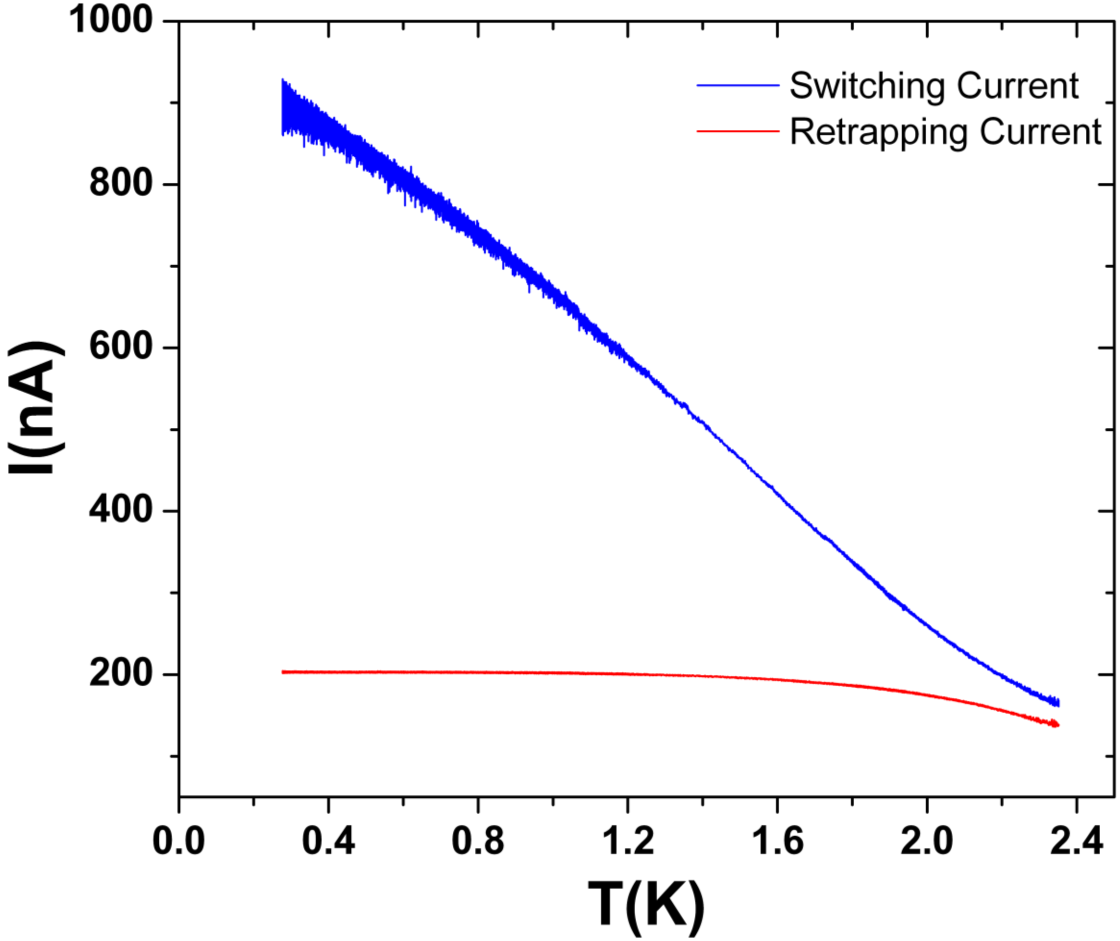


FIG. 17. (a) $[\Gamma(P)-\Gamma(0)]/\Gamma(0)$ vs I for a 80×10 μm^2 junction at 28 mK in the presence of 2.0 GHz microwaves ($k_B T/\hbar\Omega=0.29$). Arrows indicate positions of resonances. Inset represents the corresponding transitions between energy levels. (b) Calculated energy level spacings $E_{n,n+1}$ vs I for $I_0=30.572\pm0.017$ μA and $C=47.0\pm3.0$ pF. Dotted lines indicate uncertainties in the $0\rightarrow1$ curve due to uncertainties in I_0 and C. Arrows indicate values of bias current at which resonances are predicted.

V-I curves of our nanowire samples are similar to underdamped JJs, i.e., they are hysteretic

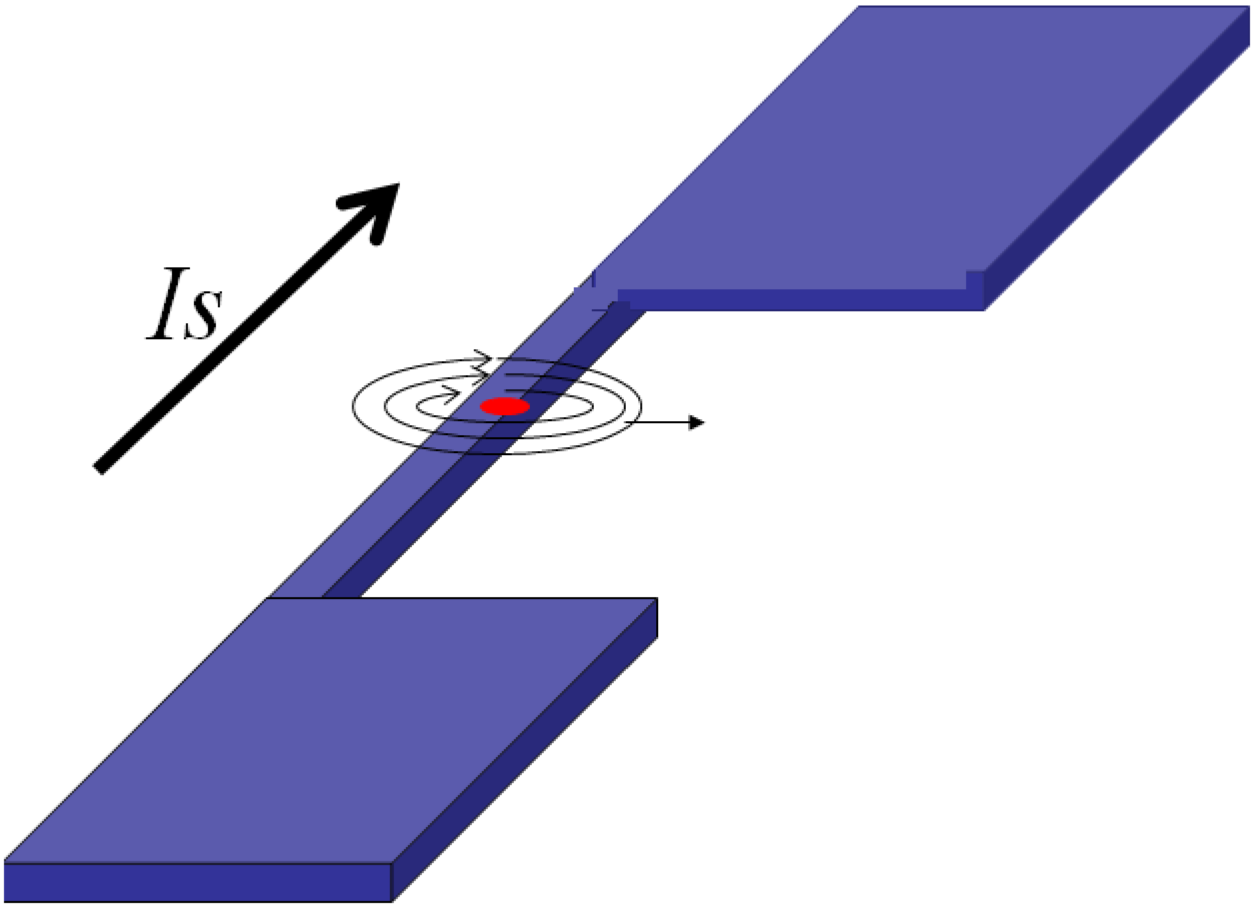


We find pronounced intrinsic fluctuation of the switching current



MoGe Nanowire

Is there one-to-one correspondence between the switching events and the phase slips? Yes, if the temperature is sufficiently low.

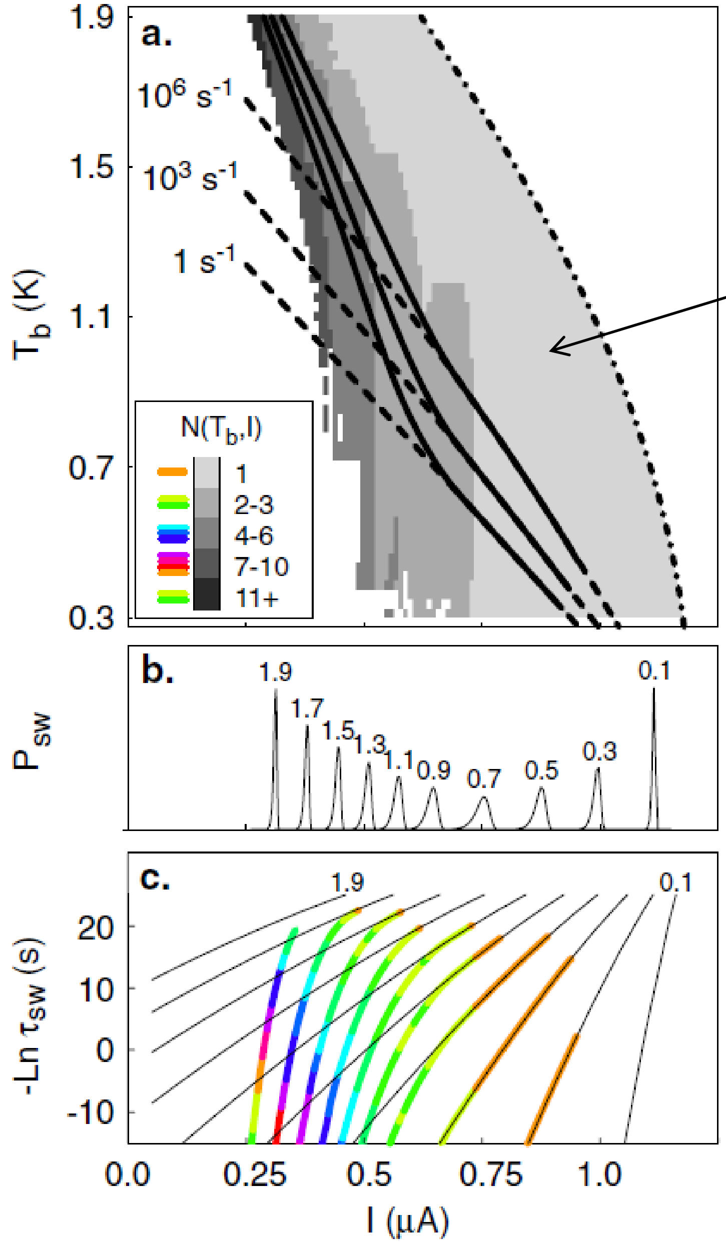


Model of stochastic switching dynamics

- Competition between
  - heating caused by a single Little's phase slip event $\left(=\dfrac{hI}{2e}\right)$
  - cooling
- At higher temperatures a larger number of phase slips are required to cause switching.
- At sufficiently low temperatures each *single* phase slip causes switching. **In such case there is one-to-one correspondence between switching events and phase slips!**

1. M. Tinkham, J.U. Free, C.N. Lau, N. Markovic, *Phys. Rev. B* **68**,134515 (2003).
2. Shah, N., Pekker D. & Goldbart P. M.. *Phys. Rev. Lett.* **101**, 207001 (2008).
3. P. Li et al., *Phys. Rev. Lett.* **107**, 137004 (2011).

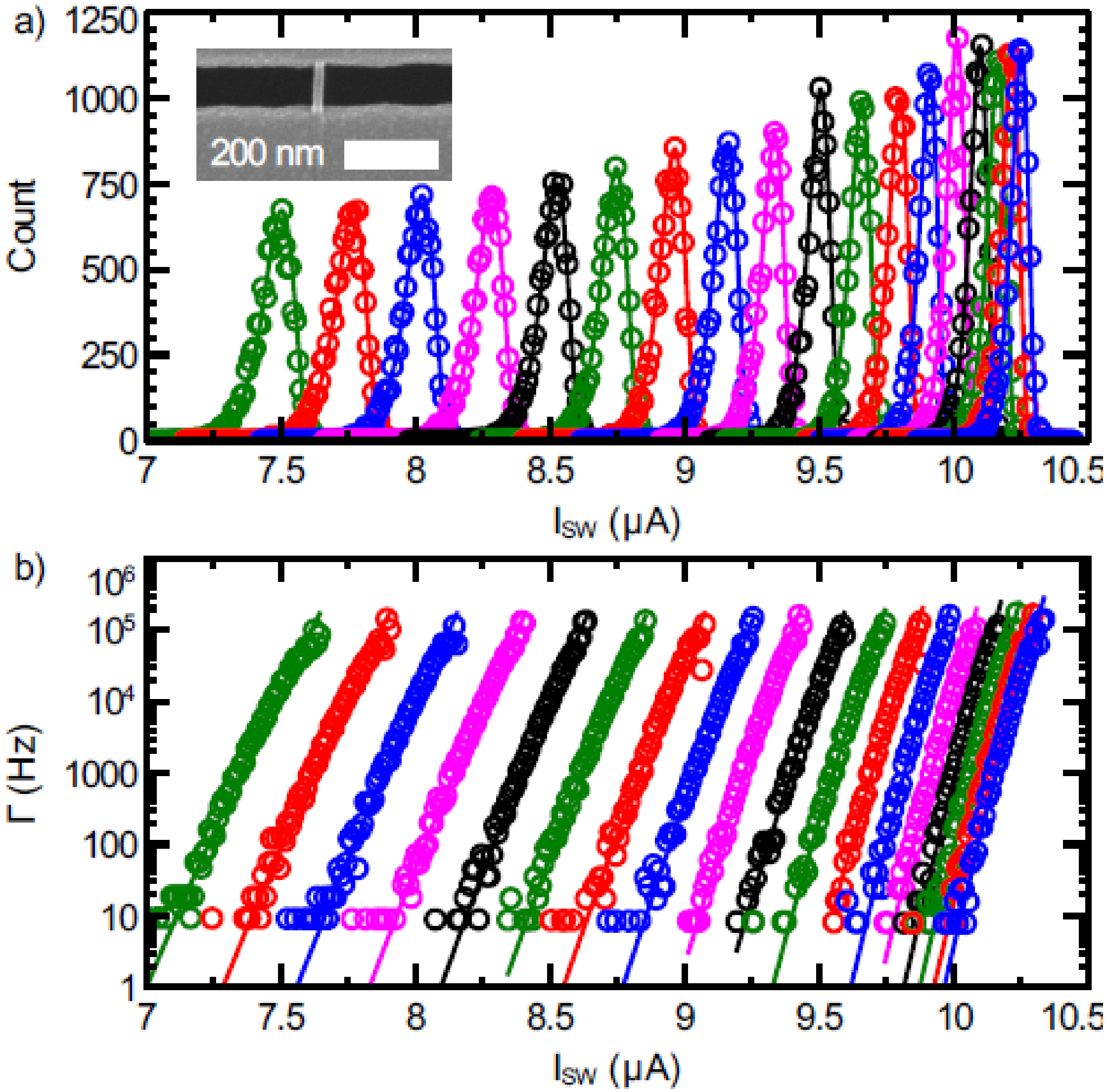
Theoretical modeling of nanowire switching by phase slips



Single phase slip switching regime

Shah, N., Pekker D. & Goldbart P. M.. *Phys. Rev. Lett.* **101**, 207001 (2008).

Distributions of the switching current can be converted into switching rates



2 K - 0.3 K

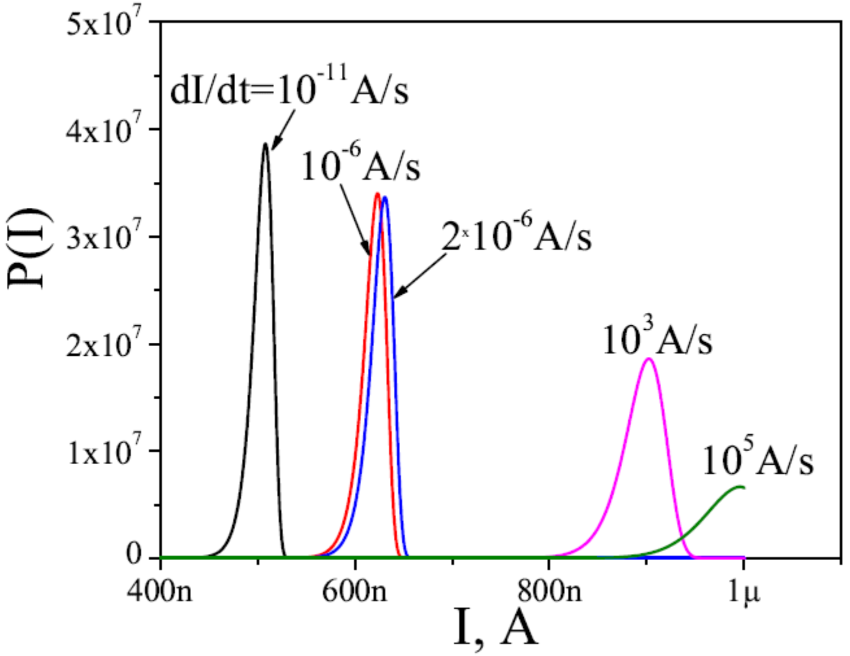
2 K - 0.3 K

Kurkijärvi-Fulton-Dunkleberger transformation

It is used to convert the measured distribution function P into the switching rate

$$\Gamma(I) = P(I)v_I\left(1 - \int_0^I P(I')dI'\right)^{-1}$$

In this modeling, the attempt frequency Ω is assumed 1000 GHz, as is typical.

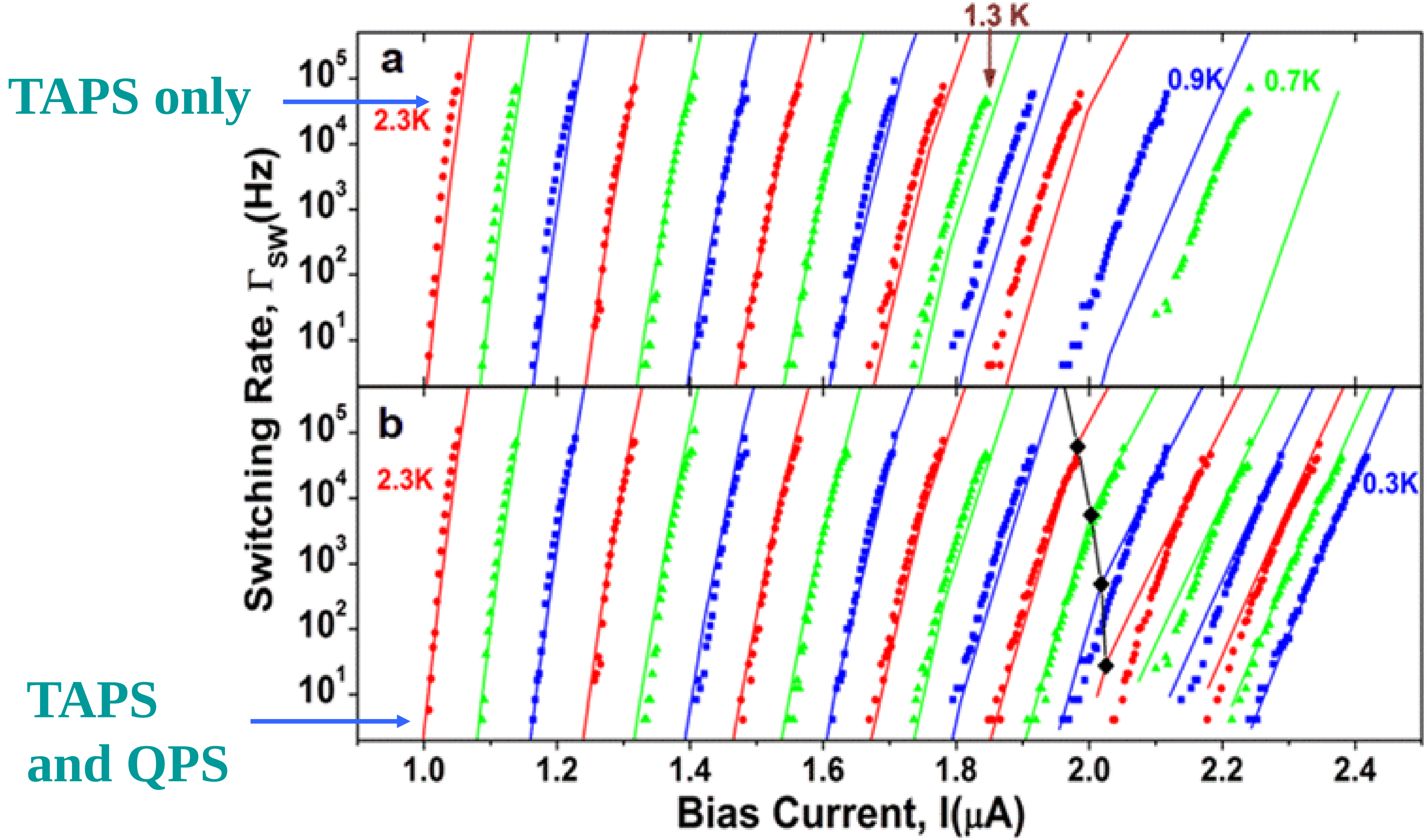


$$\Gamma(I) = \Omega(I)\exp(-\Delta F(I)/k_B T)$$

$$\Delta F(I) = \Delta F(0)(1 - I/Ic)^{3/2}$$

$$P(I) = \frac{\Gamma(I)}{v_I}\exp[-\int_0^I \Gamma(I')v_I^{-1}(I')dI']$$

Switching rates at different temperatures



M. Sahu, M.-H. Bae, A. Rogachev, D. Pekker, T. Wei, N. Shah1, P. M. Goldbart, and A. Bezryadin, *Nature Physics* ***5****, 503 (2009).*

Equivalence of $T_q = T_{esc}$ and T*

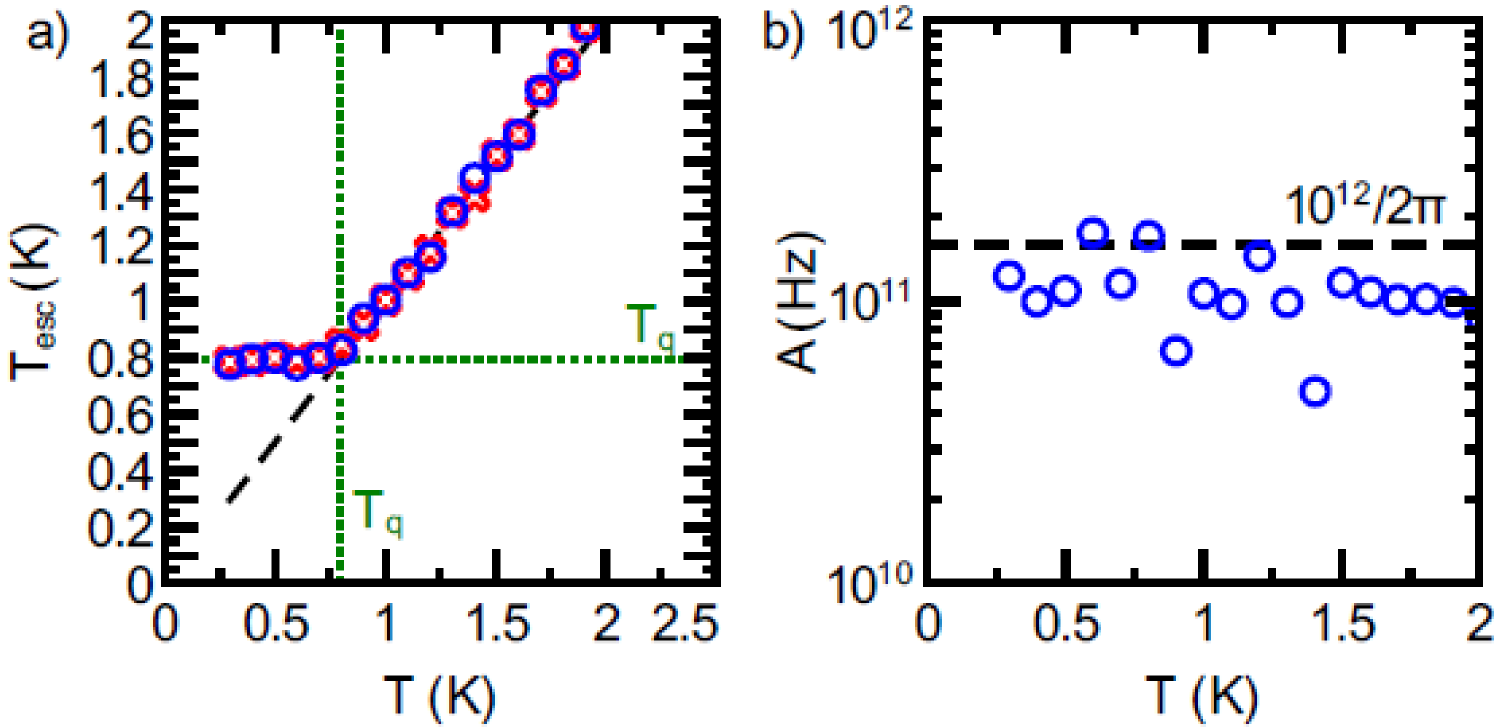
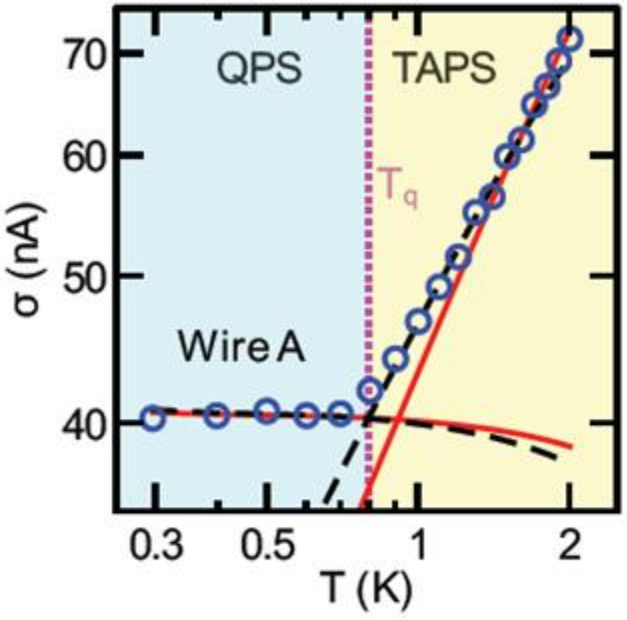
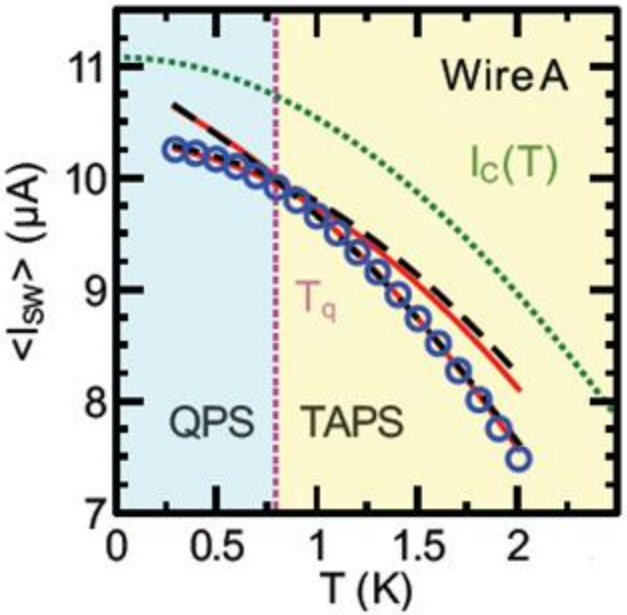


FIG. 4: [Color online] a) The fitting parameter T_{esc} that defines escape rate in Eq. (1) presented as a function of temperature. b) Temperature dependence of the escape frequency $A = \Omega/2\pi$.

Saturation of the switching standard deviation is observed





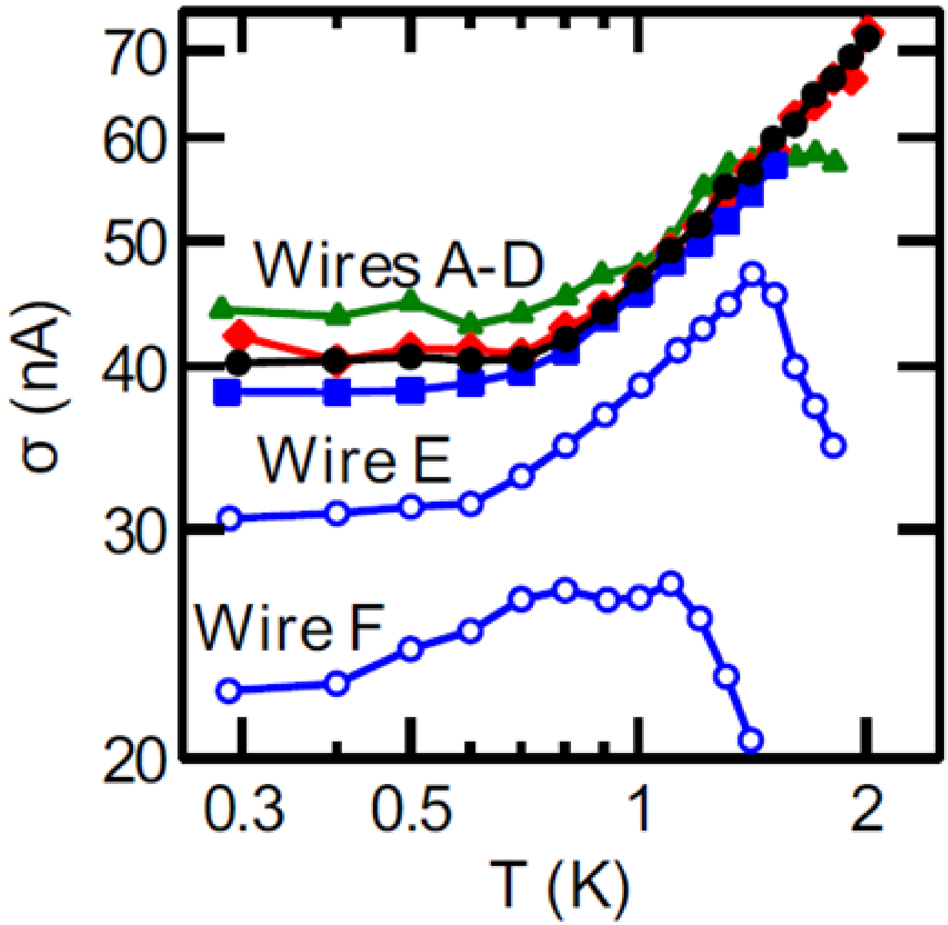
1) **Kurkijarvi power law is observed at high temperatures. This proves that we are in the single-phase slip regime.**

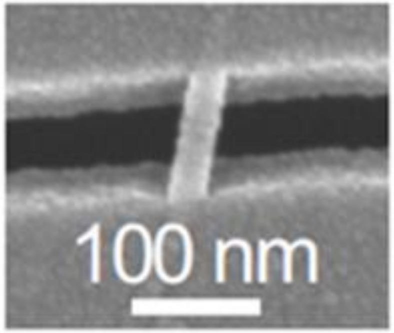
2) **Such saturation is a strong indicator of macroscopic quantum tunneling.**

3) **The mean value of the switching currenet does not saturates, as expected. This rules out external noise and presence of out-of-equilibrium hot electrons.**

T. Aref et al., Phys. Rev. B **86**, 024507 (2012)

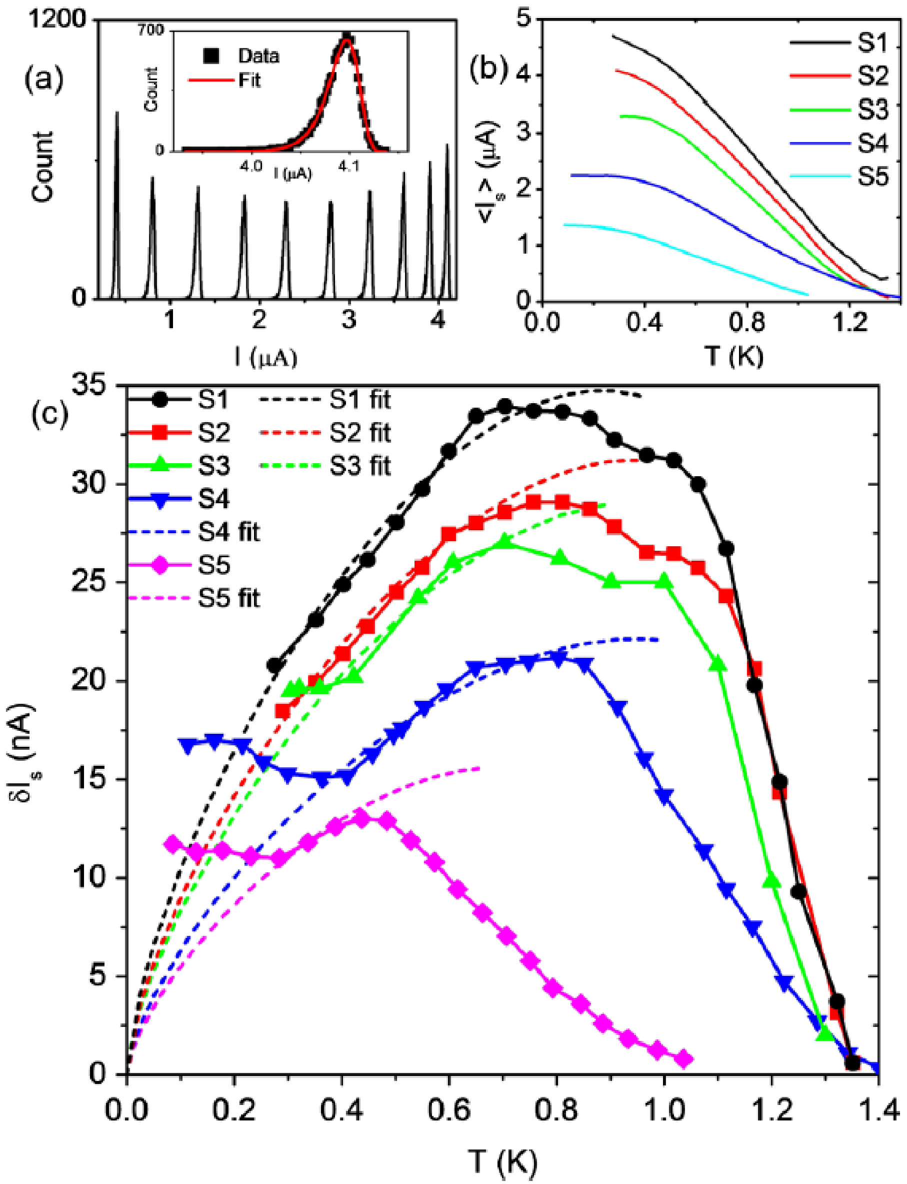
Multiple phase slips can be seen in samples with low critical currents





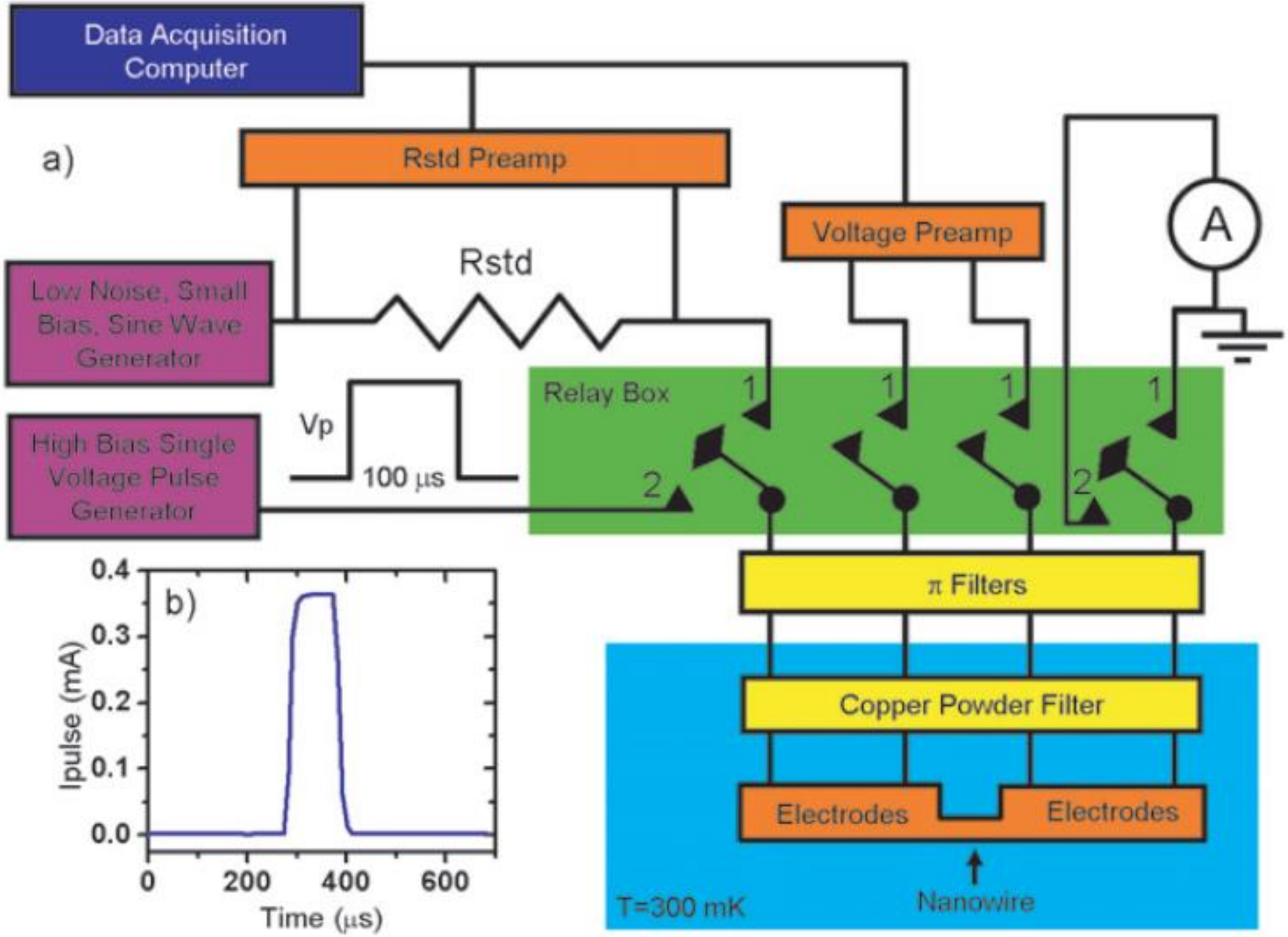
The saturation of σ at low temperatures is seen on all tested samples, A–F [Fig. 1(c)], which have critical currents of 11.1, 12.1, 13.1, 9.23, 5.9, and 4.3 μA, respectively (see the

Similar results have been published by an independent team on thin Al nanowires



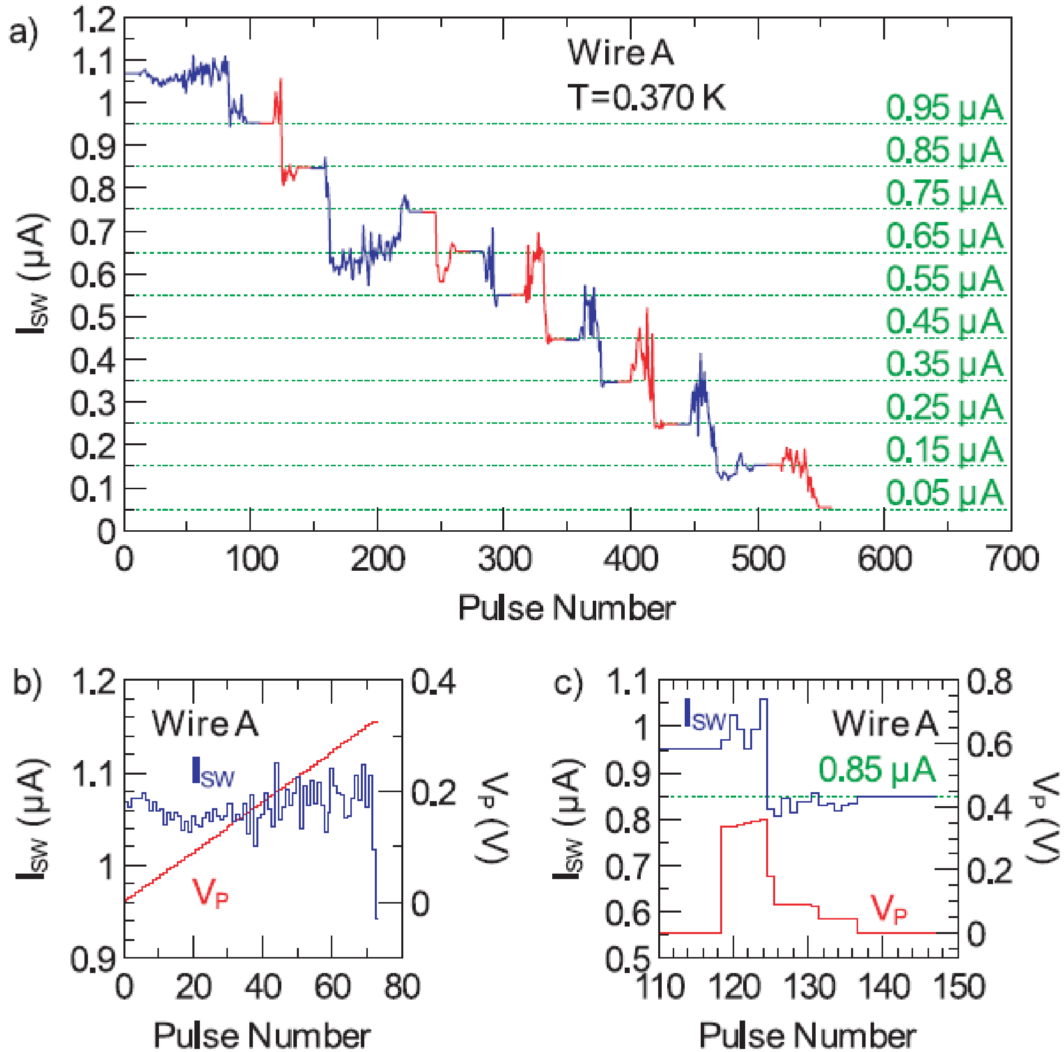
P. Li et al., "Switching Currents Limited by Single Phase Slips in One-Dimensional Superconducting Al Nanowires"
Phys. Rev. Lett. **107**, 137004 (2011)

Pulsing technique used to make wires crystalline



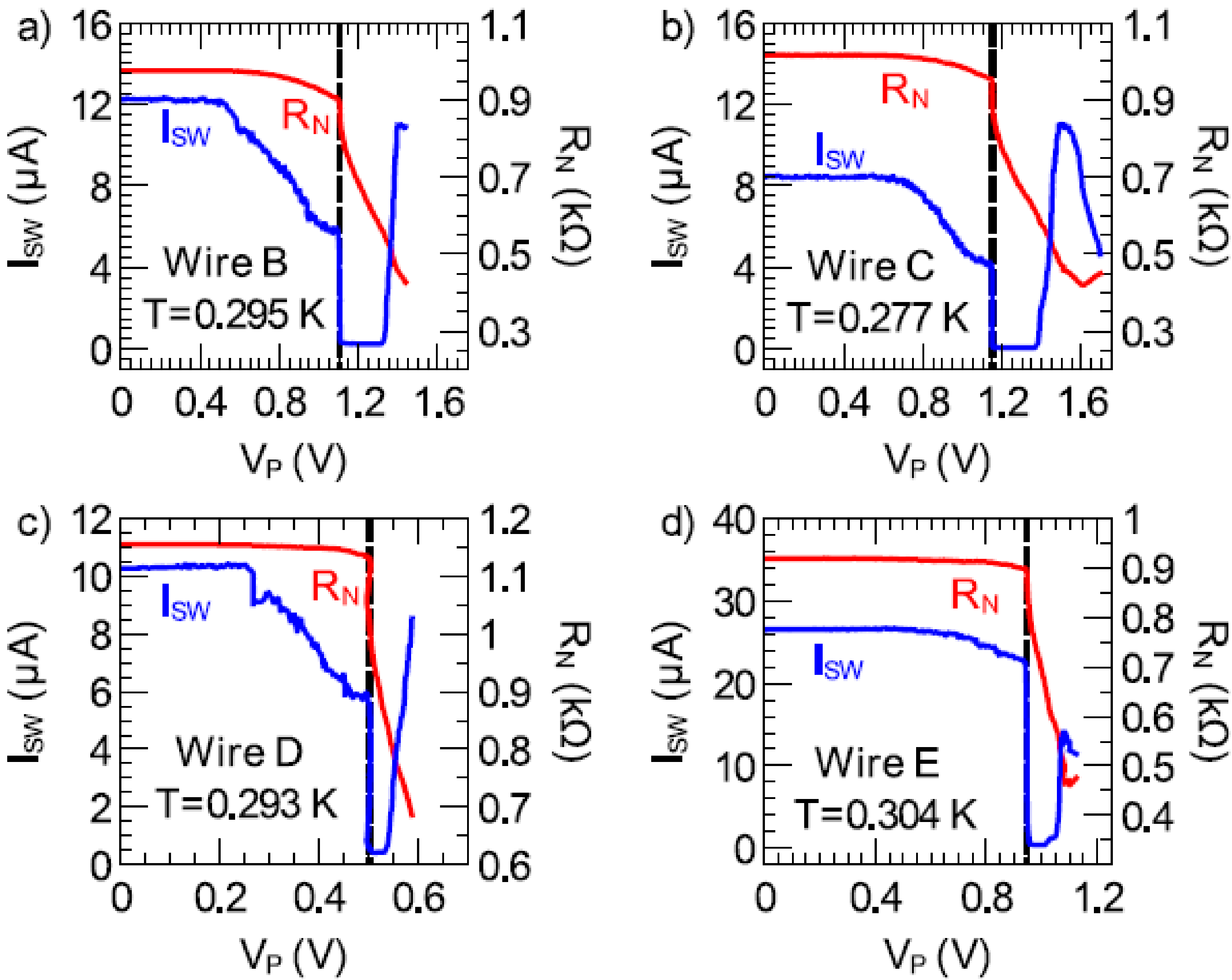
T. Aref and A. Bezryadin, Nanotech. **22**, 1 (2011)

Pulsing technique: adjusting the critical current



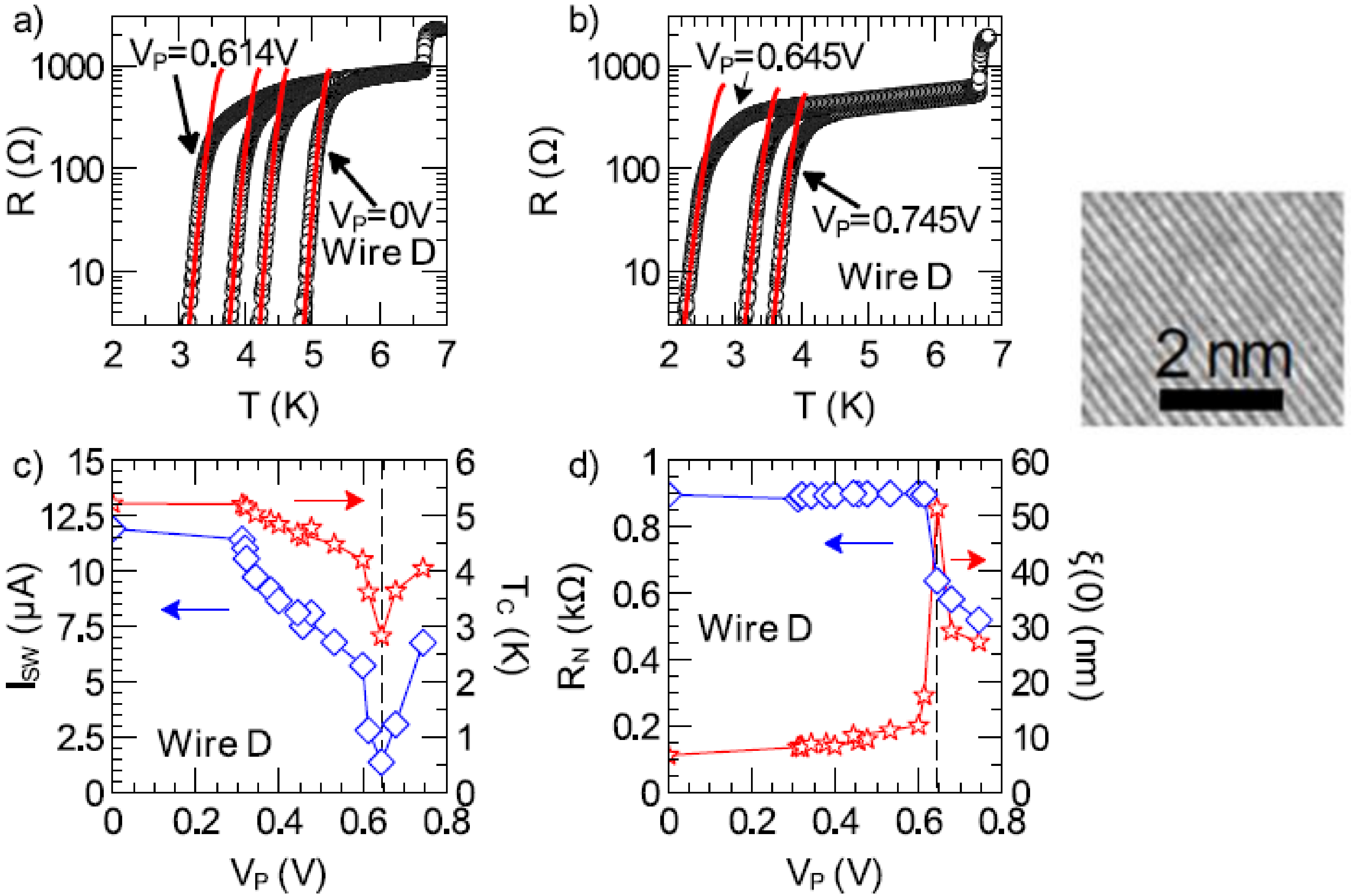
T. Aref and A. Bezryadin, Nanotech. **22**, 1 (2011)

Pulsing technique: adjusting normal resistance



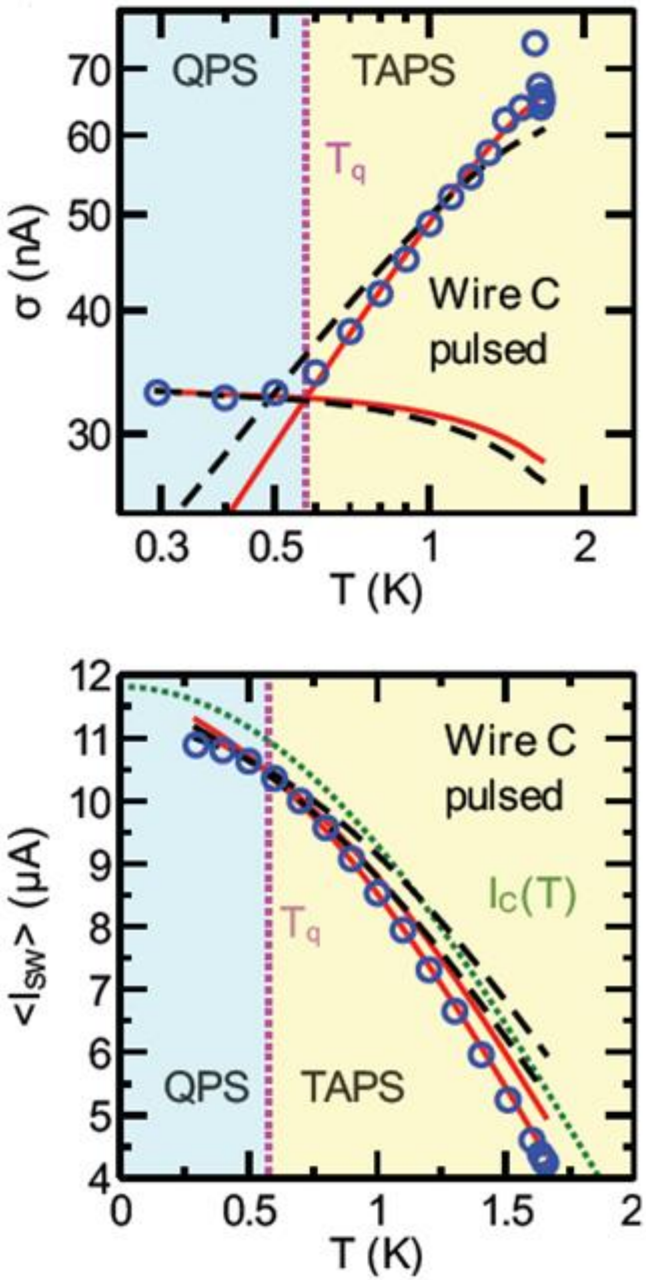
T. Aref and A. Bezryadin, Nanotech. **22**, 1 (2011)

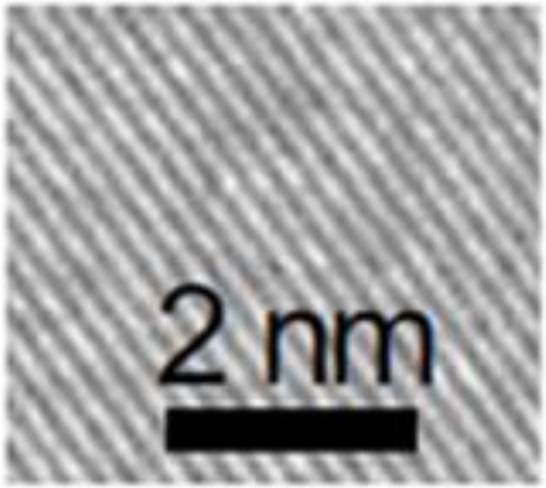
Pulsing technique: adjusting the critical temperature



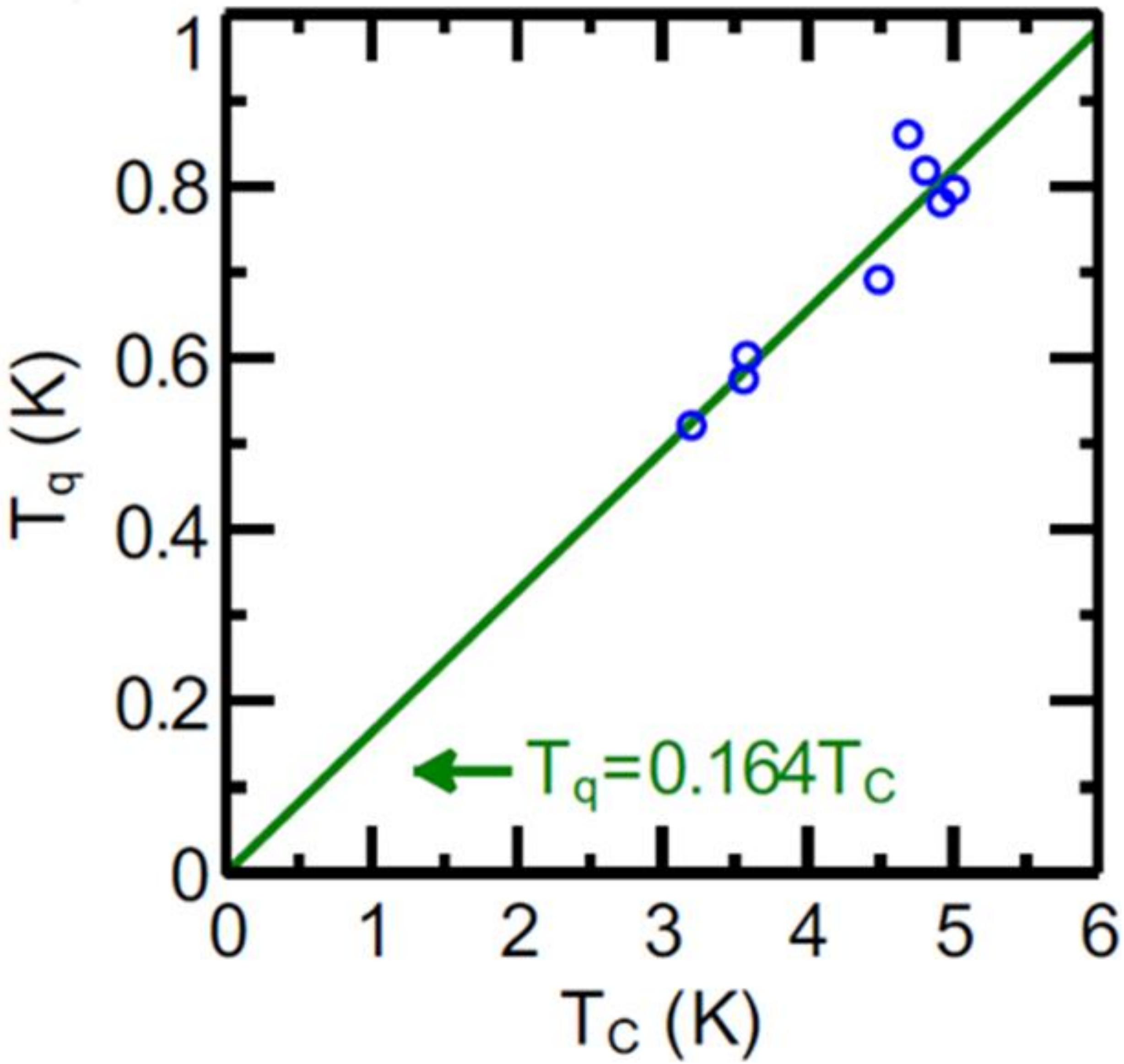
T. Aref and A. Bezryadin, Nanotech. **22**, 1 (2011)

Wires crystallized by pulsing show qualitatively the same behavior. Thus MQT does not depend on minute details of morphology

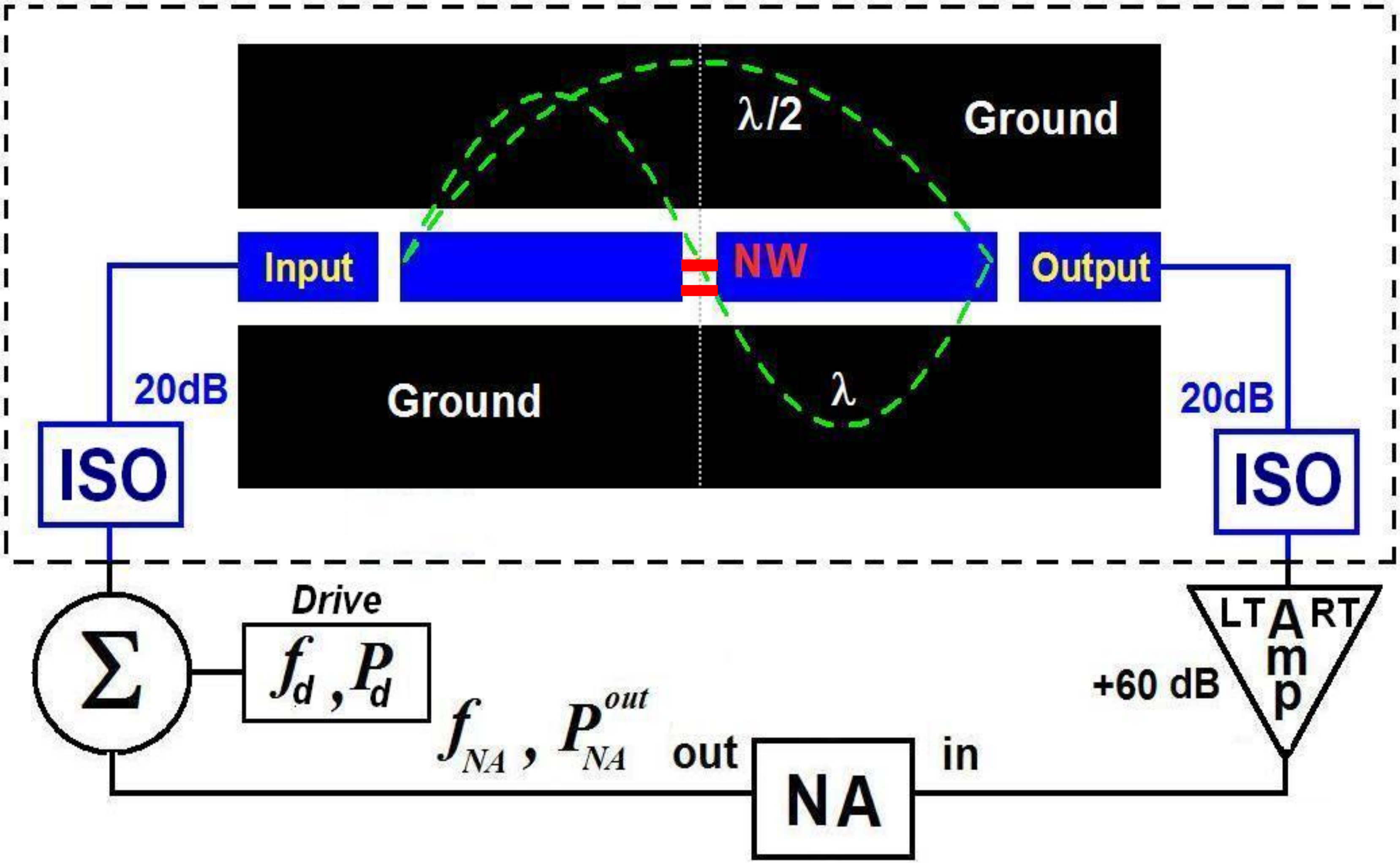




Tq scales linearly with Tc

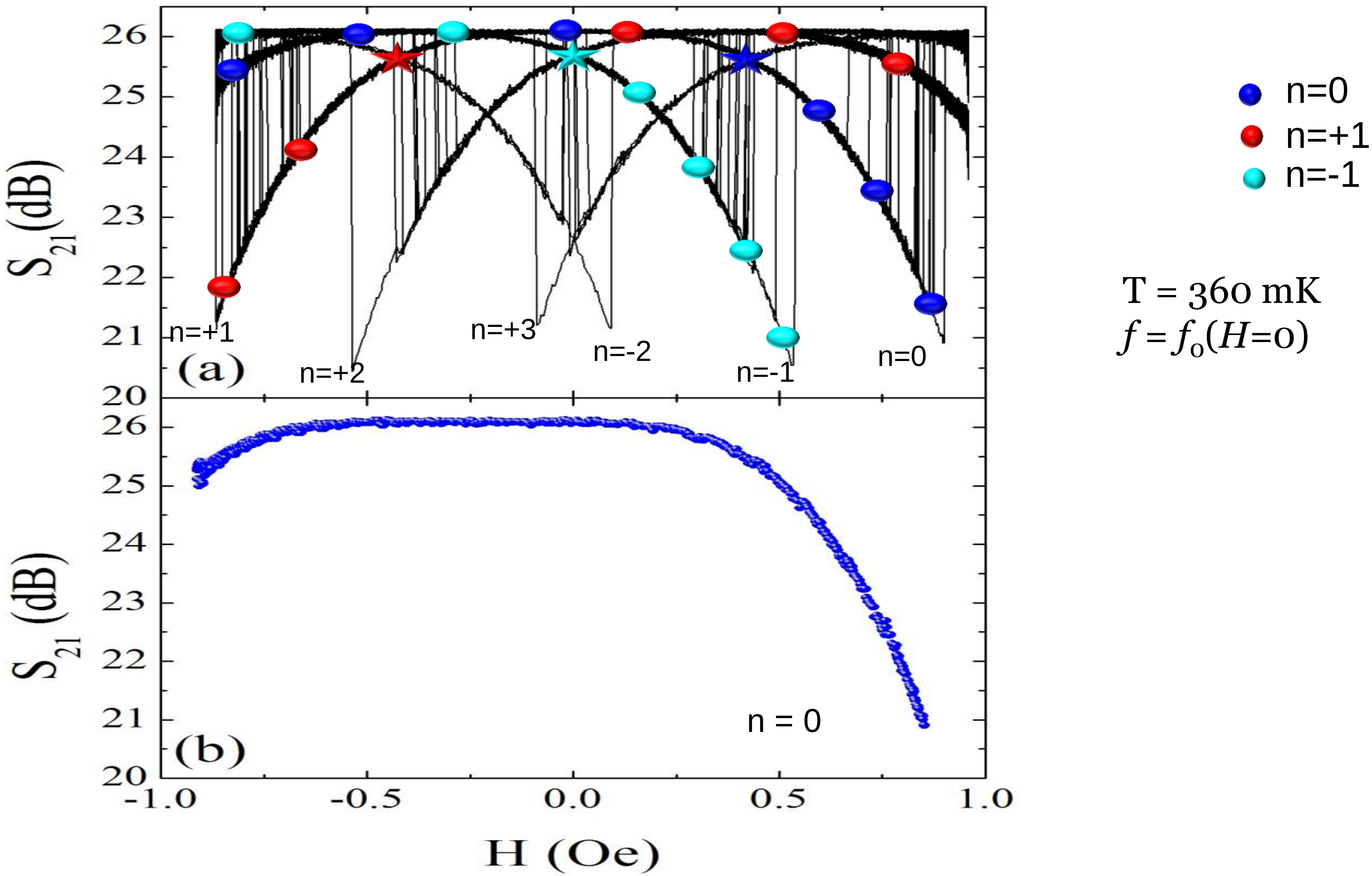


Measuring nanowires within GHz resonators.
Direct detection of single phase slips and double-slips



A. Belkin et al, *Appl. Phys. Lett.* **98**, 242504 (2011)

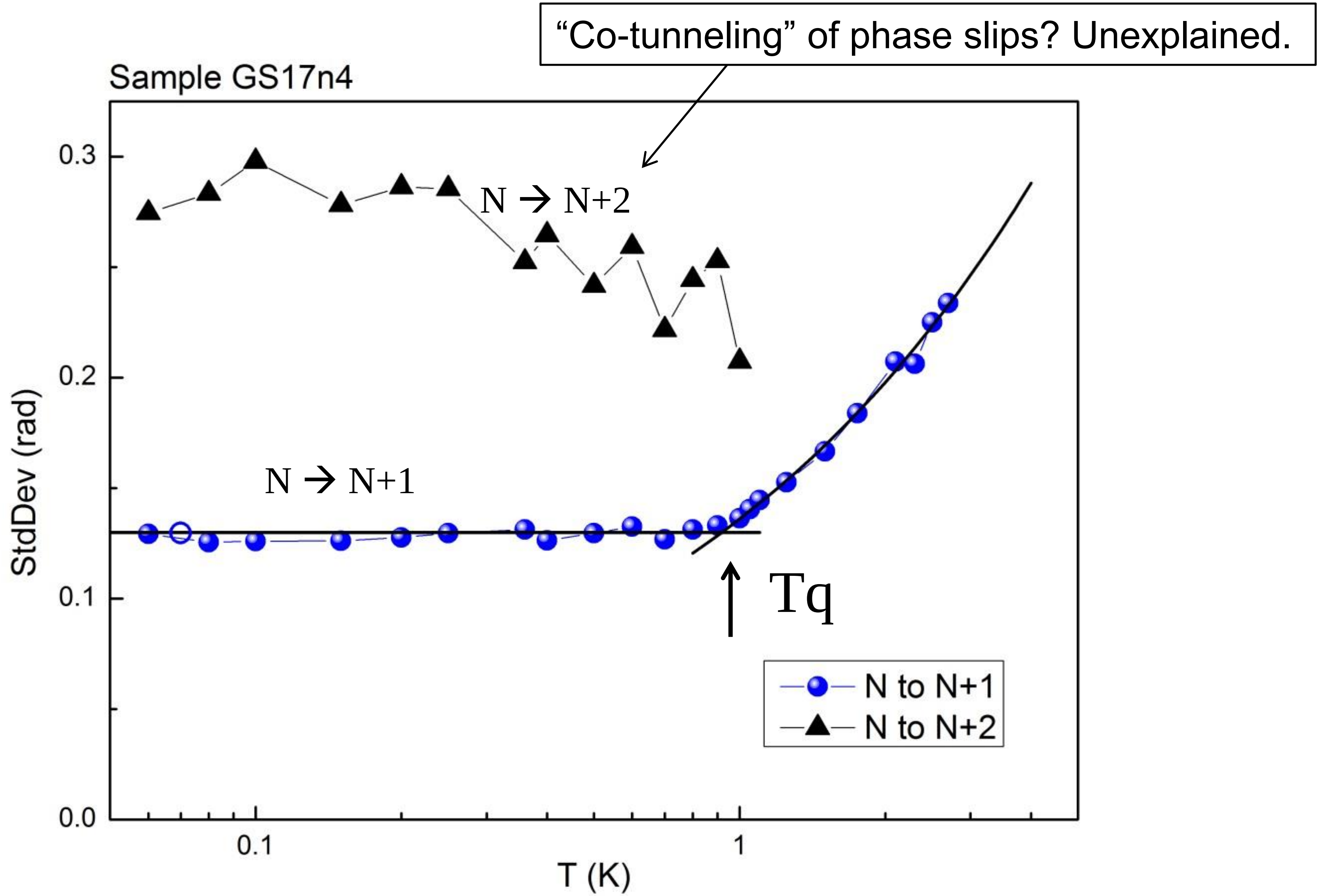
Little-Parks effect at low temperatures. Detection of single phase slips



T = 360 mK
$f = f_0(H=0)$

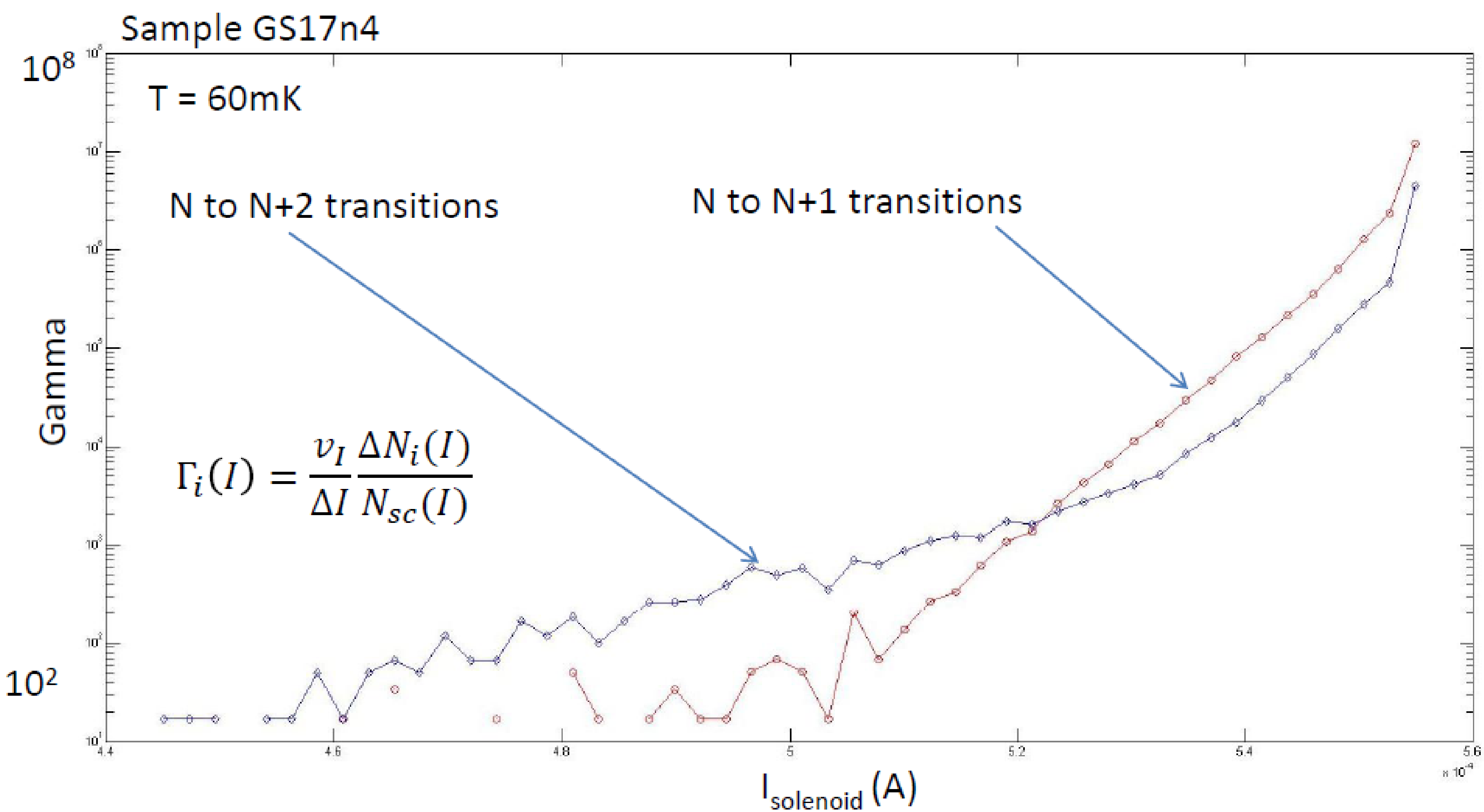
A. Belkin et al, *Appl. Phys. Lett*. **98**, 242504 (2011)

Macroscopic quantum tunneling is confirmed in microwave settings. Changing filters or setups did not alter the results.



Andrey Belkin project

Rates of single and double quantum phase slips



T<Tq

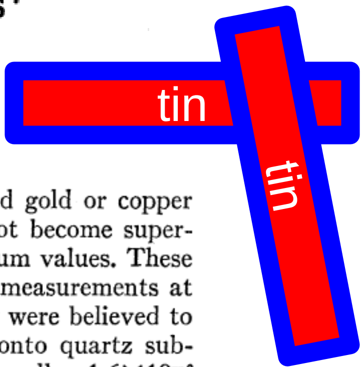
PHYSICAL REVIEW VOLUME 117, NUMBER 3 FEBRUARY 1, 1960

Discovery of the supercurrent, known now as proximity effect, in SNS junctions

Superconductivity of Contacts with Interposed Barriers*

HANS MEISSNER†
Department of Physics, The Johns Hopkins University, Baltimore, Maryland

(Received August 25, 1959)



Resistance *vs* current diagrams and "Diagrams of State" have been obtained for 63 contacts between crossed wires of tin. The wires were plated with various thicknesses of the following metals: copper, silver, gold, chromium, iron, cobalt, nickel, and platinum. The contacts became superconducting, or showed a noticeable decrease of their resistance at lower temperatures if the plated films were not too thick. The limiting thicknesses were about 35×10^{-6} cm for Cu, Ag, and Au; 7.5×10^{-6} cm for Pt, 4×10^{-6} cm for Cr, and less than 2×10^{-6} cm for the ferromagnetic metals Fe, Co, and Ni. The investigation was extended to measurements of the resistance of contacts between crossed wires of copper or gold plated with various thicknesses of tin. Simultaneous measurements of the (longitudinal) resistance of the tin-plated gold or copper wires showed that these thin films of tin do not become superconducting for thicknesses below certain minimum values. These latter findings are in agreement with previous measurements at Toronto. The measurements at Toronto usually were believed to be unreliable because films of tin evaporated onto quartz substrates can be superconducting at thicknesses as small as 1.6×10^{-6} cm. It is now believed that just as superconducting electrons can drift into an adjoining normal conducting layer and make it superconducting, normal electrons can drift into an adjoining superconducting layer and prevent superconductivity.

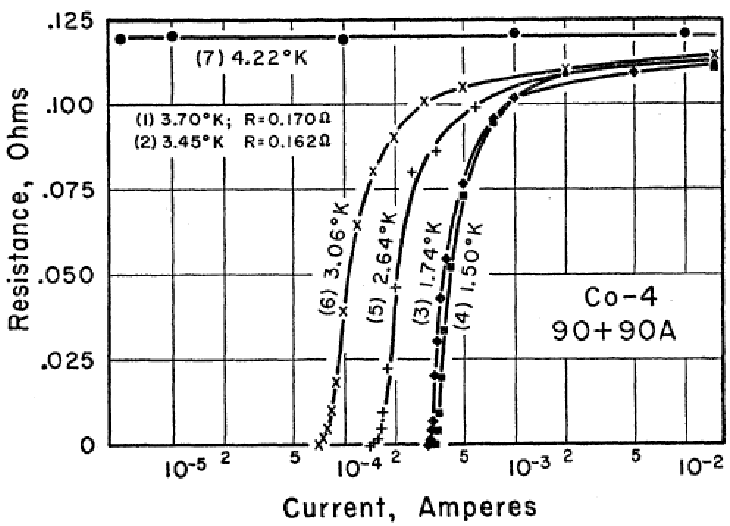


FIG. 1. Resistance *vs* current diagram of cobalt-plated contact Co 4, representative of diagrams type A.

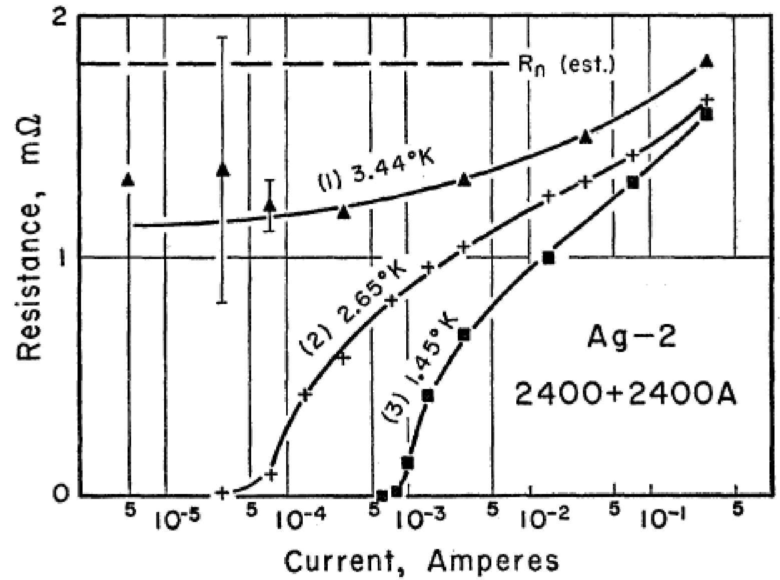
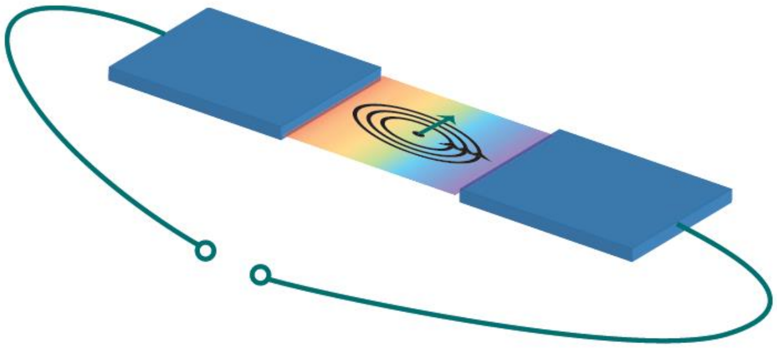


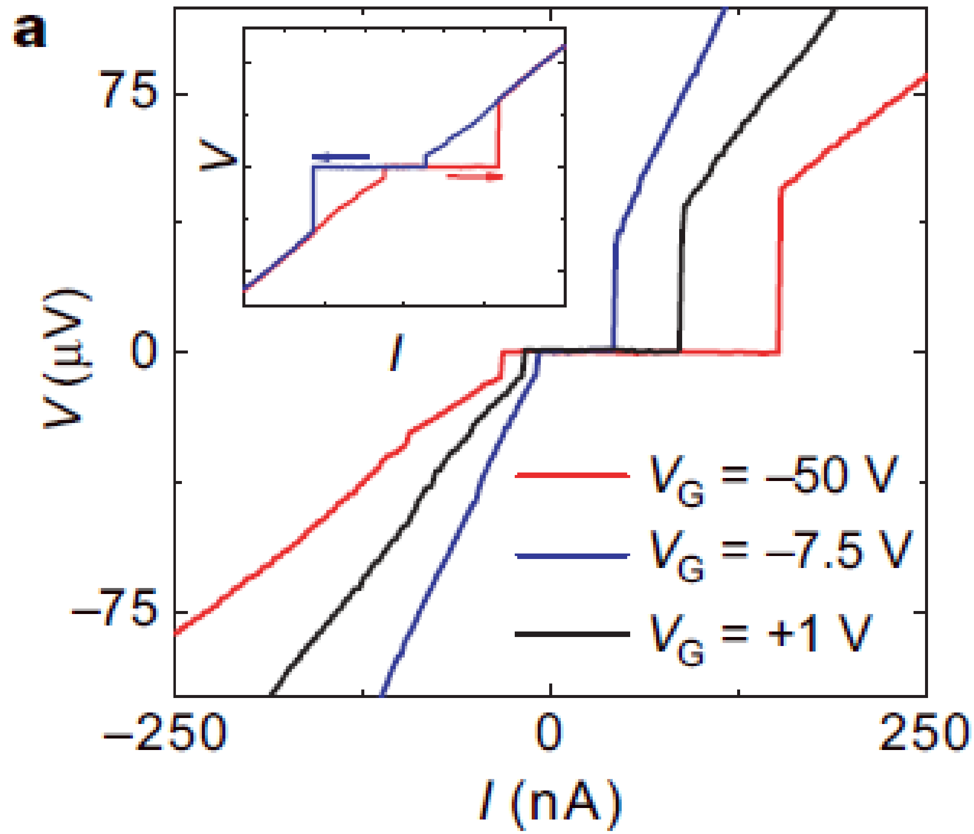
FIG. 2. Resistance *vs* current diagram of silver-plated contact Ag 2, representative of diagrams type B.

Crossing vortex heats the junction and might causes the switching

Switching is unusual for SNS junctions (see e.g. Meissner results), but graphene junctions do show switching.



HEERSCHE H.B., JARILLO-HERRERO P., OOSTINGA J.B., VANDERSYPEN L.M.K., MORPURGO A.F.:, *Nature* **446**, 56 (2007)

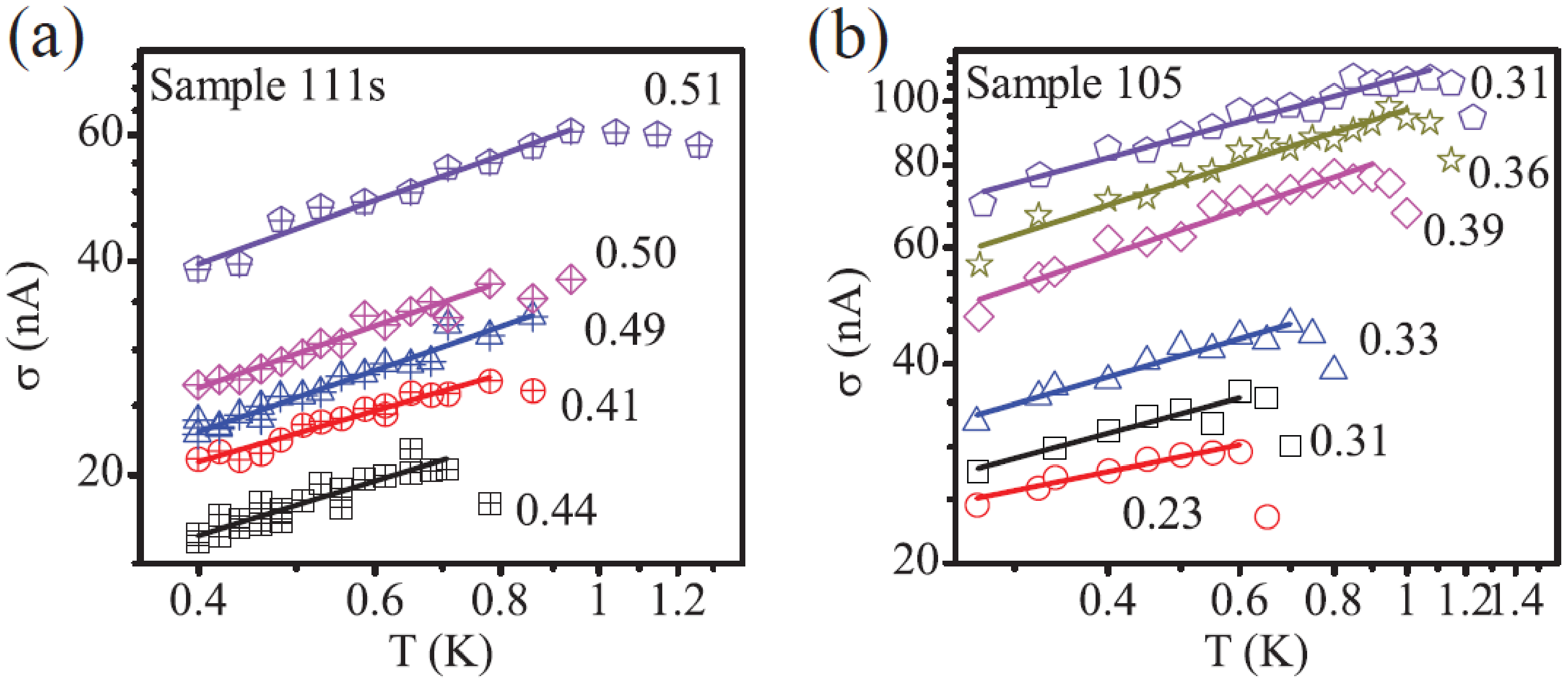


Dispersion of the switching current in graphene junctions.

The value previously found in JJs is 2/3=0.67
Thus there is a strong deviation in graphene devices, which is our new result.

Power exponent $\neq 0.66$

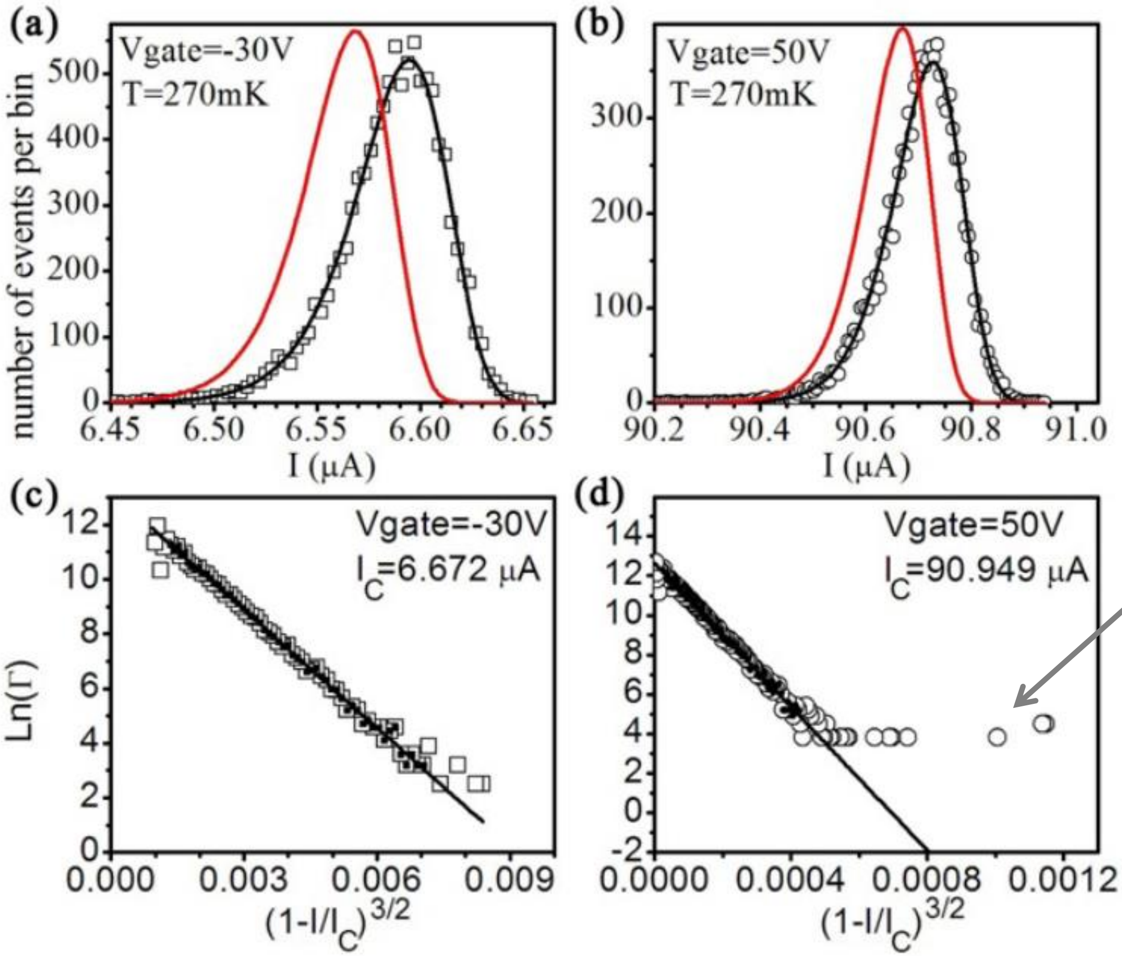
$$\sigma_I \propto (T/\Phi_0)^{2/3} I_c^{1/3}(T)$$



U. Coskun, M. Brenner, T. Hymel, V. Vakaryuk, A. Levchenko, A. Bezryadin,
Phys. Rev. Lett. **108**, 097003 (2012)

Distributions of the switching current and the switching rates

Strong, non-thermal, fluctuations have been found. Understanding and controlling them is important for the operation graphene devices

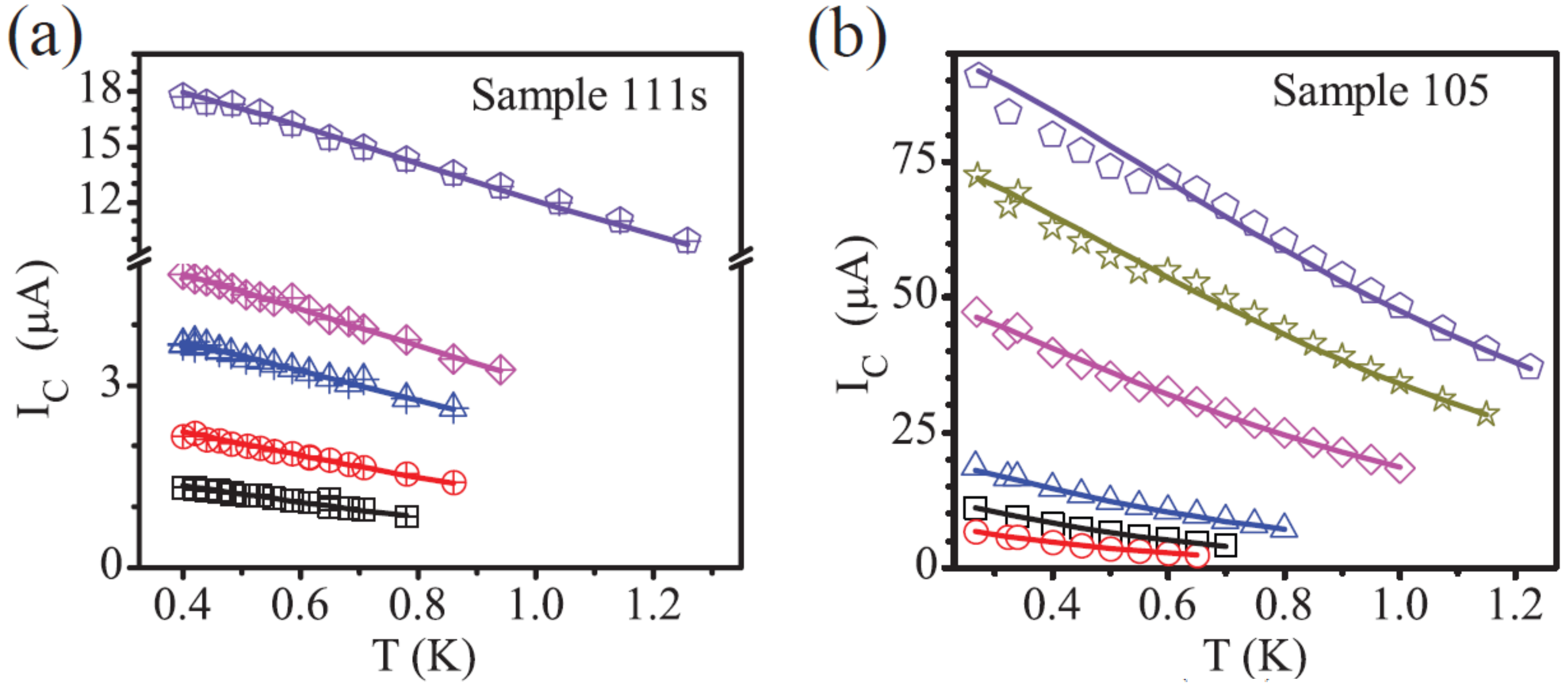


Non-thermal fluctuations

U. Coskun, M. Brenner, T. Hymel, V. Vakaryuk, A. Levchenko, A. Bezryadin, *Phys. Rev. Lett*. **108**, 097003 (2012)

Critical current versus temperature

In SGS, or SNS in general, the Ic(T) is not constant, which is different from the usual SIS JJs.

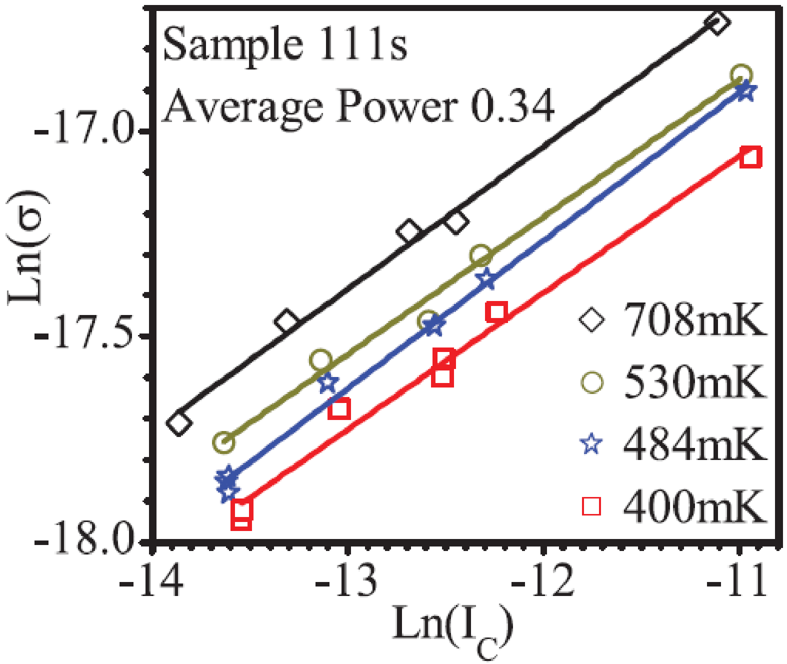


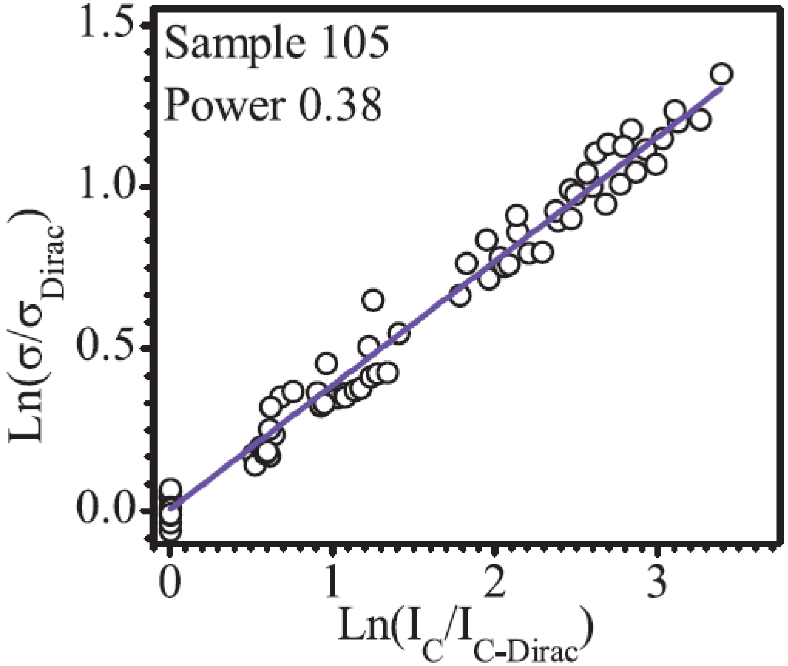
fits

A. D. Zaikin and G. F. Zharkov, Sov. J. Low. Temp. Phys. **7(3)**, 184 (1981); P. Dubos *et. al.*, Phys. Rev. B **63**, 064502 (2001).

U. Coskun, et al., submitted to *Phys. Rev. Lett.* (2011)

First observation of the Kurkijärvi dependence on the critical current.





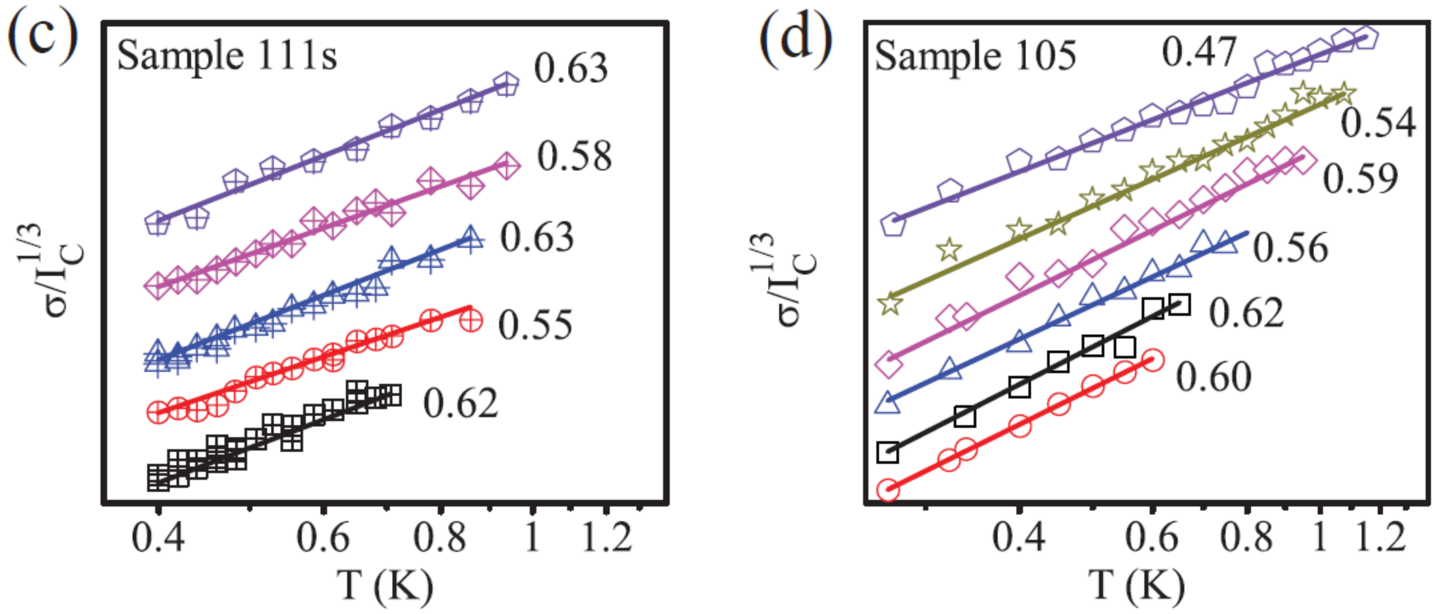
$$\sigma_I \propto (T/\Phi_0)^{2/3} I_c^{1/3}(T)$$

Predicted power is 1/3=0.33

U. Coskun, et al., submitted to *Phys. Rev. Lett.* (2011)

Use complete Kurkijärvi theory to understand the dispersion scaling with temperature

The results agree with the generalized theory. The power is close to 2/3 for the dispersion normalized by the critical current.



$$\sigma_I \propto (T/\Phi_0)^{2/3} I_c^{1/3}(T)$$

Conclusions

- Little’s phase slips can occur by means of macroscopic quantum tunneling

- Kurkijarvi scaling of the standard deviation with temperature was observed on thin superconducting wires

- Graphene junctions show thermall activated phase slips (dark counts), but no quantum phase slips. This finding might be used for the creation of superior single photon detectors
- The microwave setup is developed, which allows detection of single phase slips.
- Double phase slips are also observed. The show a higher probability at low currents.