Quantum fluctuations in superconducting nanostructures

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Outline

1. Introduction

Fluctuations in quasi-1D superconductors

Quantum Phase Slip concept

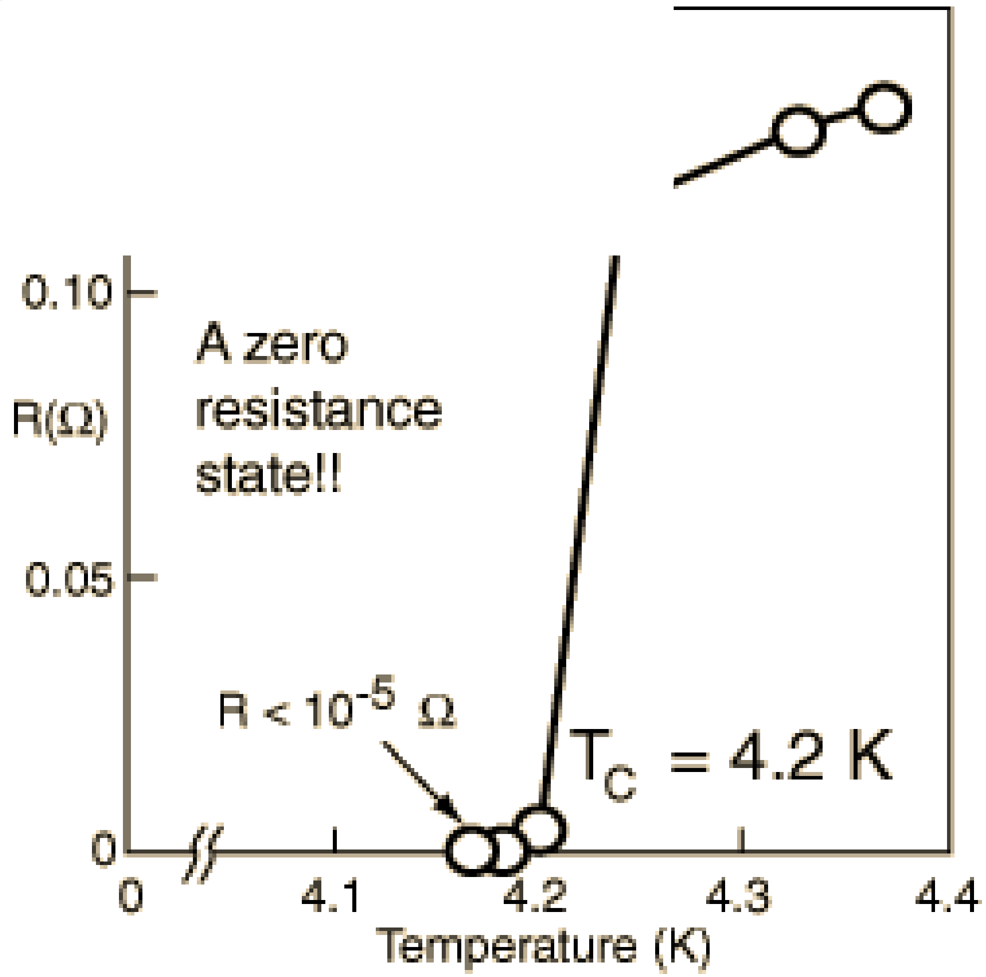
2. Applications

Junctionless Cooper pair transistor

Quantum standard of electric current

3. Conclusions

R(T) transition



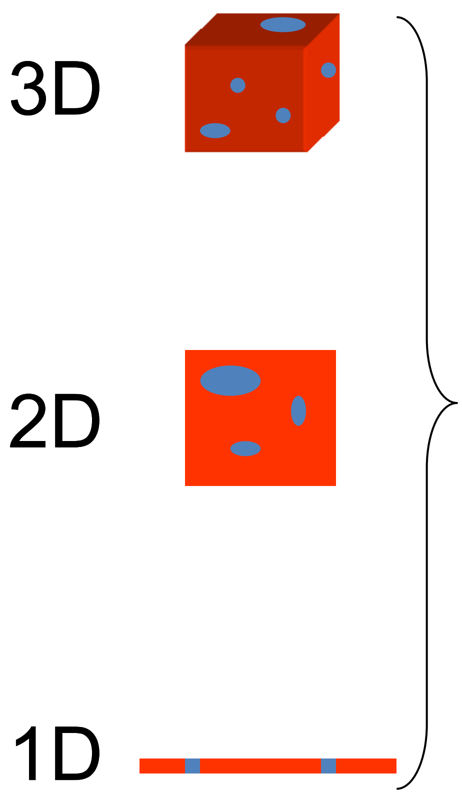
H. K. Onnes,
Commun. Phys. Lab.12,120, (1911)

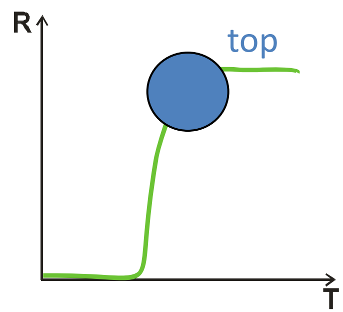
Fluctuations vs. system dimensionality

For a superconductor dimensionality is set by the temperature - dependent coherence length ξ(T).

N normal metal

S superconductor





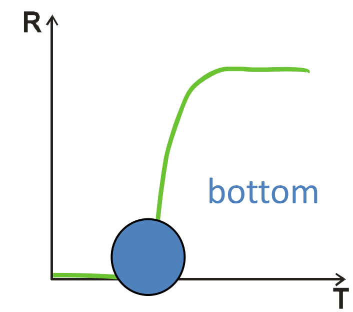
S inclusions reduce the total system resistance →

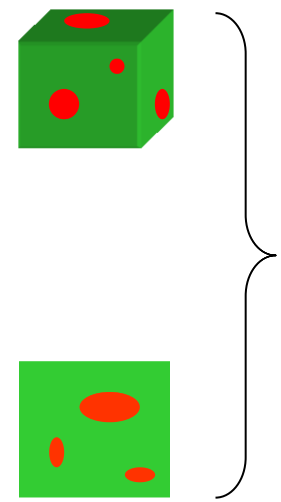
rounded top

$\sigma_{FLUCT} \sim (T-T_c)^{-(2-D/2)}$

(Aslamazov – Larkin)

Topic of the talk





no contribution of N inclusions: normal current is shunted by supercurrent →

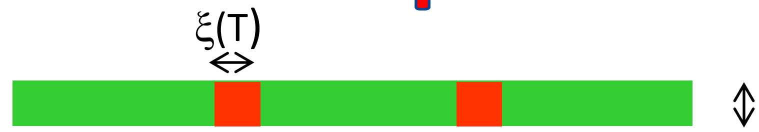
abrupt bottom

N inclusions block the supercurrent →

rounded bottom

(Langer – Ambegaokar)

Fluctuations in a 1D supercondcutor



Long 1D wire of cross section σ $\sqrt{\sigma} < \xi(T) << L$

If the wire is infinitely long, there is always a finite probability that in some fragment(s) the magnitude of the order parameter instantly becomes zero and the phase changes by 2π

The minimum length the superconductivity can be destroyed is the coherence length ξ(T)

The minimum energy corresponds to destruction of superconductivity in a volume ξ(T) σ:
$\Delta F = B_c^2\, \xi(T)\, \sigma$, where $B_c(T)$ is the critical field

In the limit <u>rare</u> events the probability of the process $P(T) \sim \exp(-\Delta F / \mathcal{E})$

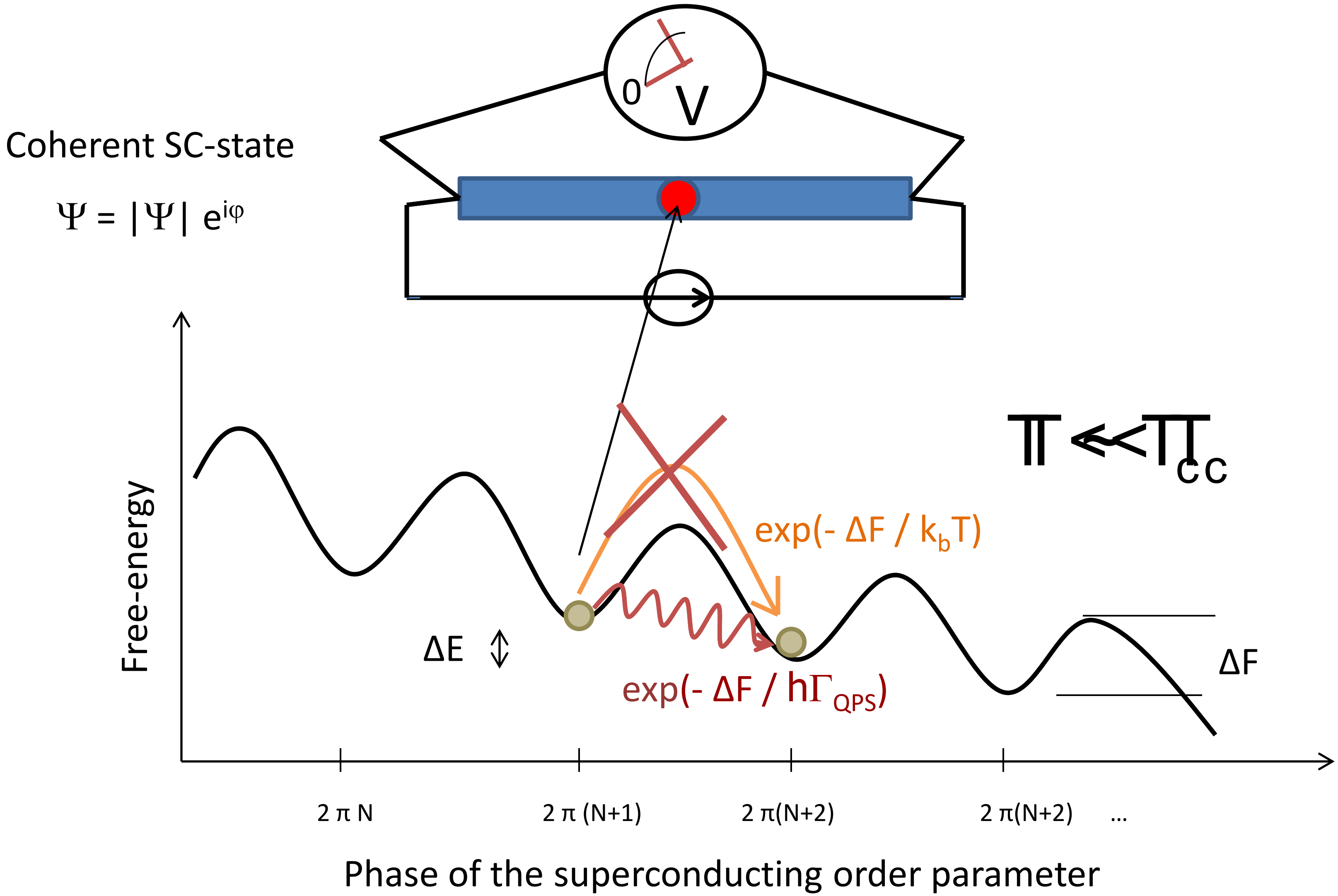
Thermal activation: $\mathcal{E} \sim k_B T$.

Important at T→Tc.

Quantum: $\mathcal{E} \sim \Delta$.
Weak temperature dependence, exist even at T→0

In current state the particular manifestation of a quantum fluctuation when magnitude of the order parameter momentary nulls and phase changes by ±2π is often called "phase slip"

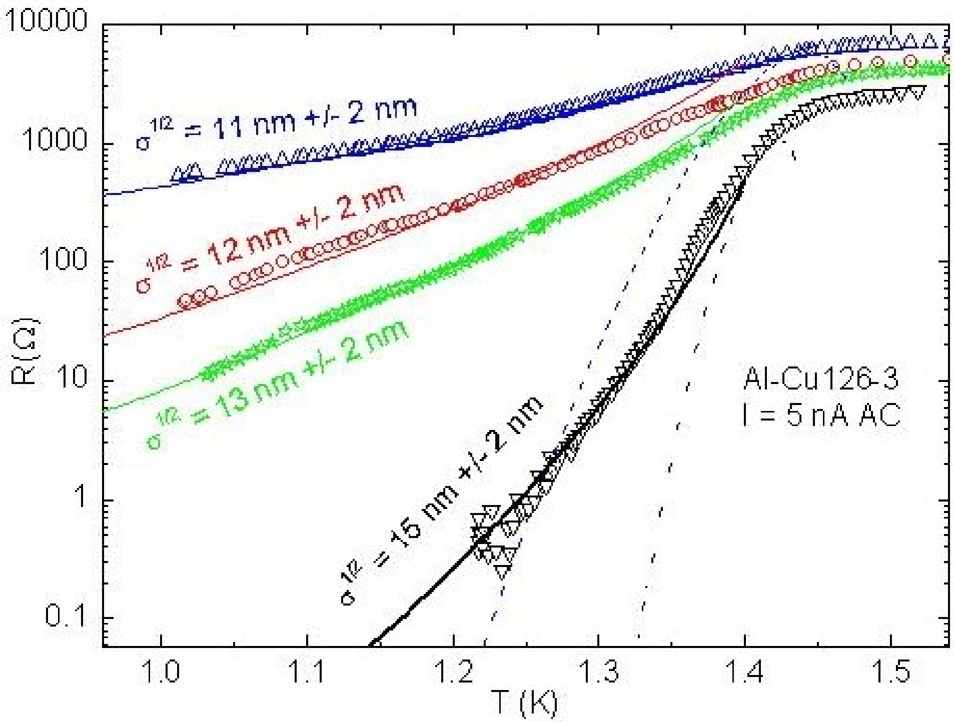
Phase slip concept



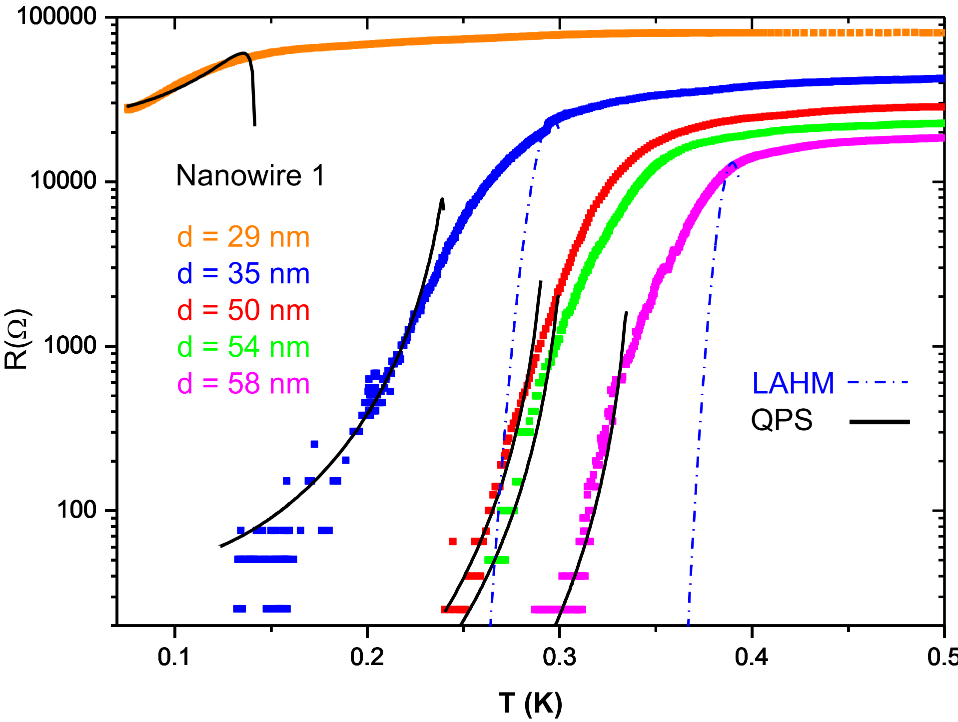
The initial and final states have different energy → dissipation in a superconductor

Manifestation of QPS: broadening of R(T) transition

Aluminium



Titanium

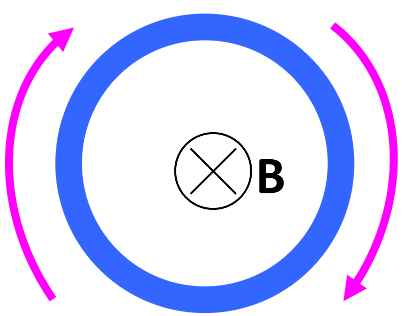


Dashed lines: thermally activated fluctuations (LAHM) at T ~Tc

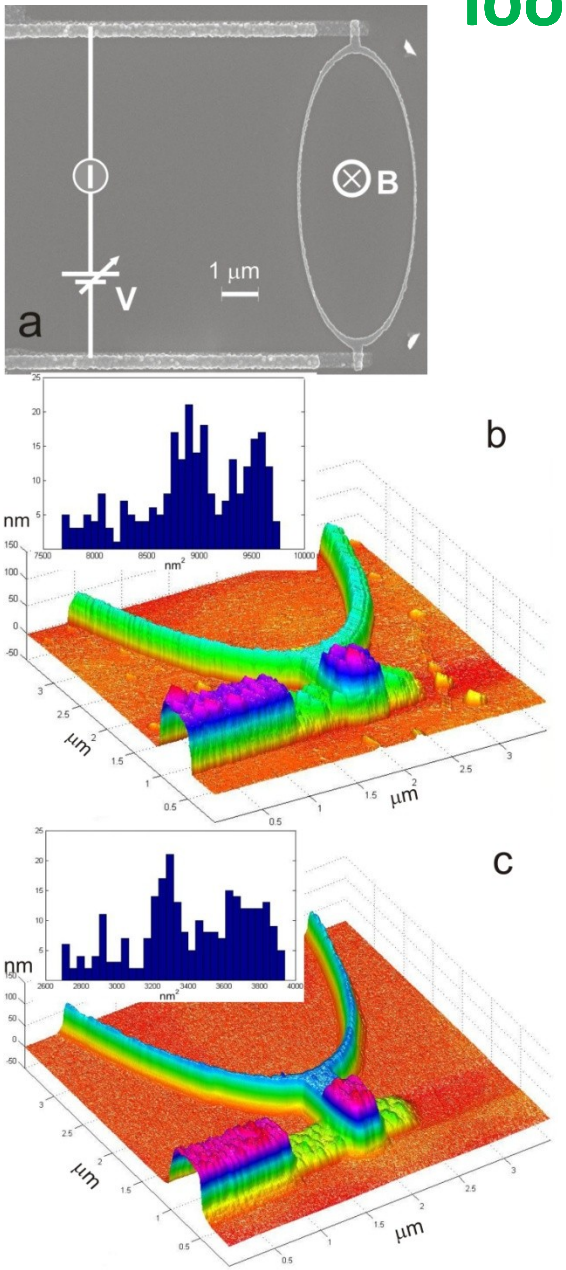
Solid lines: quantum fluctuations (Golubev – Zaikin) model at T << Tc

*M. Zgirski, K.-P. Riikonen, V. Touboltsev, and K. Arutyunov. // **Nano Letters** 5, 1029--1033 (2005).*
*M. Zgirski, K.-P. Riikonen, V. Touboltsev and K. Yu. Arutyunov.// **PRB** 77, 054508-1 -- 054508-6 (2008).*
*J. S. Lehtinen, T. Sajavara, K. Yu. Arutyunov, M. Yu. Presnjakov, and A. S. Vasiliev // **PRB** 85, 094508 (2012).*

Persistent currents in nanorings



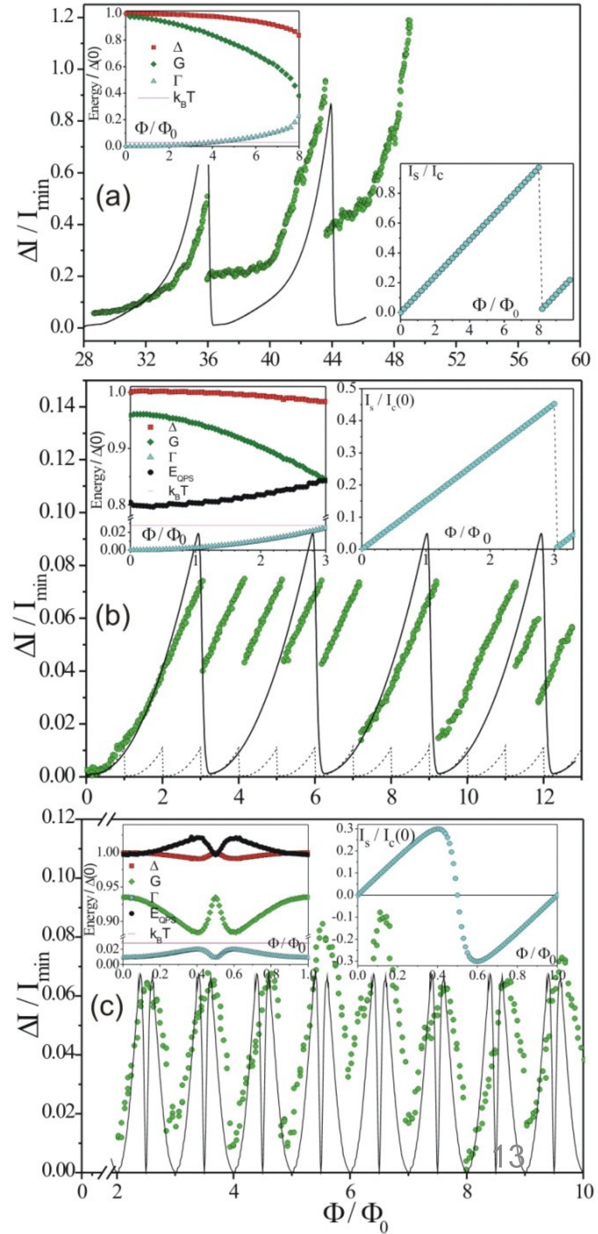
Amplitude and period of oscillations as function of the loop linewidth (aluminium)



Wide wire: classic limit
110 nm x 75 nm wire,
T_{bath}=65±5 mK, $\sigma_{fit}^{1/2}$=90.8 nm

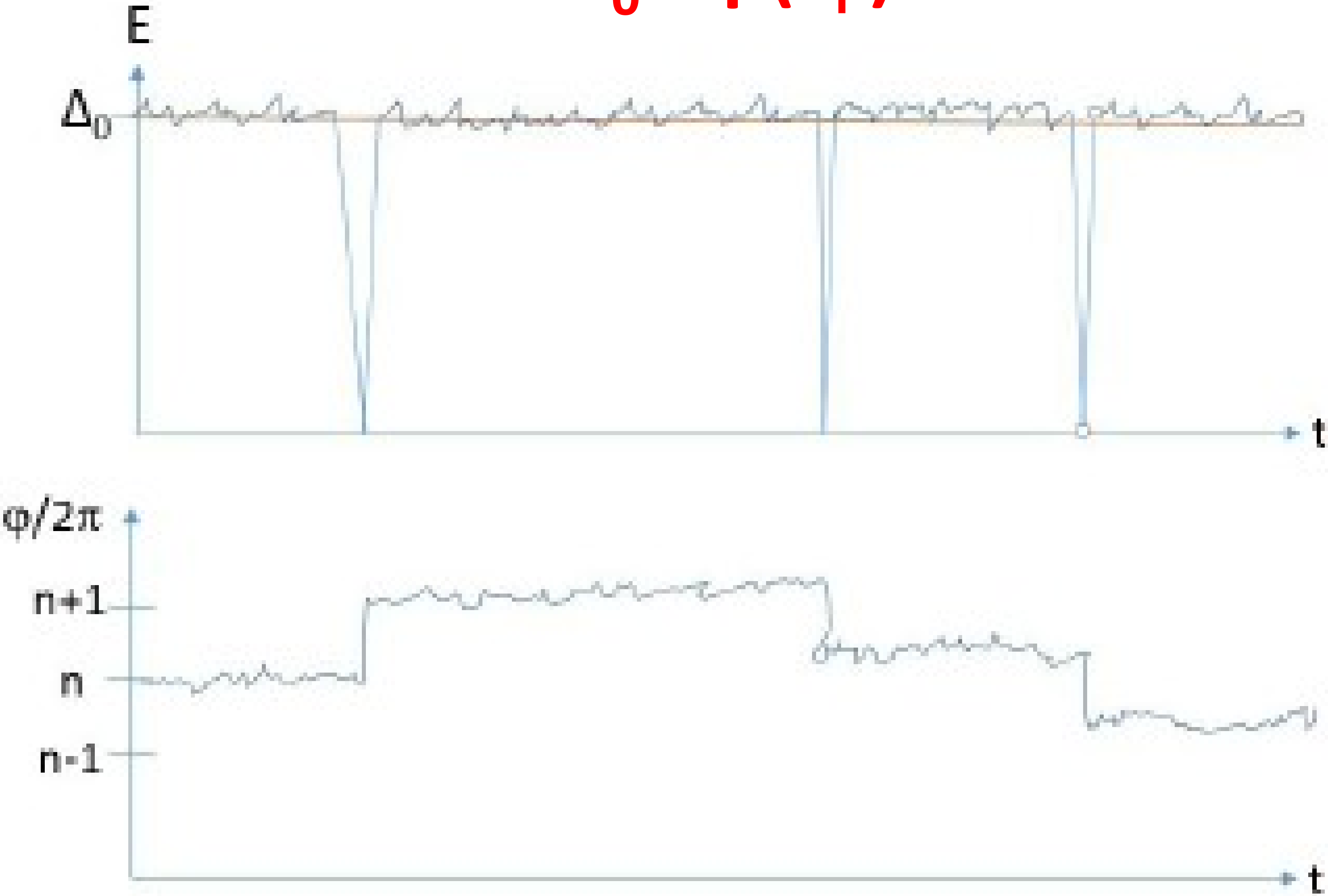
Intermediate regime:
T_{bath}=52±5mK. Solid line: $\sigma_{fit}^{1/2}$=12.49 nm and $\Delta\Phi/\Phi_0$=3 period, dashed line - calculated $\Delta\Phi/\Phi_0$=1 oscillations in a slightly narrower loop $\sigma_{fit}^{1/2}$=12.37 nm

QPS limit:
same sample as in (b) further gently sputtered at T_{bath}=54±5 mK
Solid line - calculations in the QPS limit with $\sigma_{fit}^{1/2}$=12.15 nm



Fluctuations of the superconducting gap amplitude

Fluctuations of the order parameter $\Delta = \Delta_0 \exp(i\varphi)$

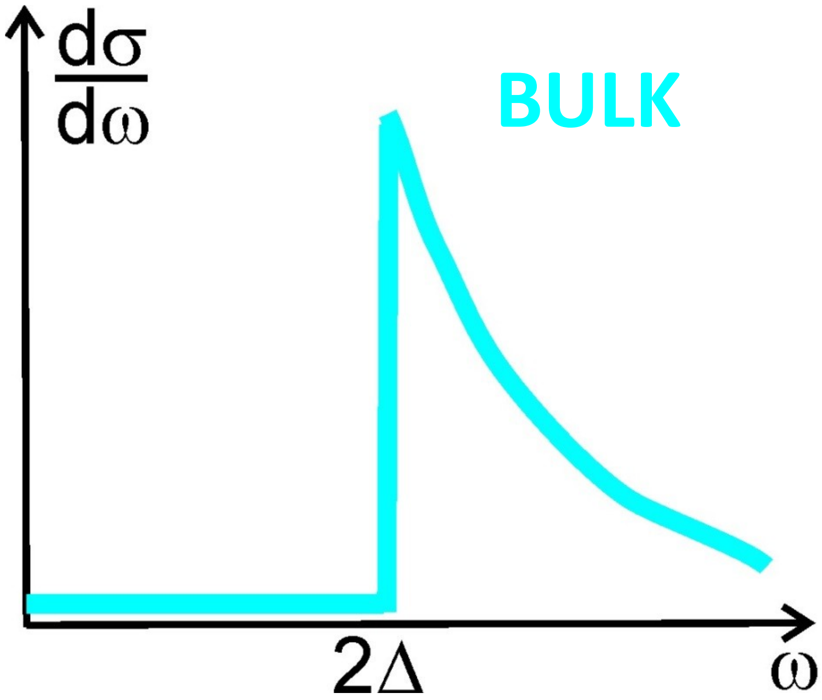


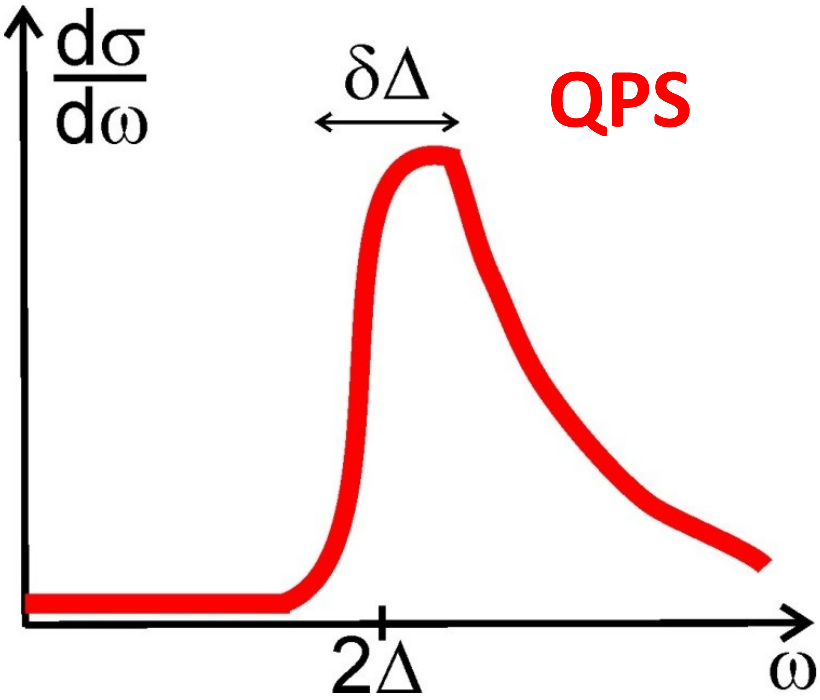
T. Rantala, MSc thesis, University of Jyvaskyla, 2013

Direct determination of the fluctuating energy gap

$$\delta|\Delta| / |\Delta| \sim (S_{QPS})^{-1}$$

Superconducting gap can be associated with E/M radiation absorption threshold



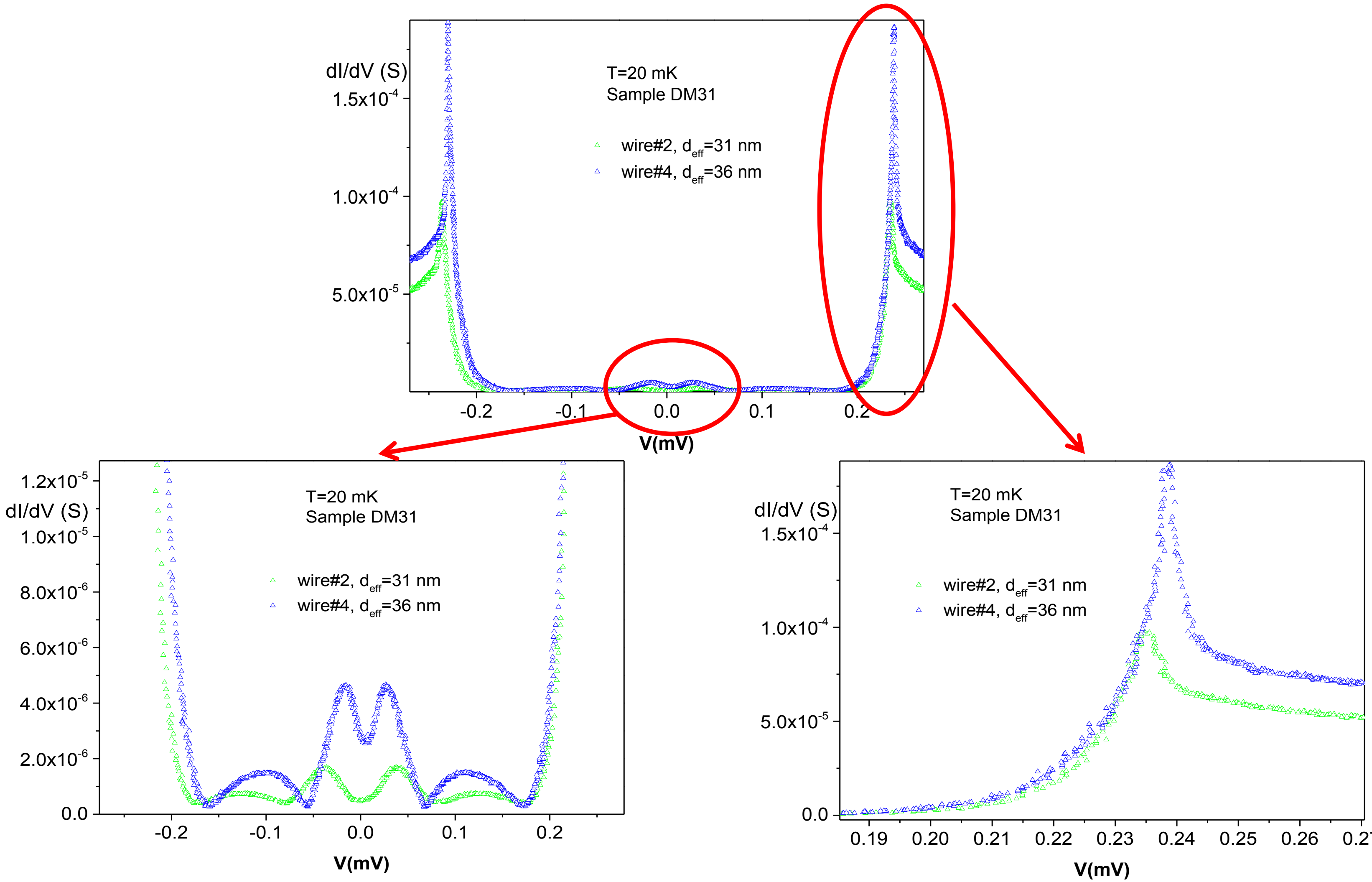


Characteristic scale

Δ(Al)~80 to100 GHz, Δ(Ti)~15 to 25 GHz.

$\delta\Delta / \Delta$ can reach 30% in sufficently thin nanowires

SIS I(V) at various diameters of nanowires



$\Delta 1 - \Delta 2$ features and
Coulomb blockade and/or Josephson current (?)

$\Delta 1 + \Delta 2$ features

The smaller the nanowire diameter (1) the smaller the average value <Δ> and (2) the larger the gap smearing $\delta\Delta$.

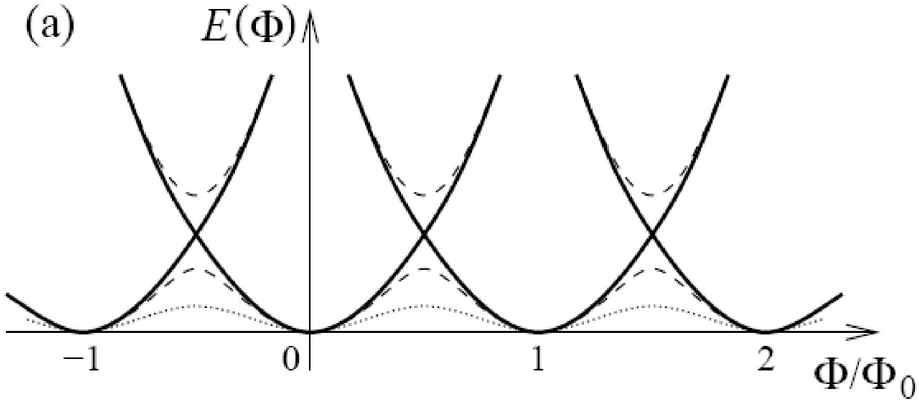
Conclusions on physics

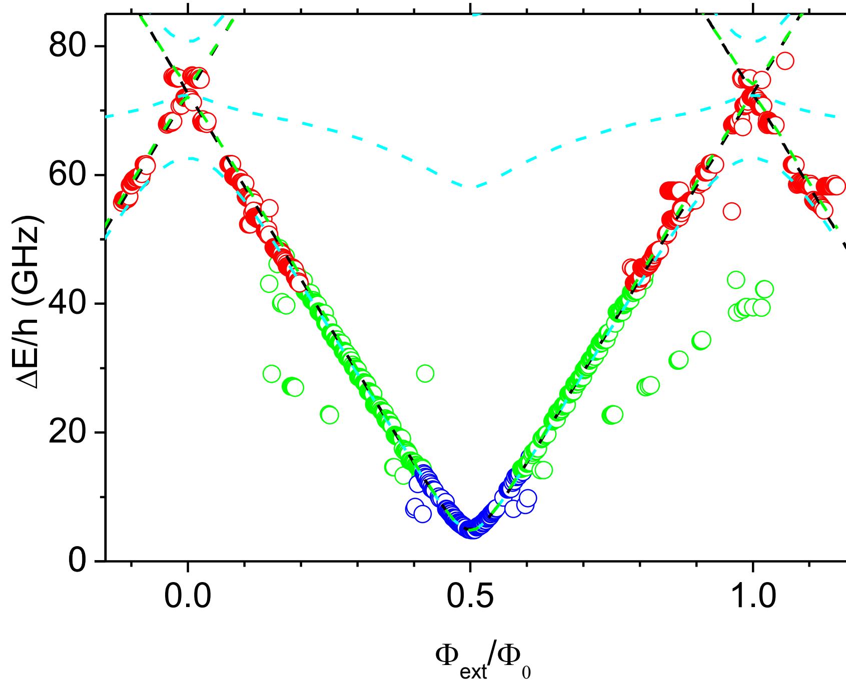
Quantum fluctuations in narrow superconducting nanowires suppress ‘basic’ superconducting attributes manifesting as:

- Broadening of the R(T) transition. In thinnest samples zero resistance is not reached even at $T \rightarrow 0$.
- Suppression of persistent currents in nanorings.
- Smearing of the superconducting gap edge.

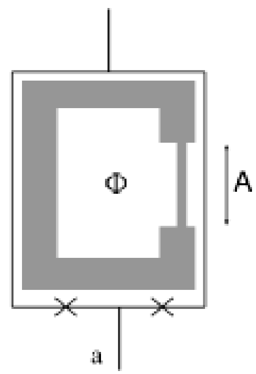
Applications

Qubit





Supercondcuting horse-shoe, shortened by a QPS nanowire

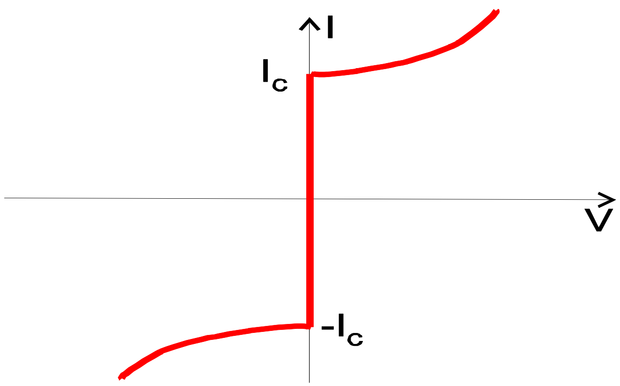


Spectroscopy of the system across a wide range of flux and frequency.

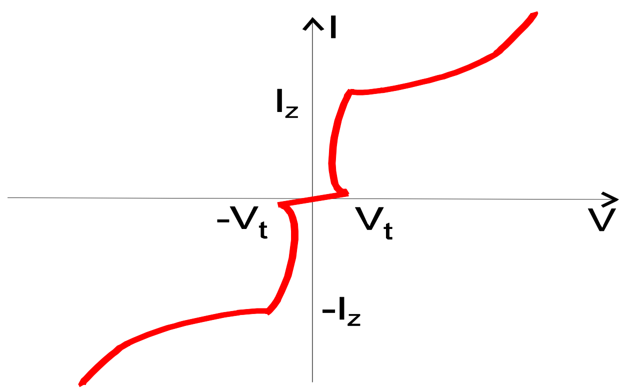
J. E. Mooij and C. J. P. M. Harmans
New J. Phys. *7,219 (2005)*

O. V. Astafiev, L. B. Ioffe, S. Kafanov, Yu. A. Pashkin, K. Yu. Arutyunov, D. Shahar, O. Cohen, and J. S. Tsai.
Nature 484, 355 (2012).

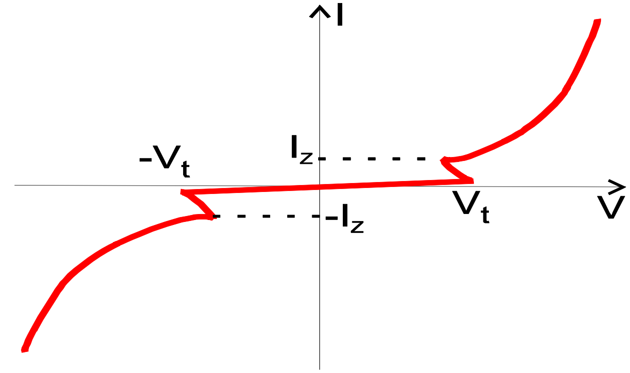
Coulomb Effects



Thick (conventional) superconducting wire



Thin wire and low-Ω environment



Very thin wire and high-Ω environment: Coulomb blockade

Quantum duality between JJ and QPS junctions

Hamiltonian of a supercondcuting nanowire in the regime of quantum fluctuations:

$$\widehat{H} = \frac{E_L}{(2\pi)^2}\widehat{\phi}^2 - E_{QPS}\cos(2\pi\widehat{q}) + \widehat{H}_{coup} + \widehat{H}_{env}$$

is dual to the corresponding Hamiltonian of a Josephson junction:

$$\widehat{H} = E_C\widehat{q}^2 - E_J\cos(\widehat{\varphi}) + \widehat{H}_{coup} + \widehat{H}_{env}$$

with the accuracy of substitution: $E_C \leftrightarrow E_L, E_J \leftrightarrow E_{QPS}, \varphi \leftrightarrow \pi q/2e$

E_L **,** E_C **,** E_J **and** E_{QPS} **are the inductive, charging, Josephson coupling and QPS energies, φ is phase and q is quasicharge.**

The extensively developed physics for Josephson systems can be 'mapped' on the superconducting nanowires in the regime of quantum fluctuations.

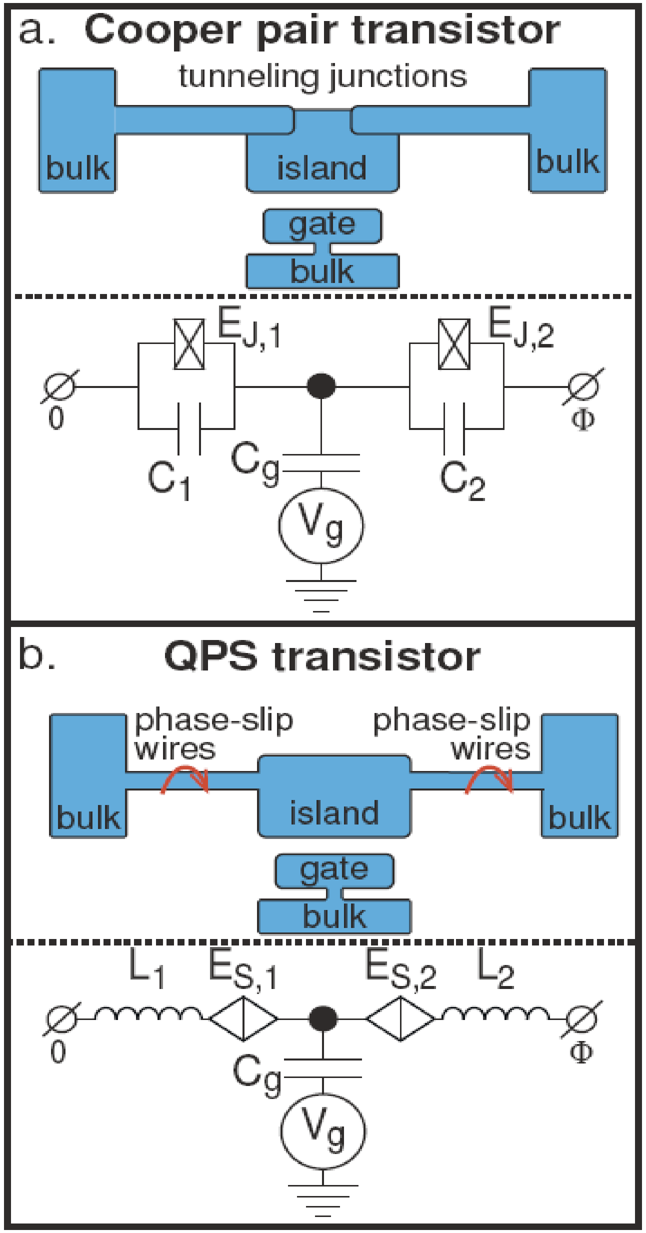
D. V. Averin and A. A. Odintsov, Phys. Lett. A ***140*** *(1989) 251*

J. E. Mooij and Yu. V. Nazarov, Nature Physics ***2*** *(2006) 169*

A. M. Hriscu and Yu. V. Nazarov. *Phys. Rev. B* 83, 174511 (2011)

Junctionless transistor

Cooper pair transistor without a tunnel junction



A.M. Hriscu and Yu. V. Nazarov. Phys. Rev. B 83, 174511 (2011)

Let us consider the simplest case of a QPS Copper pair box:

$$\hat{H}_{QPSbox} = E_c\left(\hat{Q} - \frac{q}{2e}\right)^2 + \mathrm{E_L}\hat{\phi}^2 - E_{QPS}cos(2\pi\hat{Q})$$

First two terms correspond to linear LC oscillator. If to shift the charge variable by q/2e, the induced charge disappears from the oscillator part, while the QPS amplitudes acquire the phase factors:

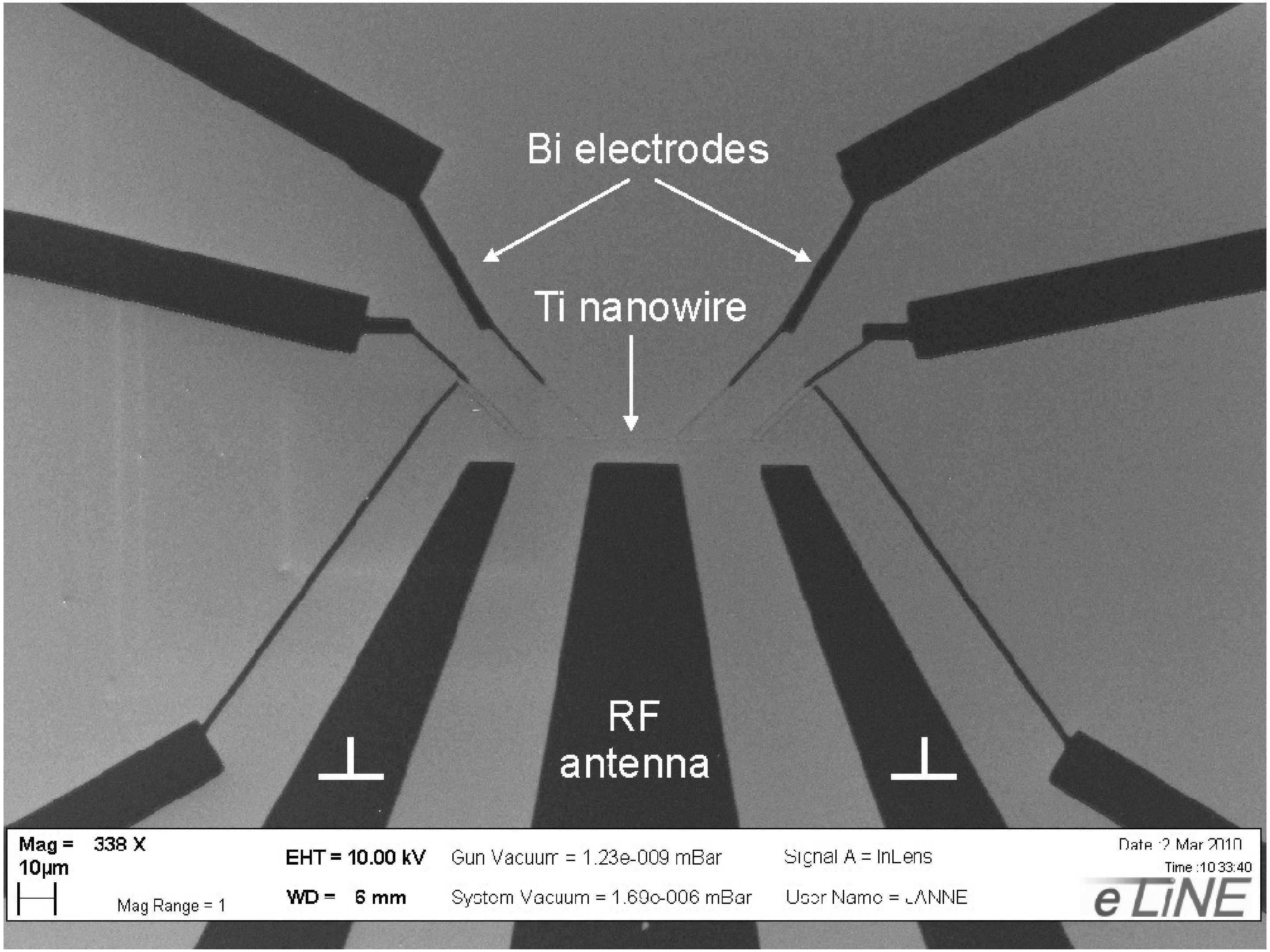
$$\hat{H}_{QPS}\psi(\phi) = -E_{QPS}e^{-\frac{i\pi q}{e}}\psi(\phi + 2\pi) - E_{QPS}e^{+\frac{i\pi q}{e}}\psi(\phi - 2\pi)$$

The charge sensitivity is purely due to the coherent QPS term: the induced charge q/2e affects the interference of the phase slips with two opposite directions ±2π.

The mandatory requirement for the charge effects observation is the high impedance of the environment: current bias→ charge is a 'good' quantum number.

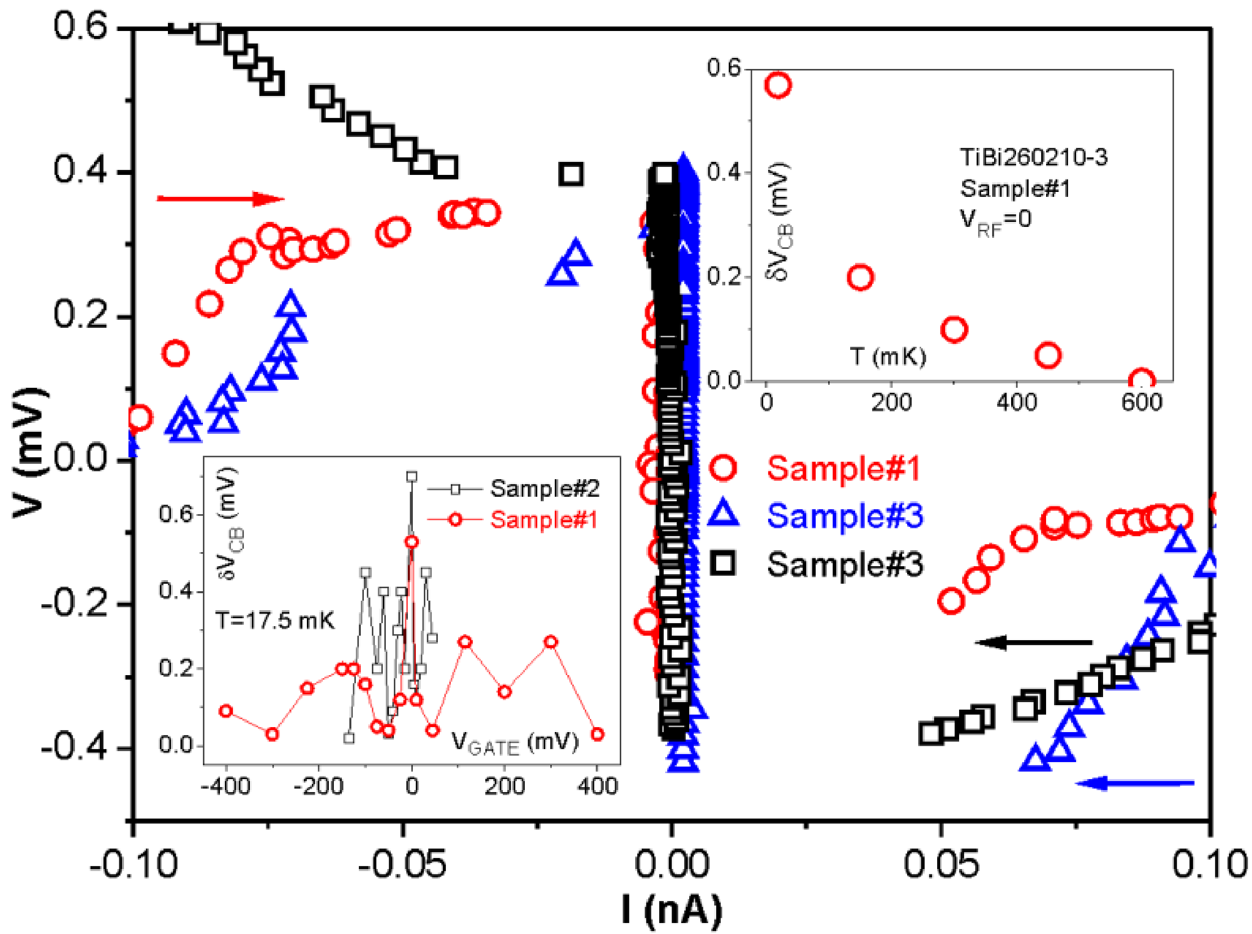
QPS is a dynamic equivalent of a conventional (static) tunnel junction.

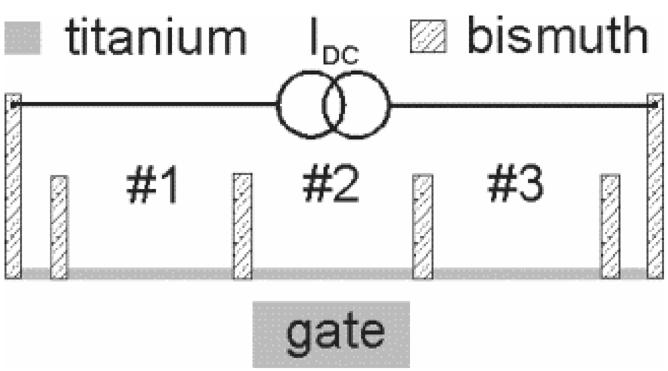
High-Ohmic environment



Purely dissipative environment:
high-Ohmic normal metal probes with R_{probe} up to 10 MOhm

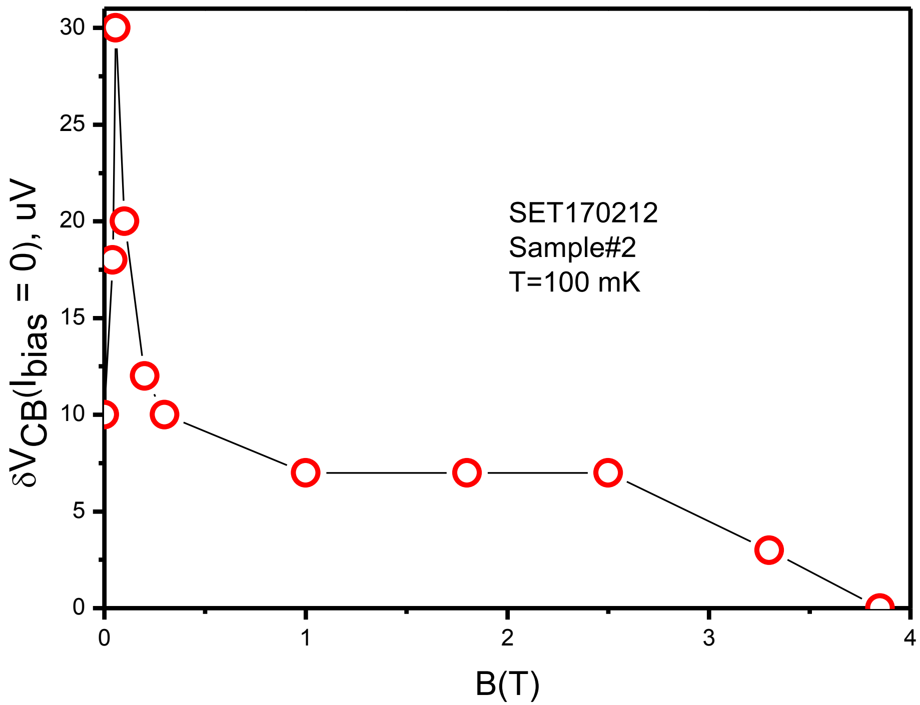
24 nm titanium nanowire, 10 MΩ contacts

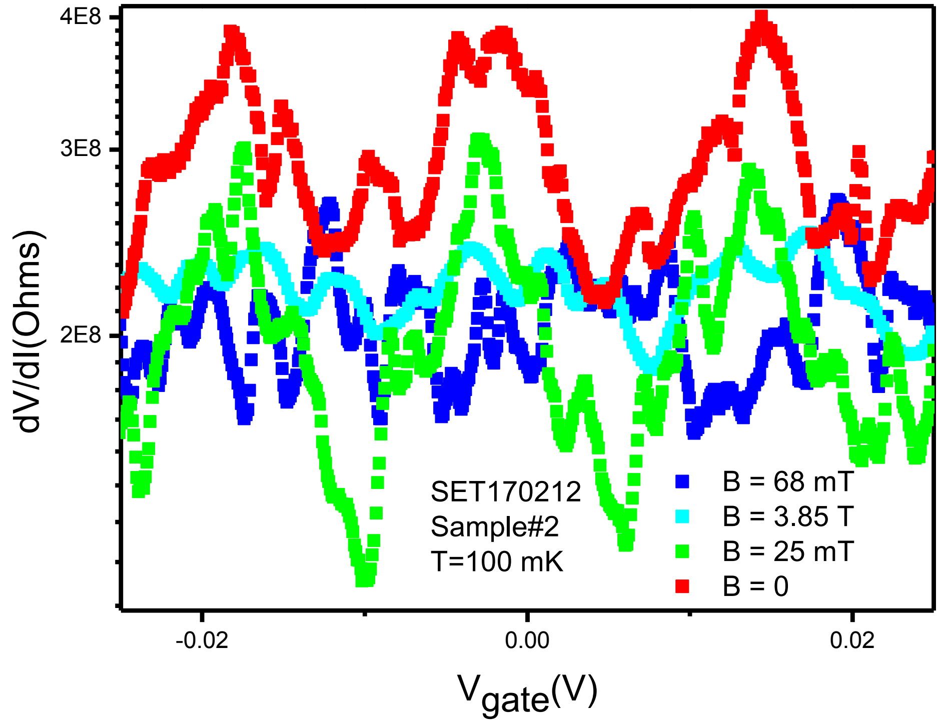




All three neighboring parts of the same multiterminal structure demonstrate the same value of the Coulomb gap. The effect disappears above T_c and/or H_c.

Magnetic field dependencies

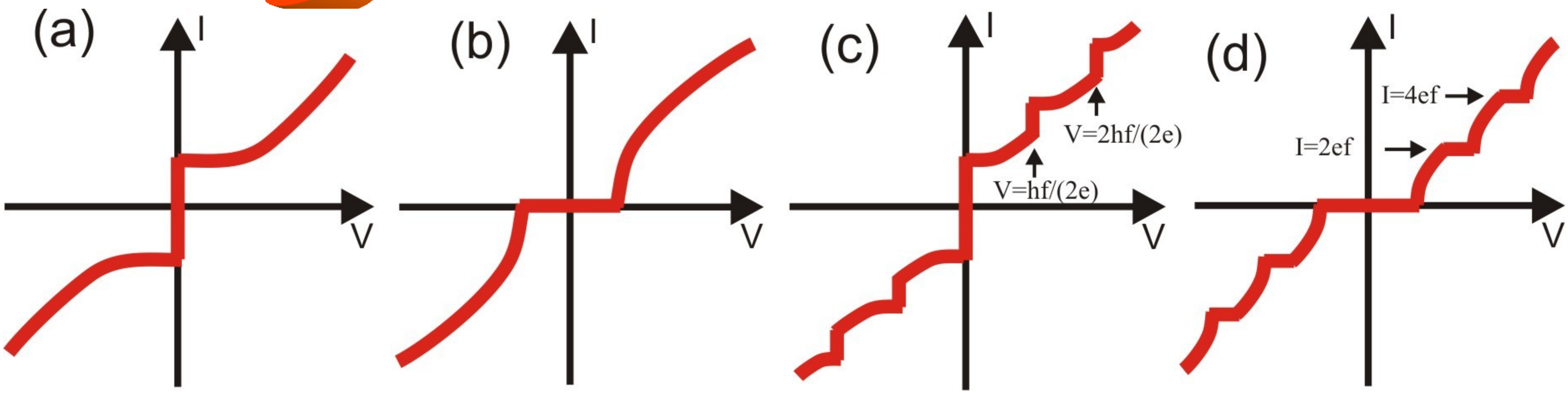




At a given (low) temperature the Coulomb gap and the gate modulation disappear above certain magnetic field (the B_c of Ti?).

Electron transport in a Cooper pair transistor is a periodic process corresponding to cyclic charging/discharging of the central island by *2e*. Syncronisation of the process with external drive should lead to resonance.

Bloch oscillations



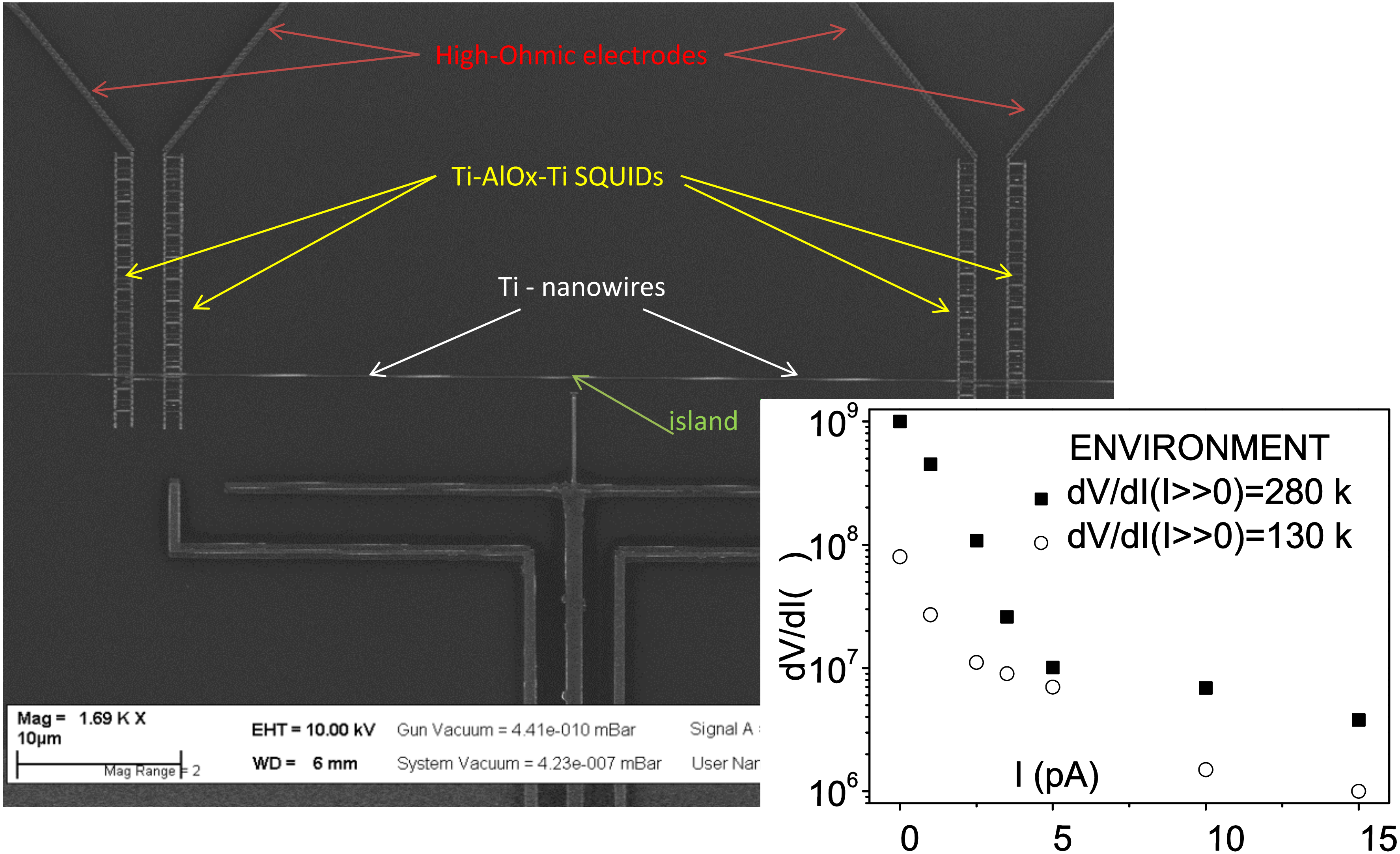
Josephson junction: critical current

QPS wire: critical voltage

Josephson junction: voltage steps (Shapiro effect)

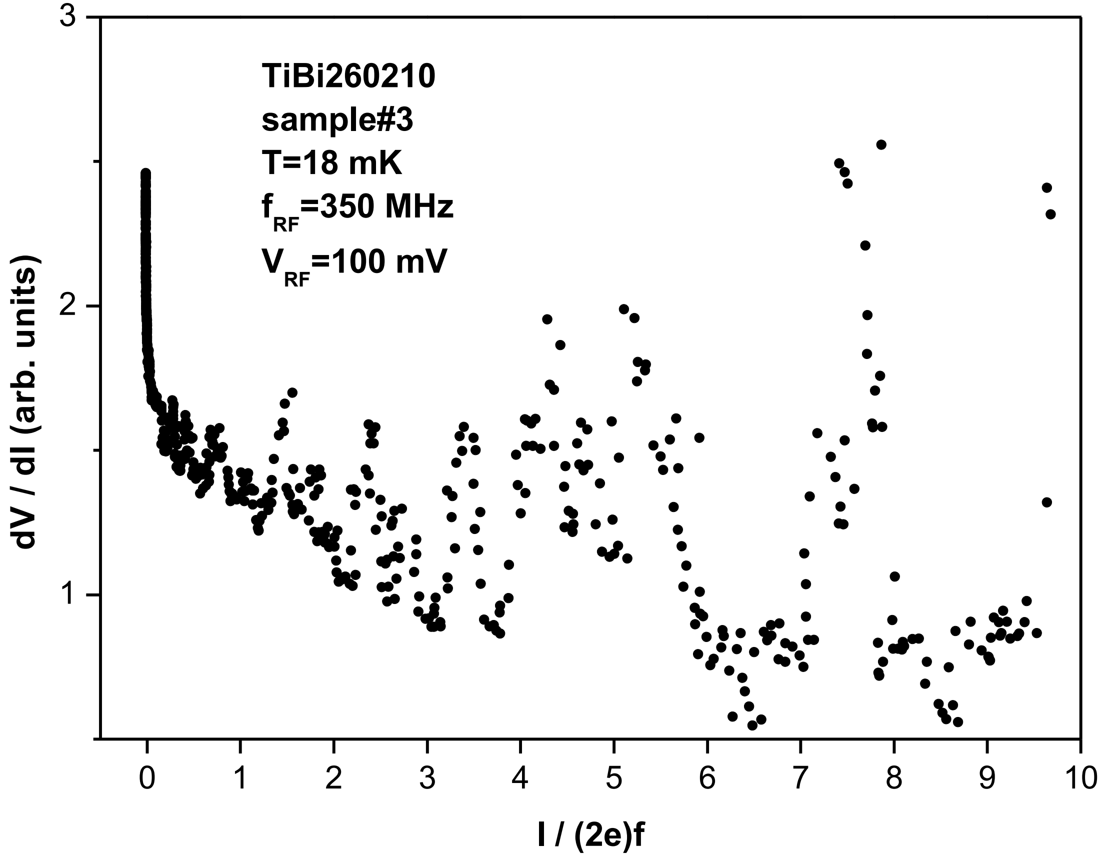
QPS wire: current steps

Hybrid high impedance environment



High-Ohmic normal metal probes with R_{probe} up to 500 KOhm and 1D array of SQUIDs.

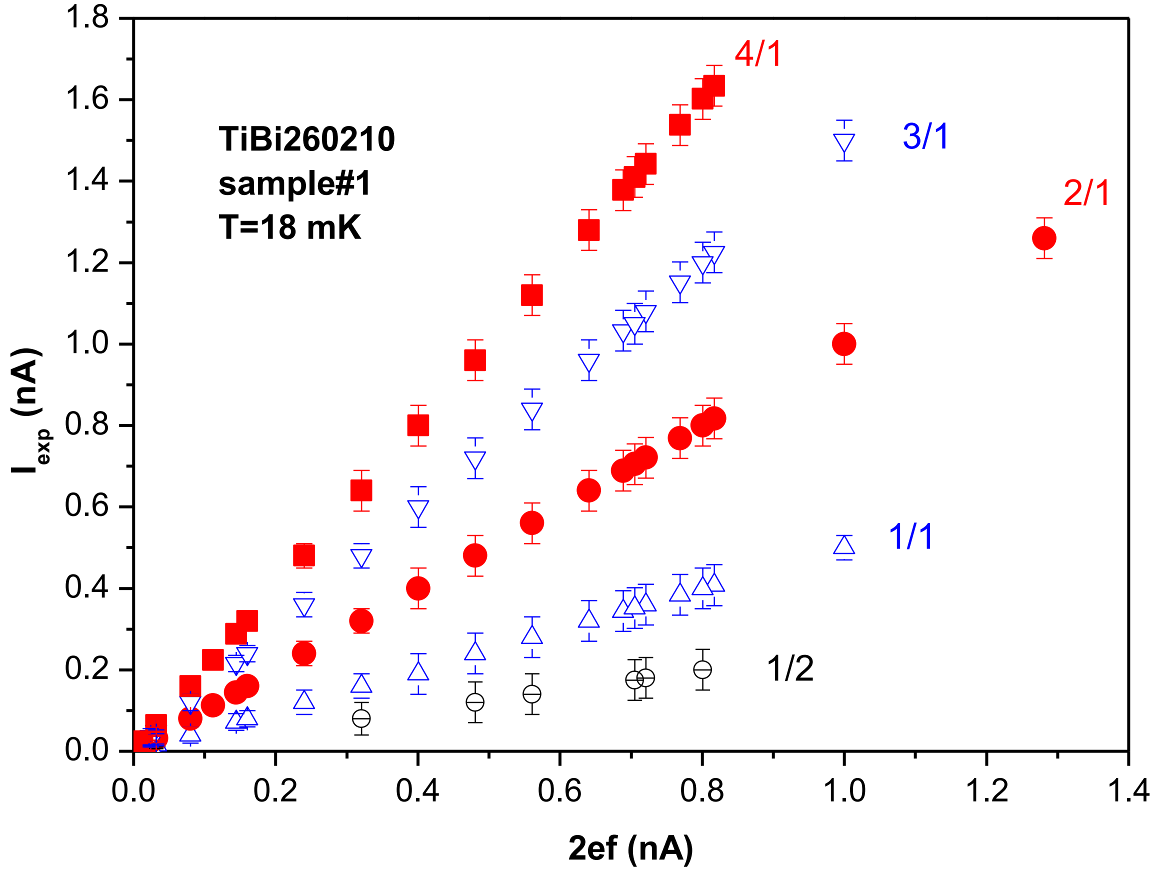
Ti-nanowire with high-Ohmic environment



dV/dI at f_{RF}=350 MHz and amplitude 100 mV. Current is normalized by (2e)×f_{RF}. One can distingush steps with quantum number n≤8.

Universal relation I(n) = (2e)*n*f_{RF}

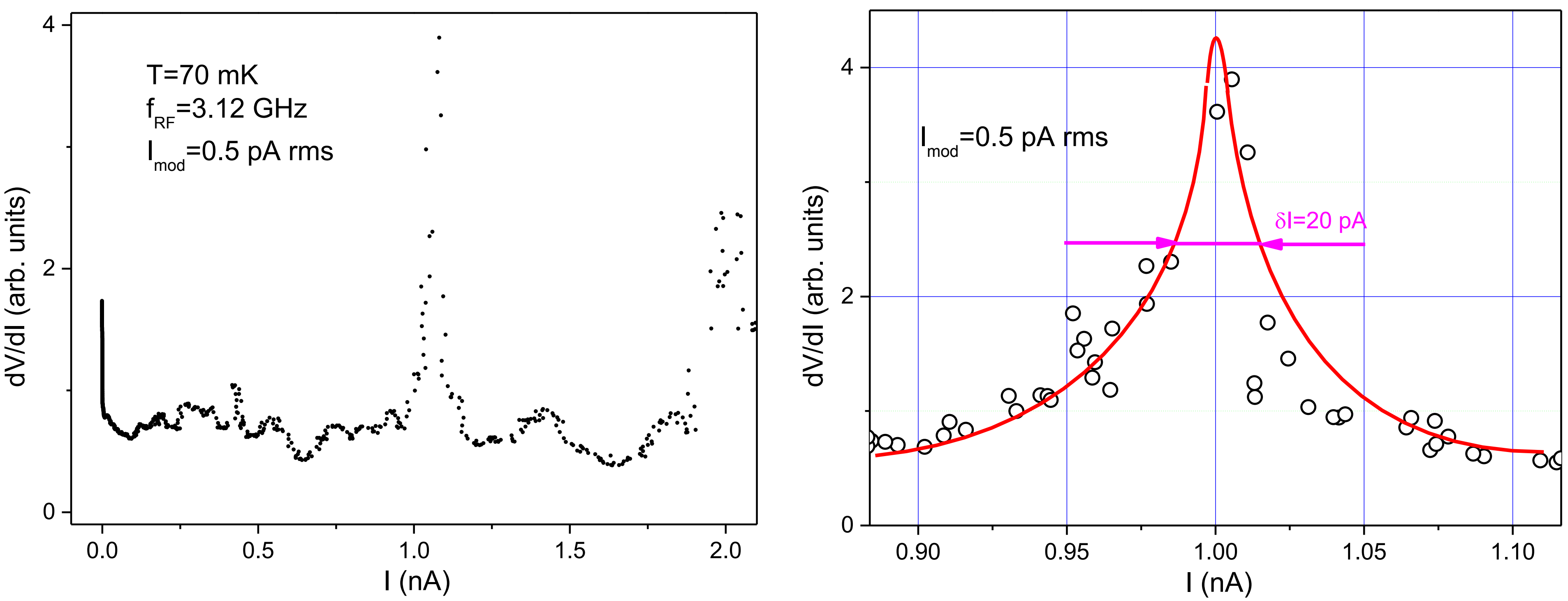
Positions of the RF-induced steps



Red symbols correspond to Bloch steps (2e), blue – single electron (e), **black – 1st subharmonic** of single electron oscillations.

Proof-of-principle demonstration of a quantum standard for electric current

Width of the Bloch step



Demonstrated accuracy is +/- 2%.
Further accuracy improovement is mandatory for practical metrology.

Digest on Coulomb effects in QPS

- Quantum phase slip and Josephson tunneling are the phenomena described by identical Hamiltonians: the quantum dynamics is indistinguishable.
- Supercondcuting nanowire (homogeneous!), in the regime of QPS, is the dynamic equivalent of a Josephson junction.
- Containing no static (in space and time) junctions, QPS nanowire can sustain much higher currents and has no undesired two-level 'fluctuators' present in tunnel contacts.
- All phenomena, observable in Josephson systems, can be observed in QPS nanowires.

Thank you!

Summer University in Moscow

Quantum Technologies

"Quantum Technologies" program provides the unique opportunity to get introduction to the quickly developing interdisciplinary topics of quantum solid state physics, quantum photonics and nanotechnology. The program includes both the introductory and the rather advanced courses at the very frontier of modern science. The invited lecturers are the world-class leading experts in corresponding fields. The training is addressed to students of bachelor / magister level who have affinity with physics, electronics, IT and computer sciences. The courses might appear attractive also to researchers in natural sciences such as chemistry and biology who wish to advance their knowledge in various phenomena related to nanoscience.

The program at the Summer University is the pilot project announcing the new English-speaking full-scale MSc program "Quantum Information Technologies (iQT)" to start at Higher School of Economics in 2017. The objective of that program is to train specialists of the highest qualification in the field of transmission, storage and processing of information using the most advanced methods of quantum physics and quantum communication. The announced courses of Summer University-2016 have been prepared by the core lecturers of the upcoming iQT program, and represent the selected and shortened versions of MSc training in quantum communication.

https://www.hse.ru/international/summer/quantum