Coulomb blockade and coherent single-electron transport in nanowires undergoing a superconductor-insulator transition

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Outline

- Fabrication, TEM, SEM

-Superconducting State (short summary)

- Insulating State

Weak Coulomb Blockade of Coherent transport

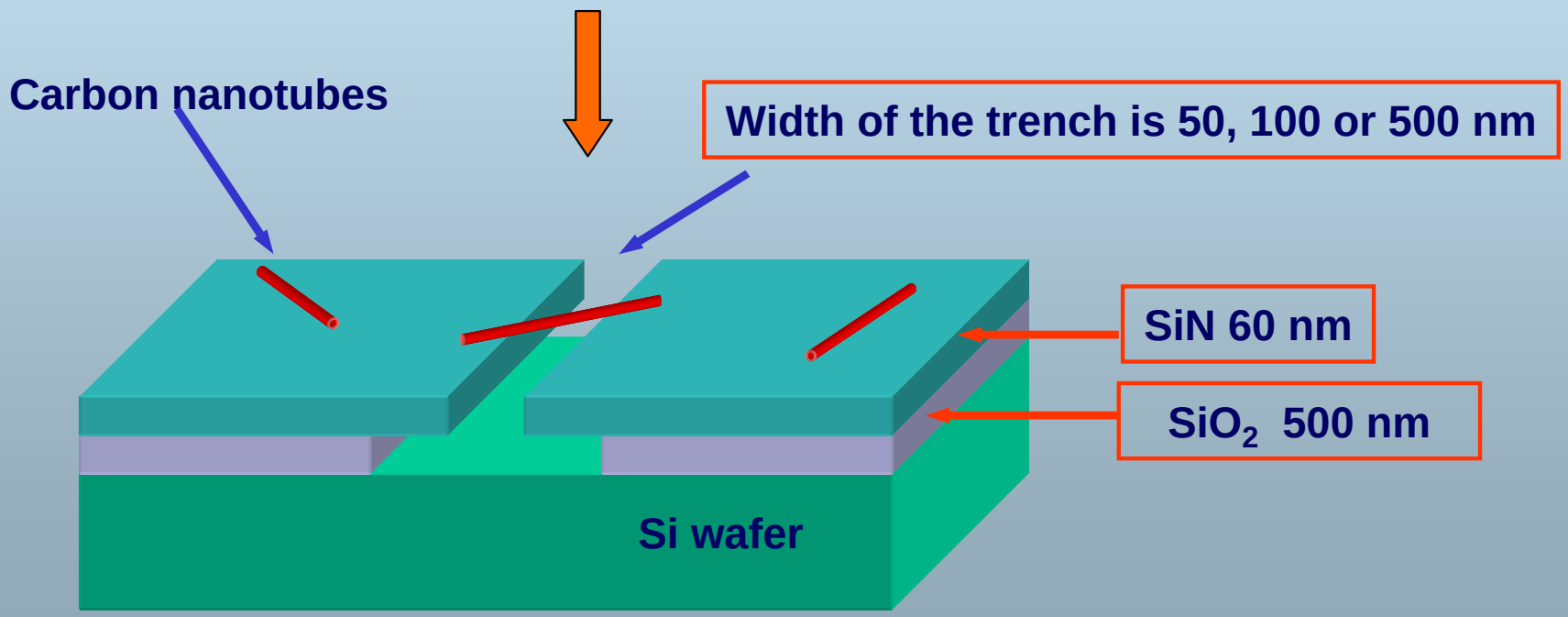
FABRICATION

Fluorinated carbon nanotube – molecular template for metal deposition

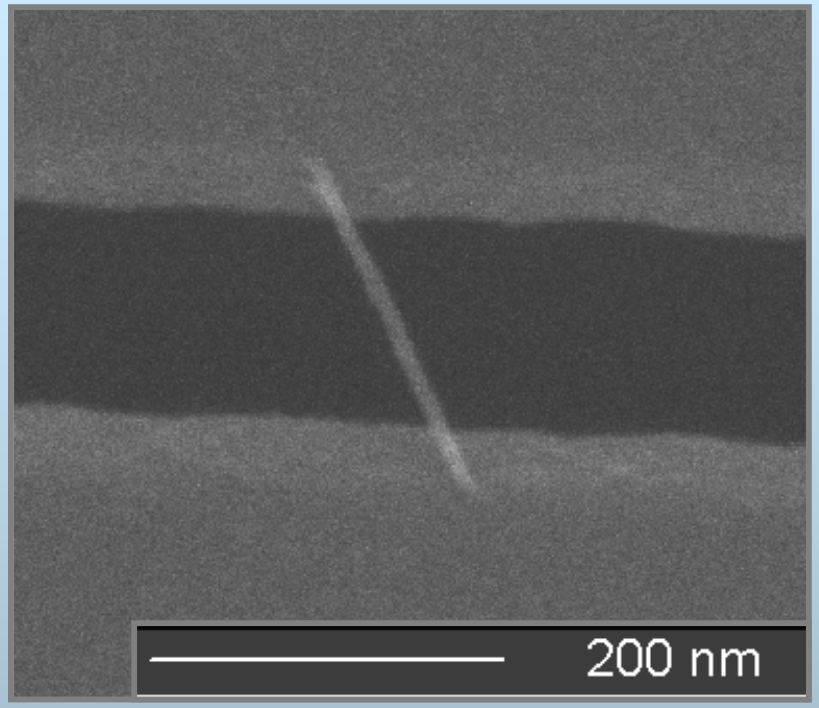
Sputter material deposition

(typical thickness 3-10 nm)

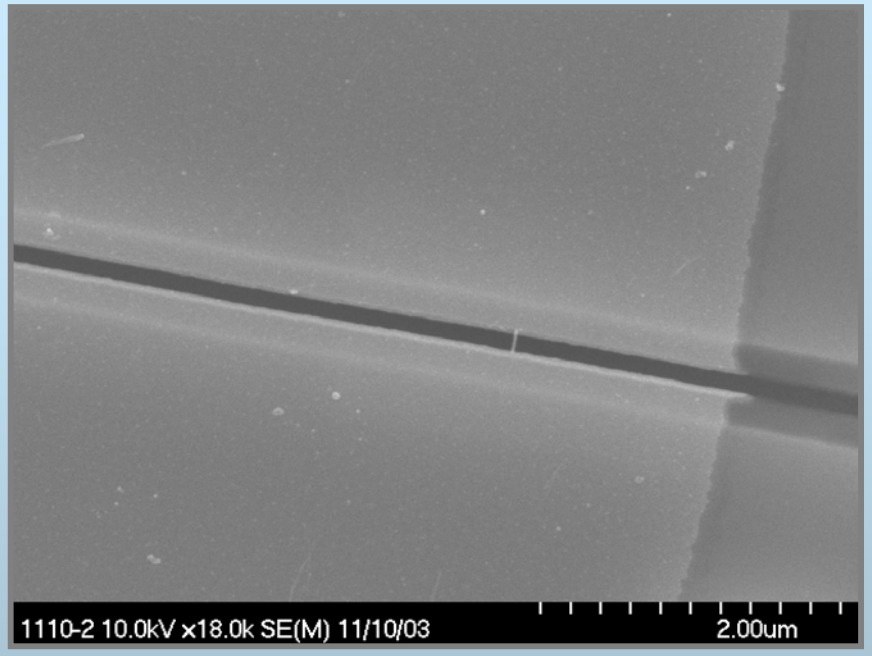
$Mo_{79}Ge_{21}$ alloy
Amorphous superconductor
T_c~7.4 K
ρ ~180 $\mu\Omega$ cm



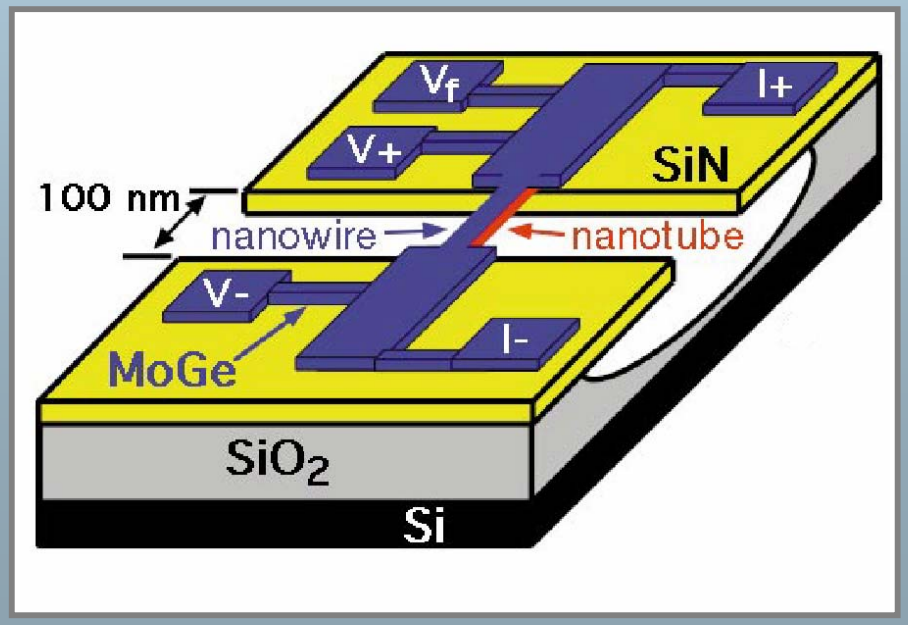
SEM image of a typical wire



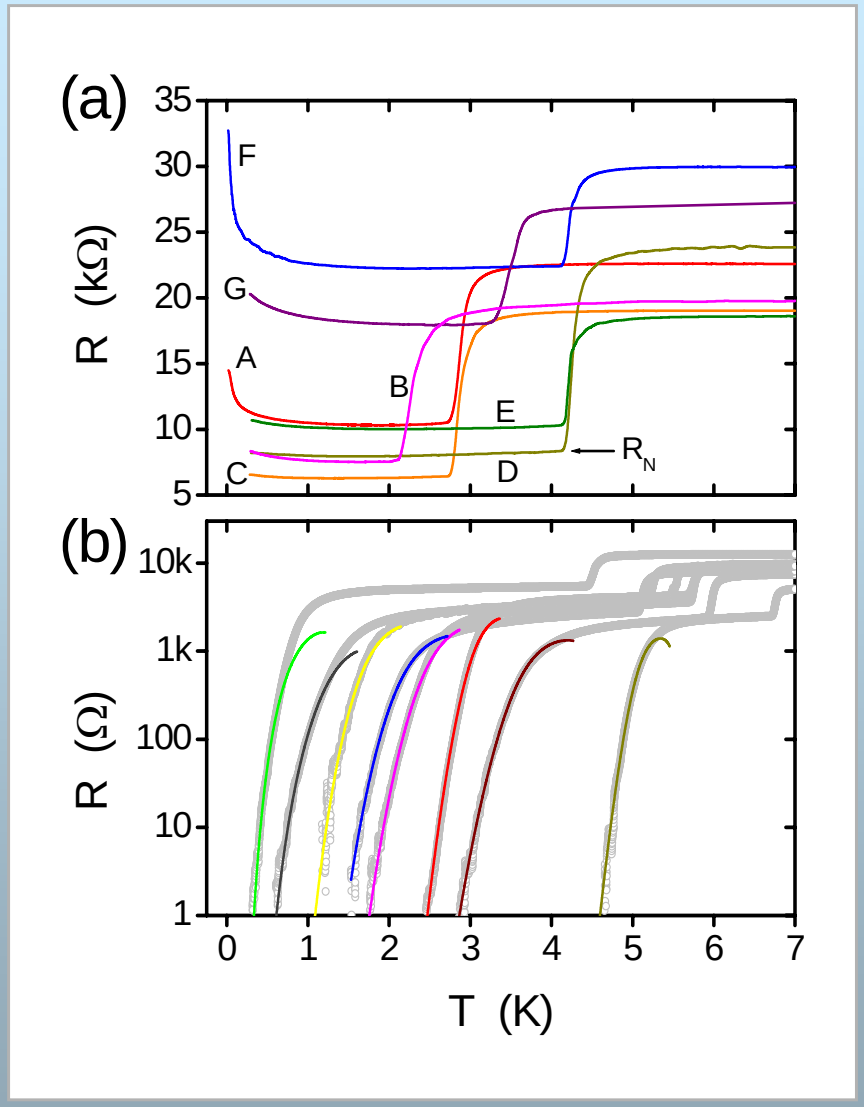
A nanowire and film electrodes



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



Superconducting wires. Summary.



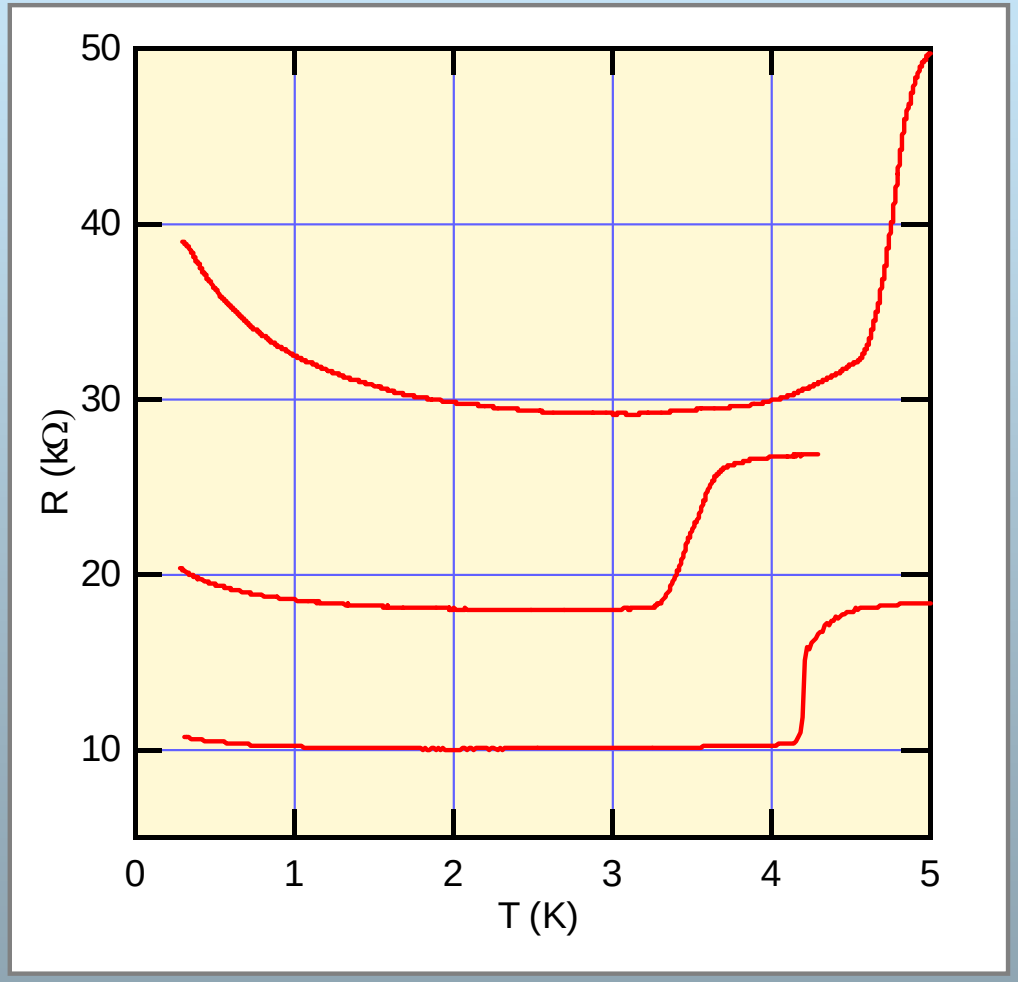
1. The LAMH theory of thermally activated phase slips explain R(T) dependence both at low and high current biases.
2. Effects of magnetic filed are well explained by the theory of pair-breaking perturbations.
3. No evidence of Quantum Phase Slips was found in superconducting-phase wires. There are no crossover.
4. Superconductor - insulator transition is abrupt. Quantum phase transition does take place**.**

Questions

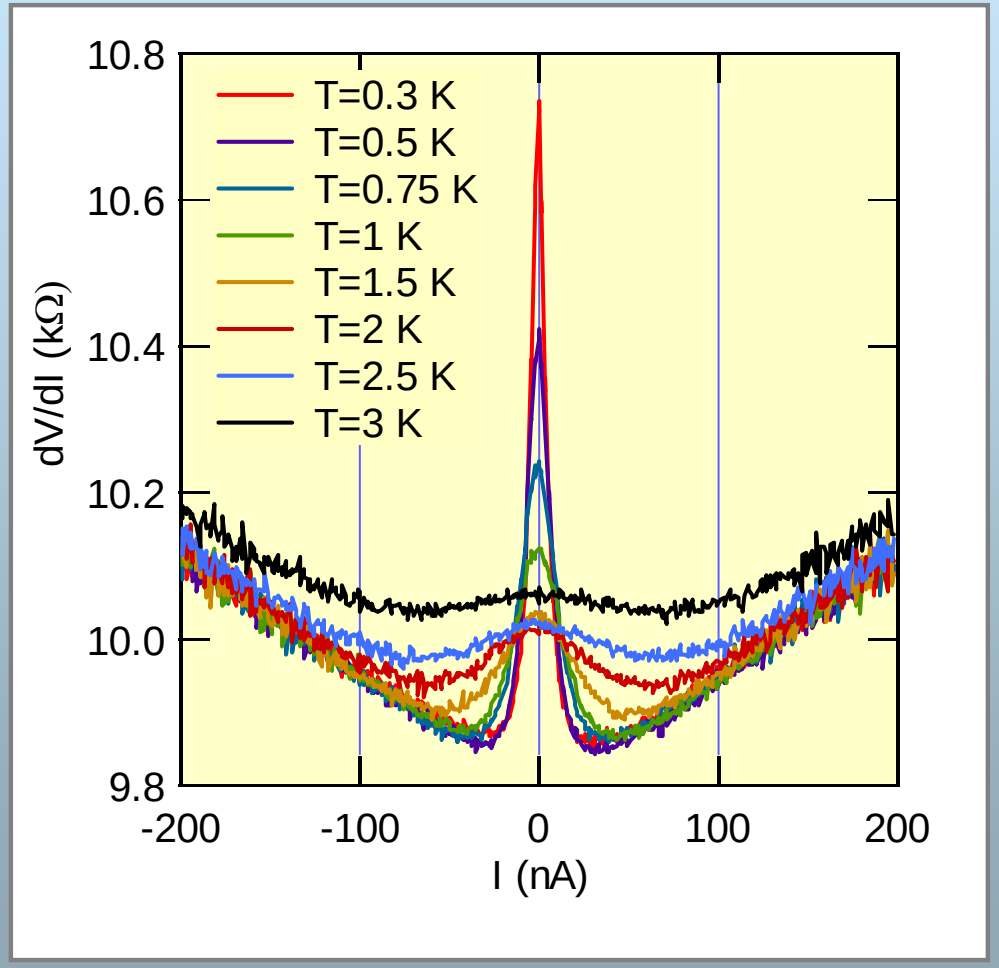
What parameter drives wires into the insulating state?
What is the nature of the SIT?

Insulating State

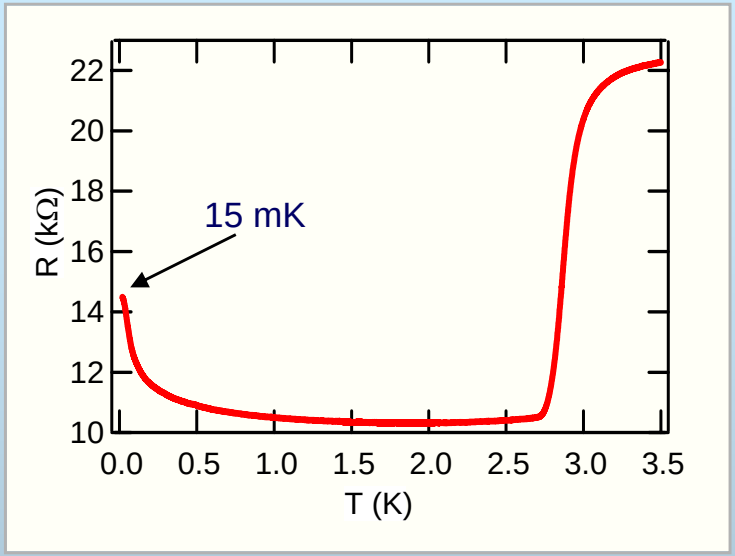
R vs T

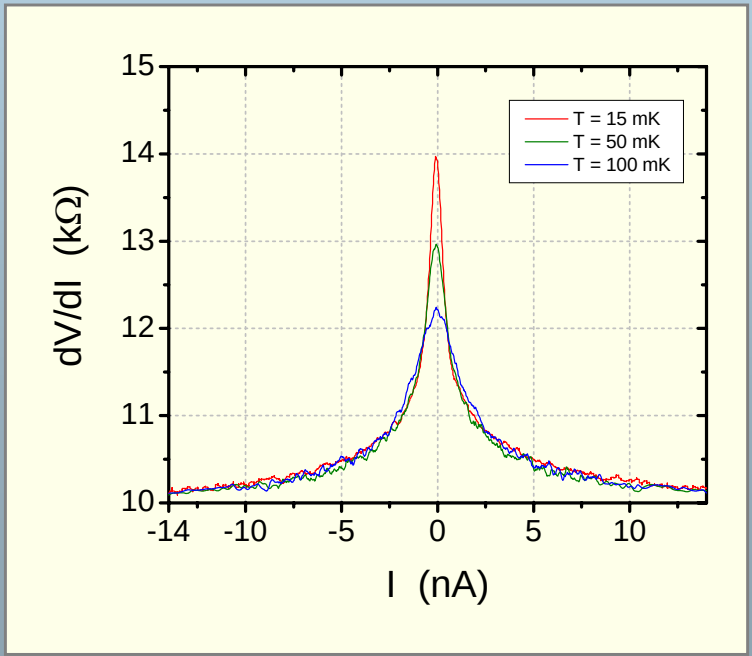


dV/dI vs I



Proximity effect is suppressed





Diffusive **S-n-S** structure

P. Dubos *et al*. PRB 63, 064502 (2001)
Low-T limit of the Josephson critical current

$$eR_N I_C = 10.82 E_{Th}$$

$$E_{Th} = \hbar D / L^2$$

$$D = 0.5\ (\mathrm{cm}^2/\mathrm{s}), \quad L = 50\ \mathrm{nm}$$

$$E_{Th} = 150\ \mathrm{mK}, \quad I_C = 13\ \mathrm{nA}$$

Probing current - 100 pA

$$E_J = \hbar I_C / 2e = 650\ \mathrm{mK}$$

Thermal fluctuations should not destroy supercurrent

Coulomb Blockade without Tunnel Junctions

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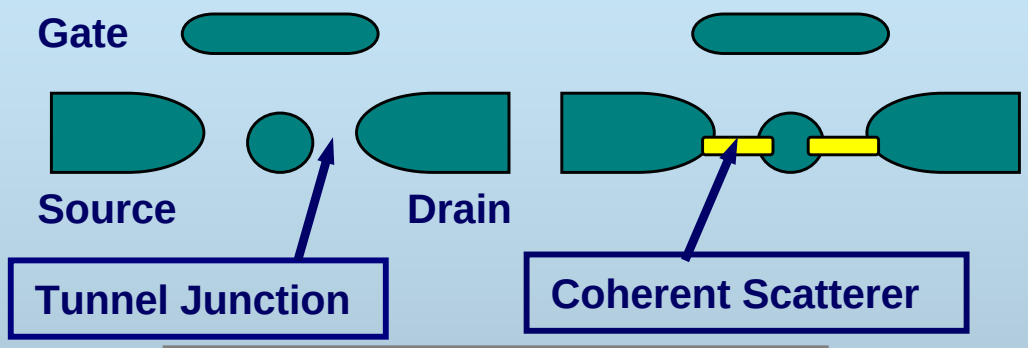
(Received 21 August 1998)

Tunnel junctions are not needed to provide single electron effects in a metallic island. Eventually the tunnel junction may be replaced by an arbitrary scatterer. To formulate this in exact terms, we



$$\tilde{E}_C / E_C \propto \exp(-\pi^2 R_K / 8R_0)$$

E_C – bare charging energy, $R_K = h/e^2$

$\tilde{E}_C$ – renormalized charging energy

R_0 – resistance without CB

Conditions $L<L_\phi$ $L<L_T$

A. Kamenev, PRL, 85, 4160 (2000)
Effect survives at $L>L_T$

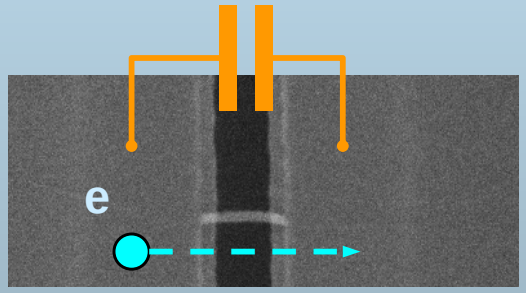
D. Golubev and A. D. Zaikin, PRL, 82, 4887 (2001).
Prediction for R(T) and I(V) dependences

LevyYeyati *et al*. PRL 87, 046802 (2001)
Link between Coulomb blockade and a shot noise reduction

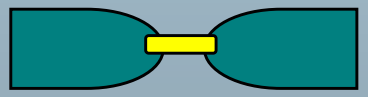
Our nanowires are coherent.

Nanowire length: 50 - 150 nm.
T=1 K, L_{in}=280 nm, T=0.3 K L_{in}=950 nm

$$L_T = \sqrt{hD/k_B T} \approx 20 \text{ nm at } T=1 \text{ K}$$



Our case is a single tunnel junction



Complications:

1. **Capacitance is not easy to define.**
2. **CB is environmental.**
3. **Electrodes are superconducting.**

GZ theory

(Golubev, Zaikin PRL 2001)

$$I = \frac{V}{R} - e\frac{1}{3}k_B T \,\mathrm{Im}\left[w\Psi\left(1+\frac{w}{2}\right) - iu_{GZ}\Psi\left(1+\frac{iv}{2}\right)\right]$$

$$g = R_K / R_0 \;?\; 1$$
$$\max(eV, T) \;?\; gE_C \exp(-g/2)$$

$\Psi(x)$ – digamma function, $w = u_{GZ} + iv$

$u_{GZ} = gE_C / \pi^2 k_B T, \quad v = eV / k_B T$

first order in $E_C / k_B T$

$$\frac{G(T)}{G_0} = 1 - \frac{1}{3}u\frac{v\sinh(v) - 4\sinh^2(v/2)}{8\sinh^4(v/2)}$$

$$u = e^2 / Ck_B T$$

Coulomb blockade for Tunnel Junction at high temperatures

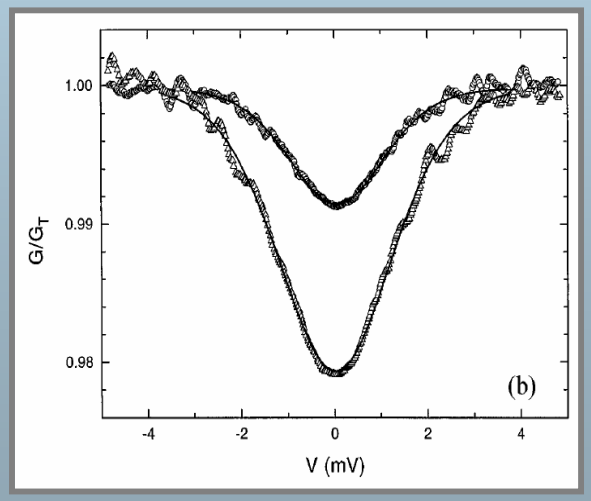
(Pekola, Hirvi, Kauppinen, Paalanen, PRL 1994)

$$\frac{G(T)}{G_0} = 1 - u\frac{v\sinh(v) - 4\sinh^2(v/2)}{8\sinh^4(v/2)}$$

$$\beta = \frac{\sum_N T_N(1-T_N)}{\sum_N T_N} = \begin{cases} 1 & \text{for tunneling junction} \\ 1/3 & \text{for diffusive conductor} \end{cases}$$

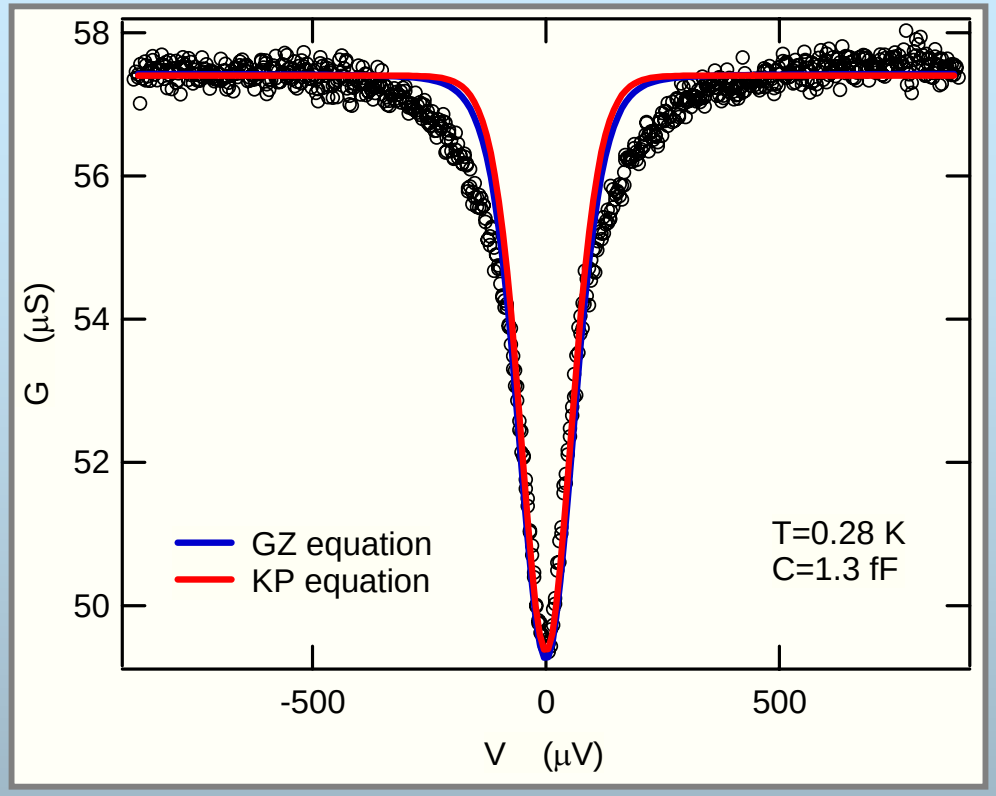
Temperature defines the width $V_{1/2} = 5.44 k_B T / e$

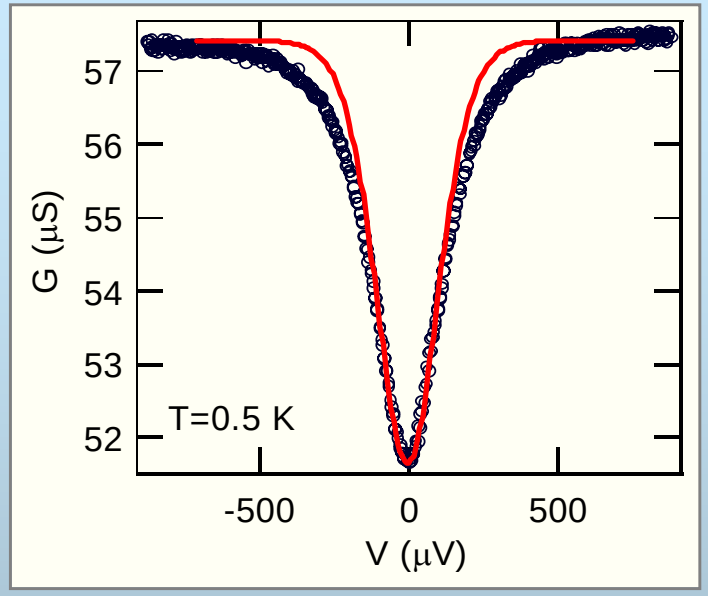
Capacitance and temperature define the height

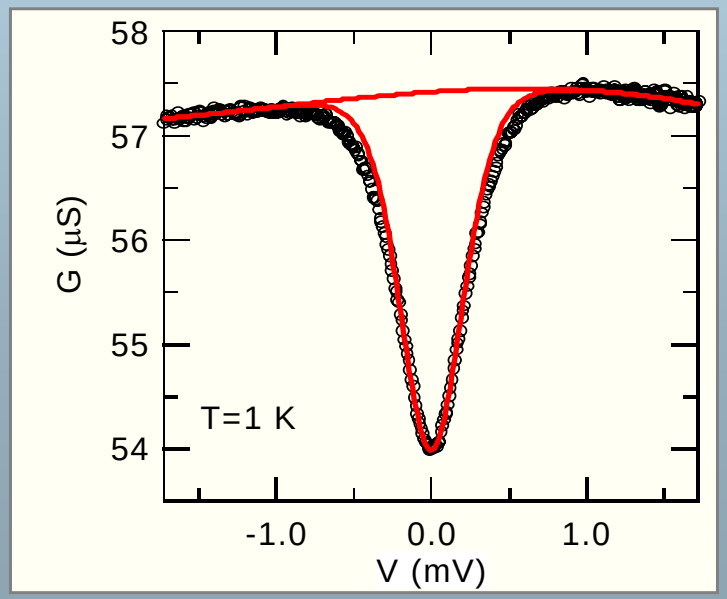


(Kauppinen, Pekola PRL 1996)

Comparison with weak Coulomb blockade theory



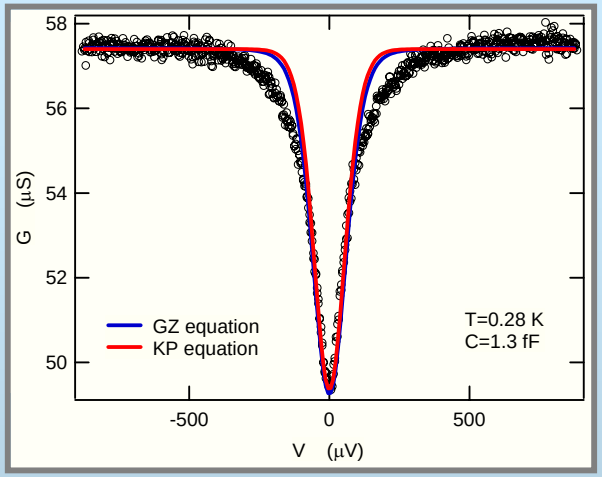




Fitting parameters G_0 and C

$$V_{1/2} = 5.44 k_B T / e$$

G(T) dependence at zero bias

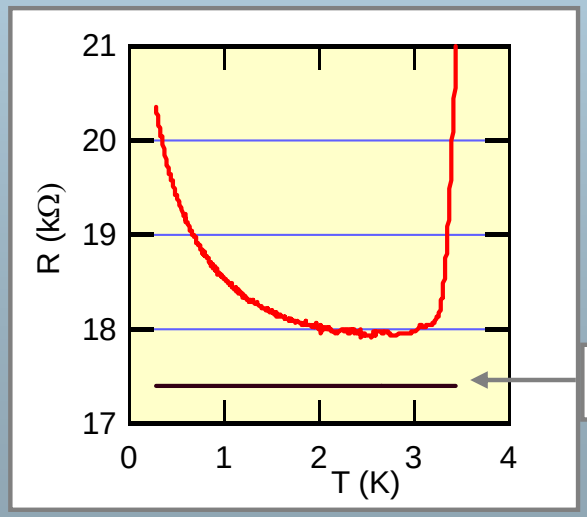


G_0=57.5 μS

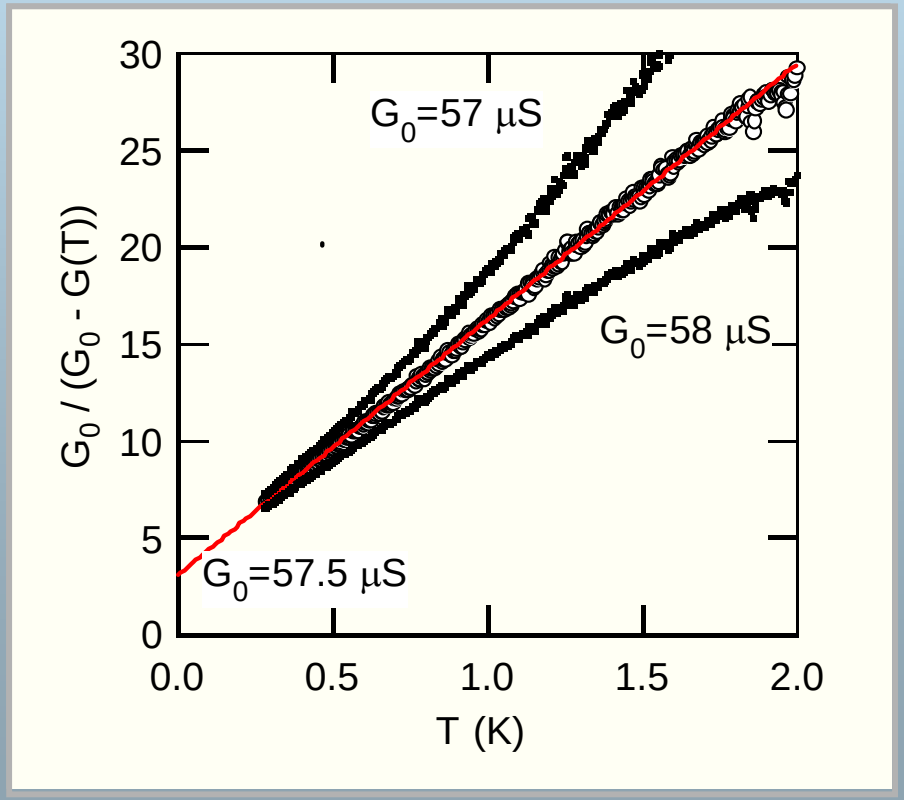
$$\frac{G(T)}{G_0} = 1 - \frac{1}{3}\left\{\frac{E_C}{3k_BT} - \left(\frac{3\zeta(3)}{2\pi^4}g + \frac{1}{15}\right)\left(\frac{E_C}{k_BT}\right)^2\right\}$$

$$\frac{G_0}{G_0 - G(T)} = 9\frac{k_BT}{E_C} + 27\left(0.019\frac{R_K}{R_0} + 0.067\right)$$

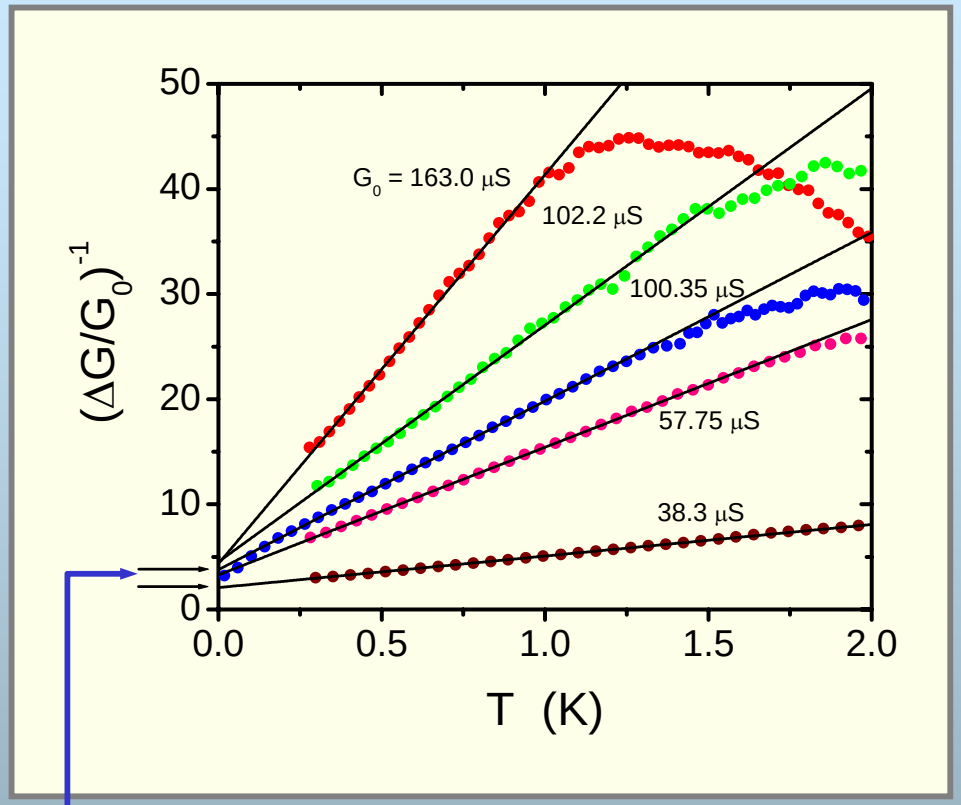
G_0 =1/R_0 conductance without CB is taken from high bias dV/dI measurements



R_0=17.4 kΩ



G(T) dependence. Impedance of environment.



Range of offsets expected from the GZ theory

$$\frac{G_0}{G_0 - G(T)} = 9\frac{k_B T}{E_C} + 27\left(0.019\frac{R_K}{R_0} + 0.067\right)$$

Dynamical (environmental) CB

P. Joyez and D. Esteve, PRB 56, 1848 (1997)

Resistive environment

At high temperature

$$\frac{G_0}{G_0 - G(T)} = 3\frac{k_B T}{E_C} + 9\left(0.019\frac{R_K}{R_{ENV}} + 0.067\right)$$

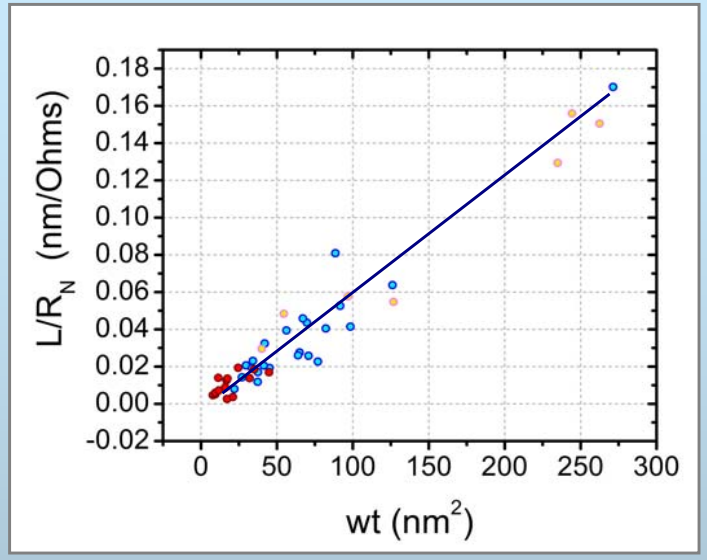
$R_{ENV} = Z_{vac} \approx 377\ \Omega$

$offset = 12.3$ for tunnel junction

$offset = 37$ for diffusive conductor

Where is the capacitance?

Granularity of wires ?



L – length, W – width, t – thickness of a wire

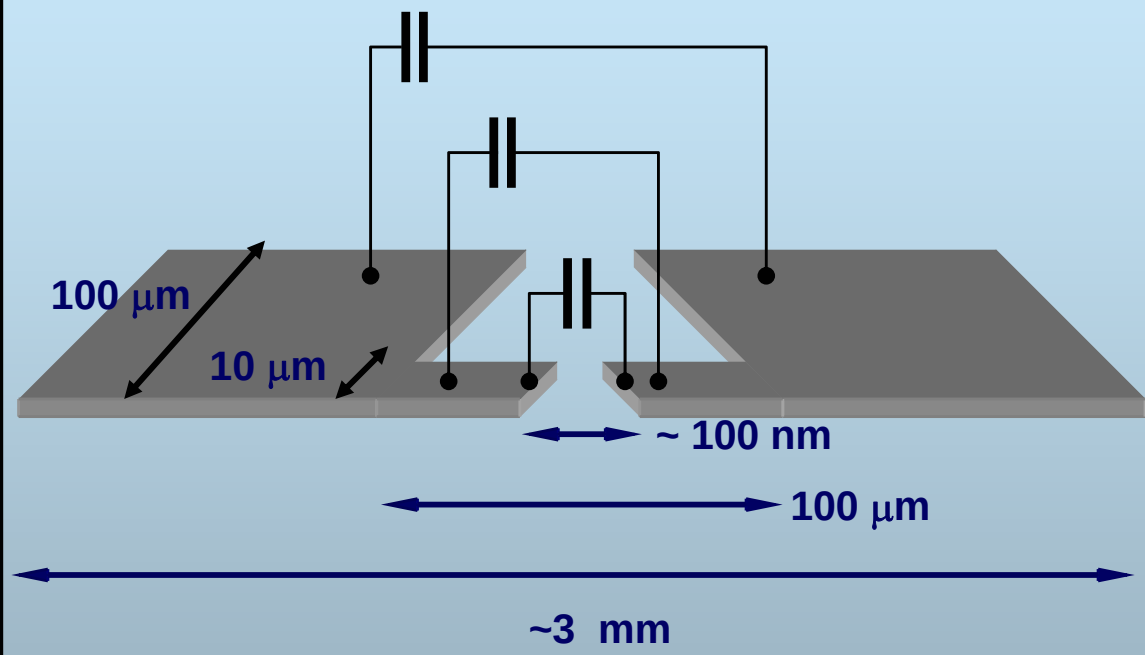
ρ=180 $\mu\Omega$ cm – close to ρ of MoGe

Array of tunneling junctions

(Pekola, Hirvi, Kauppinen, Paalanen, PRL 1994)

$$V_{1/2} = N 5.44 k_B T / e$$

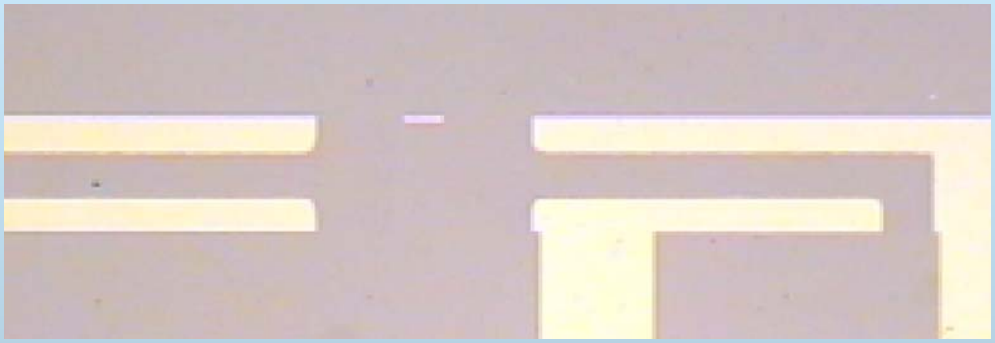
Geometry of the structure



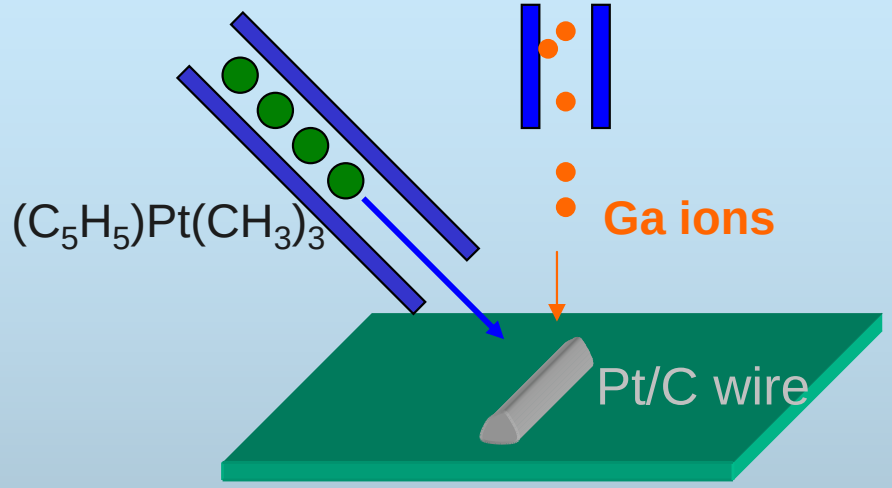
Edges C ~ 4 aF
Fingers C ~ 1 fF
All C ~ 10 fF

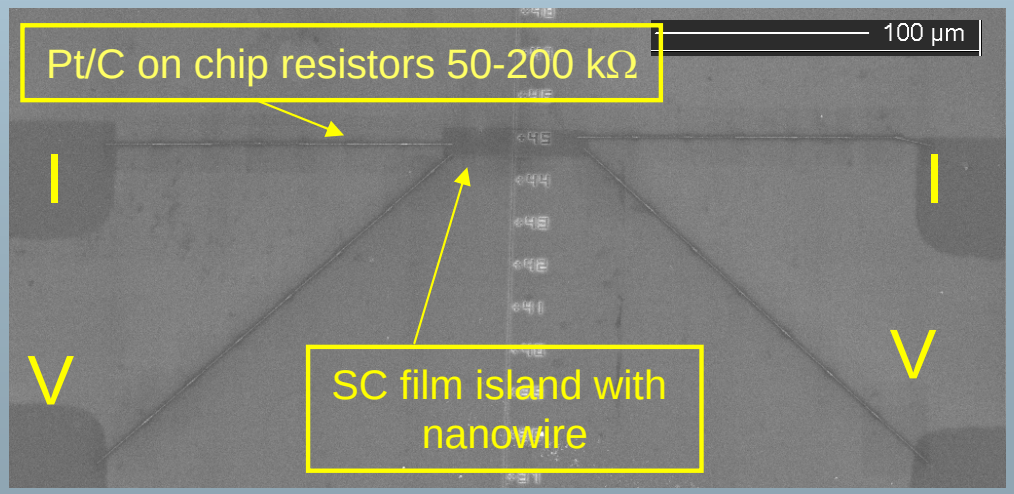
Fabrication of nanowire structures isolated from environment

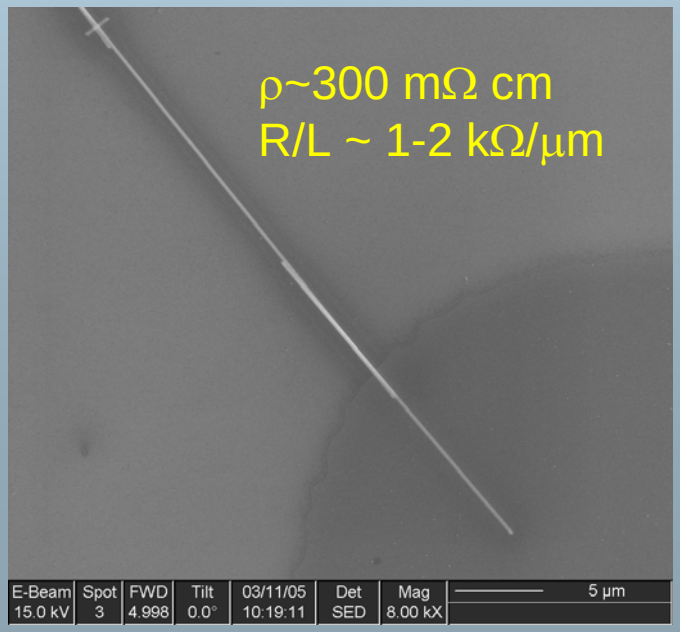
High-Ω on chip Pt/C resistors

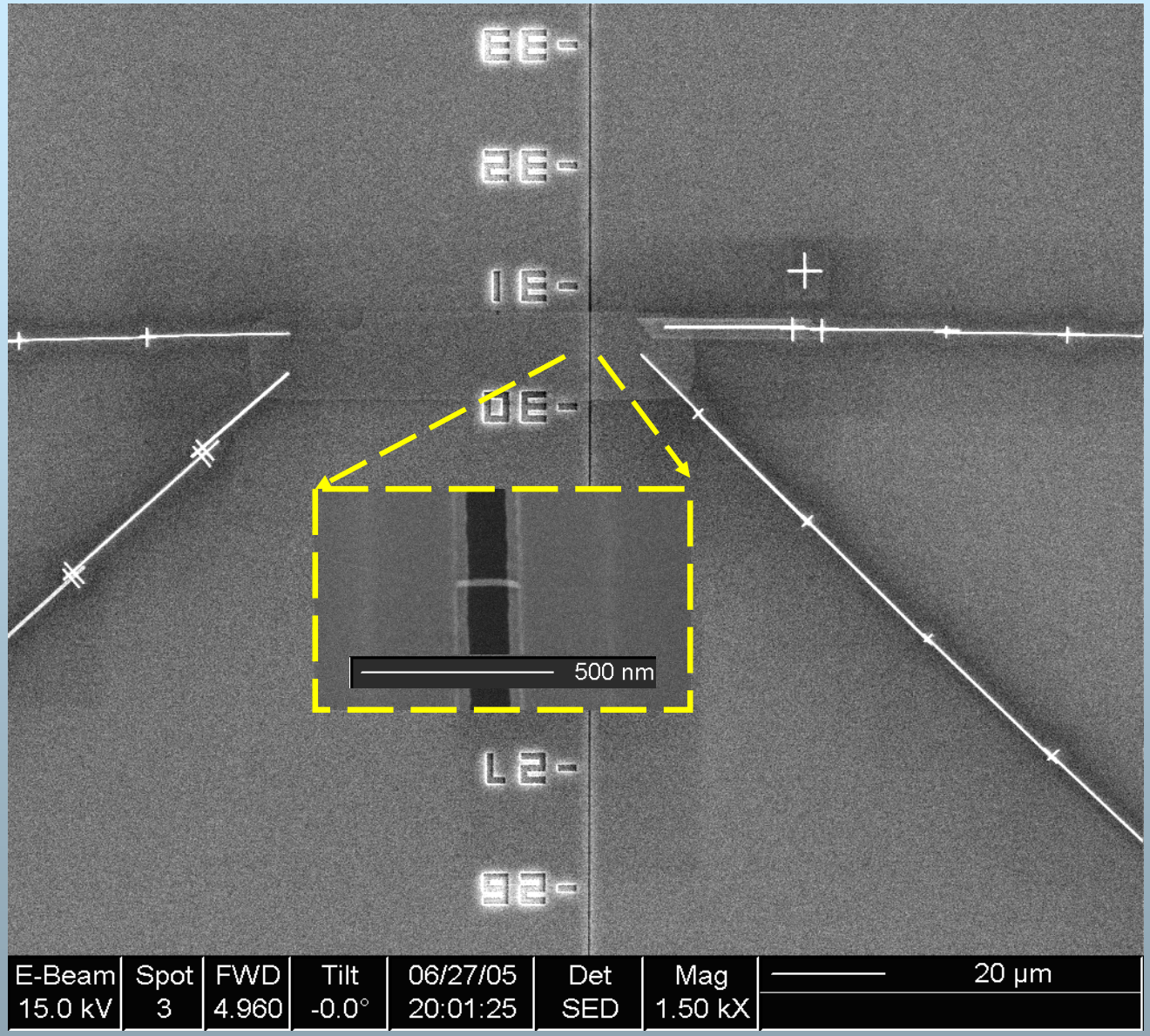


Focused Ion Beam assisted wire deposition
FEI DB 235 FIB

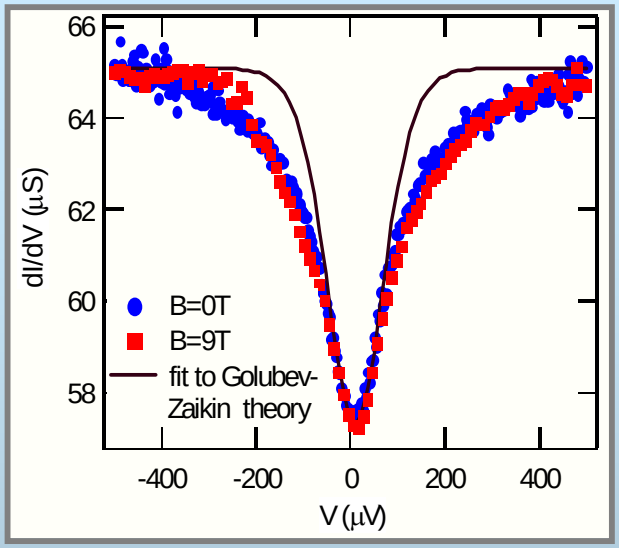




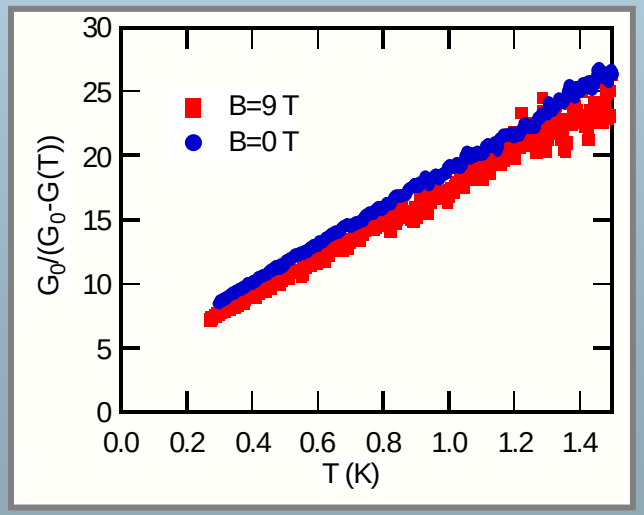



500 nm
E-Beam
15.0 kV
Spot
3
FWD
4.960
Tilt
-0.0°
06/27/05
20:01:25
Det
SED
Mag
1.50 kX
20 µm

Insulating wire far from transition R_N=15.7 kΩ



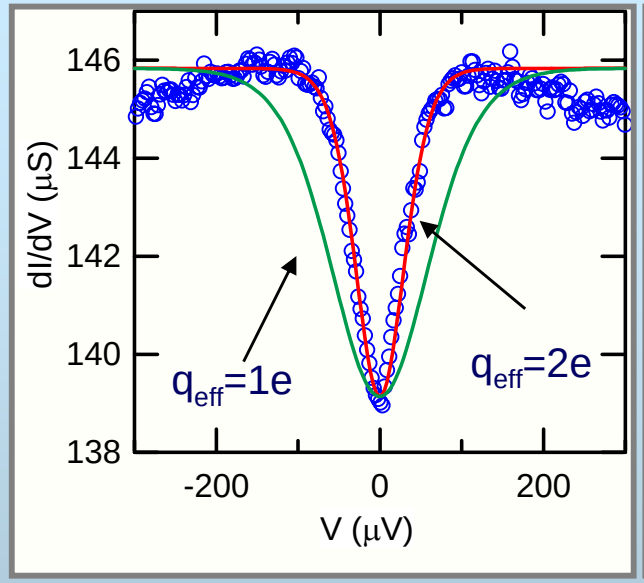
$$V_{1/2} = 5.44 k_B T / e$$

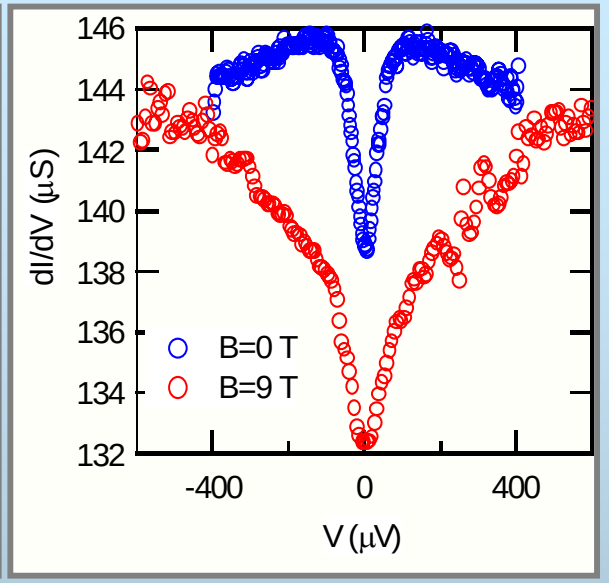


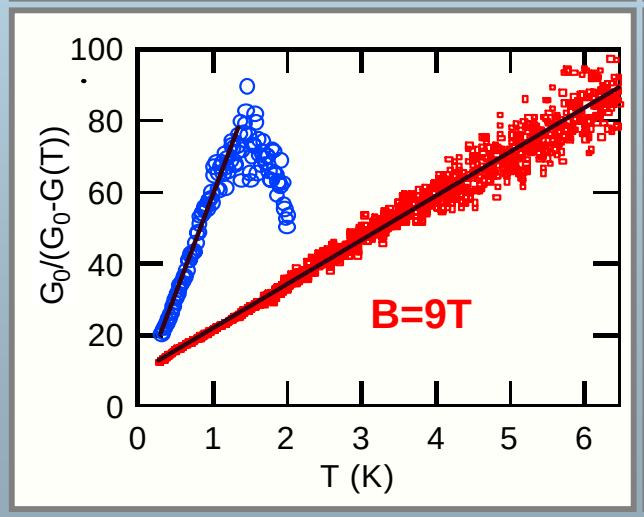
E_C ; 5.2×10^{-5} eV

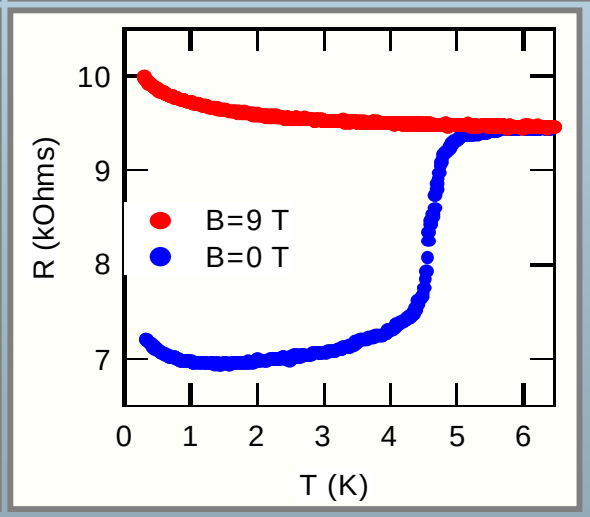
C ; 1.5 fF

Insulating wire close to the superconductor-insulator transition, R_N=7 kΩ







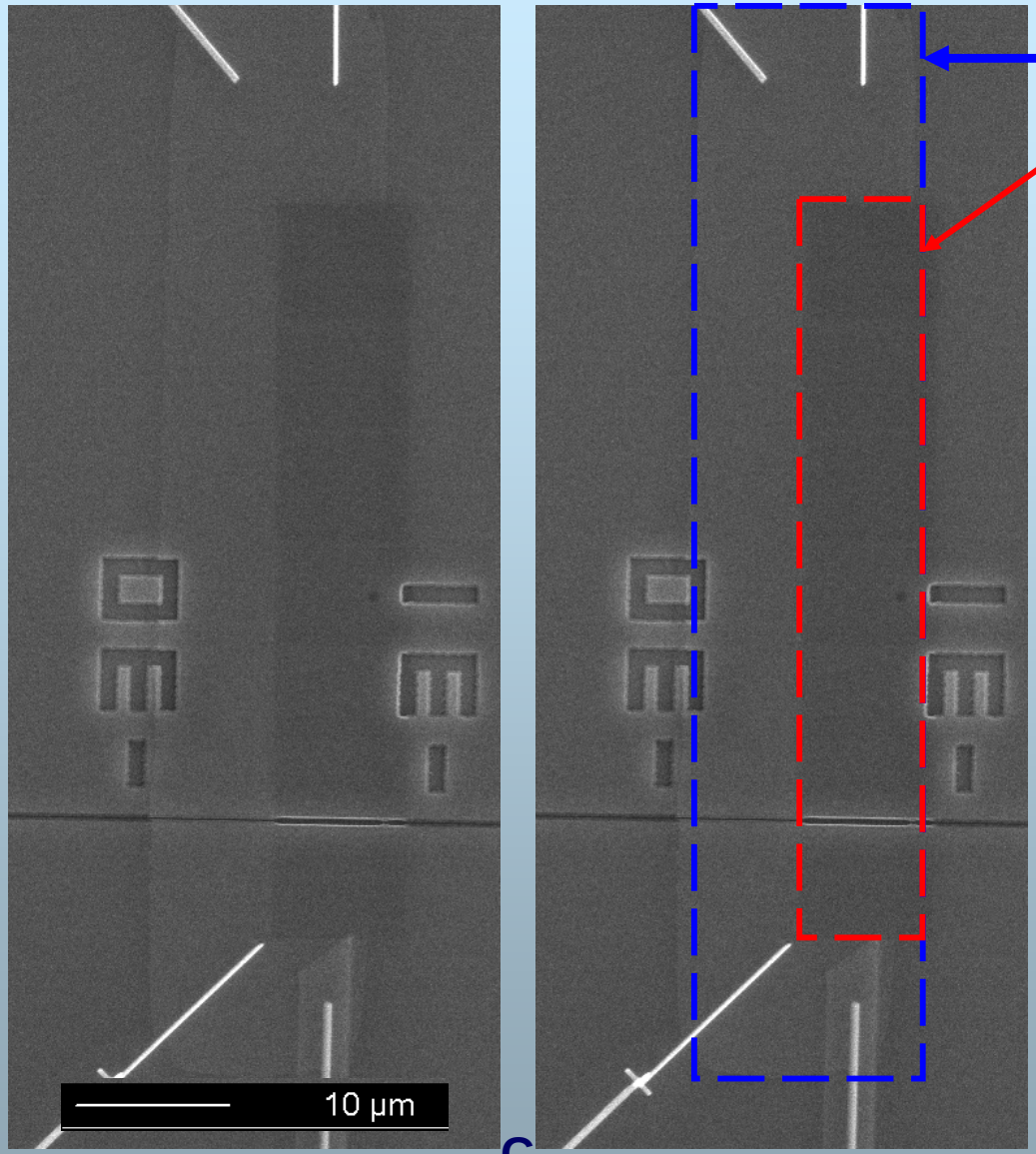


$$\frac{G_0}{G_0 - G(T)} = 9\frac{k_B T}{E_C} + 27\left(0.019\frac{R_Q}{R_0} + 0.067\right)$$

E_C ; 6.2×10^{-5} eV

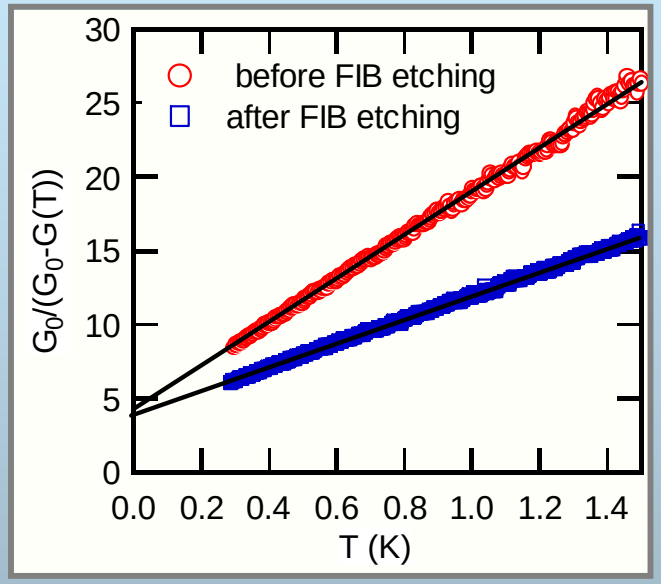
C ; 1.3 fF

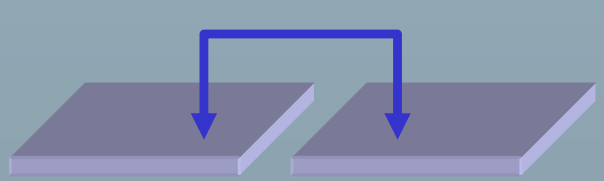
Changing an area contributing to the capacitance



Initial area of the structure

The area cut by FIB

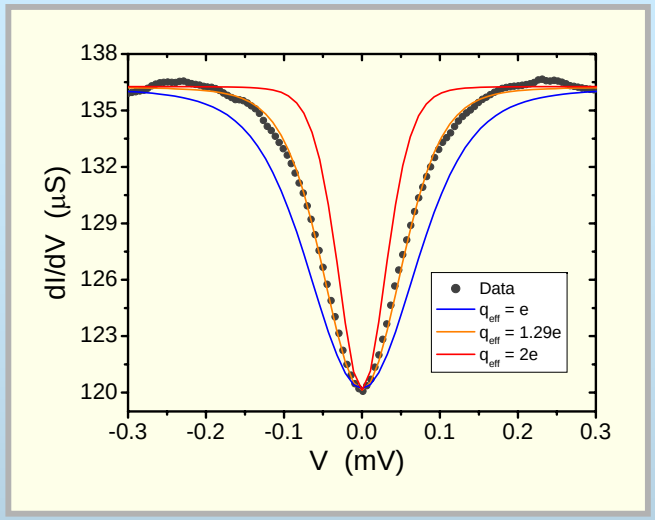


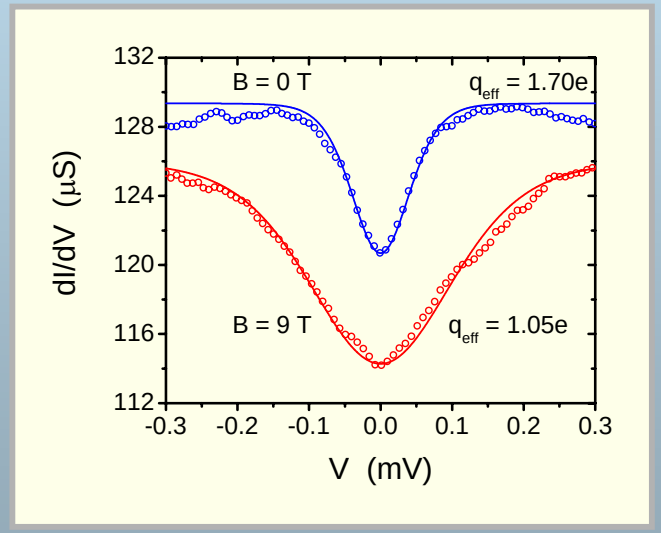


Capacitance

	Experiment	FASTCAP (ε_r=2.2)
Before FIB	1.5 fF	1.4 fF
After FIB	0.83 fF	1.0 fF

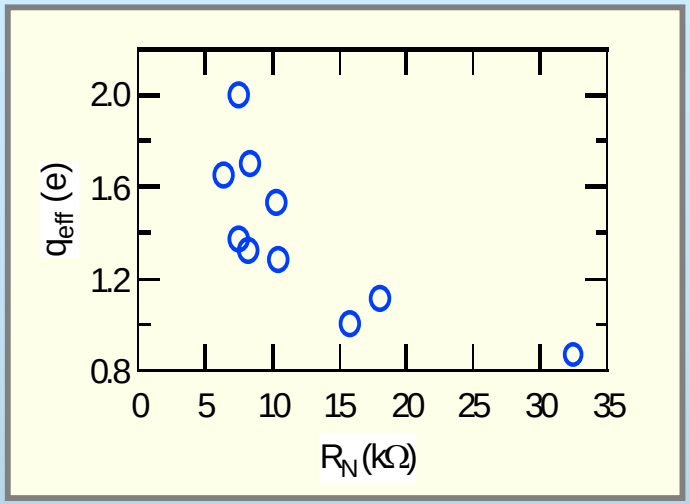
Effective charge





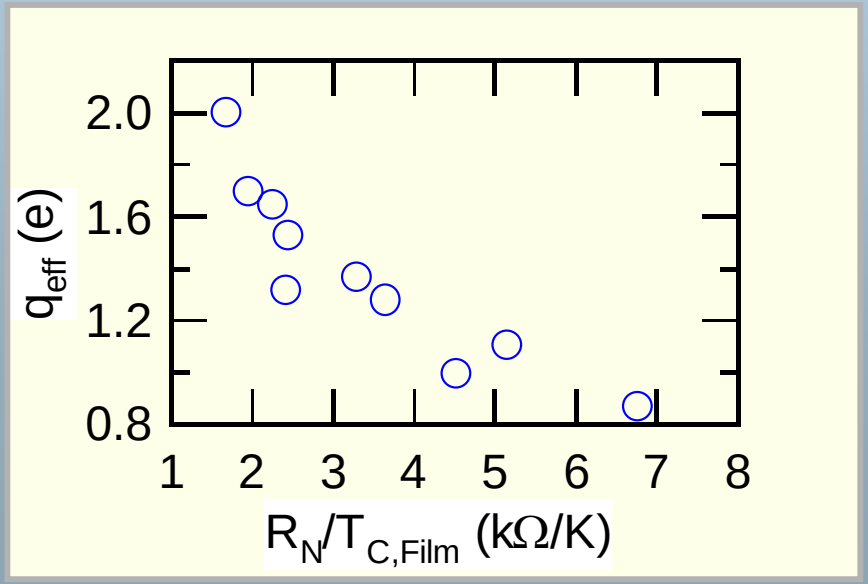
Conductance dip at V=0

$$\Delta G / G_0 \propto (e^2 / C) / k_B T$$



$$E_C^0 / E_C \propto \exp(-\pi^2 R_K / 8R_0)$$

$$N_{qp} \propto \exp(-\Delta_{FILM} / k_B T)$$

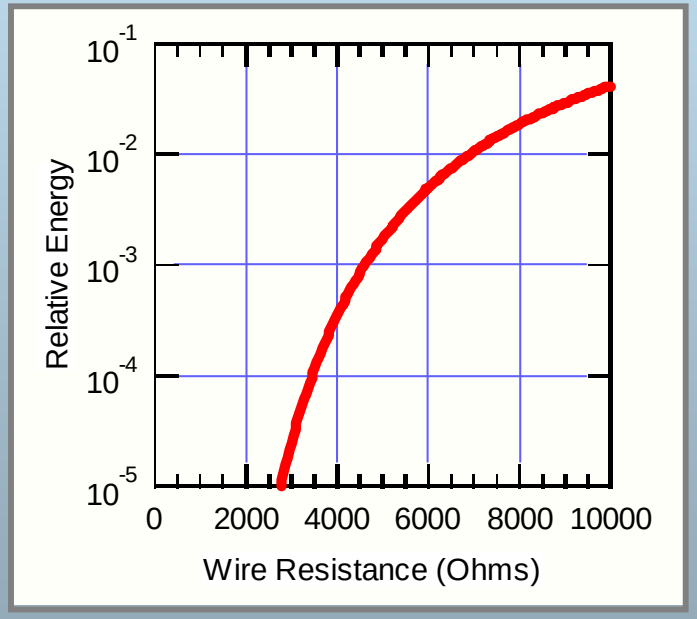


What parameter drives the SIT?

Charging energy of the structure

(total resistance of the wire)

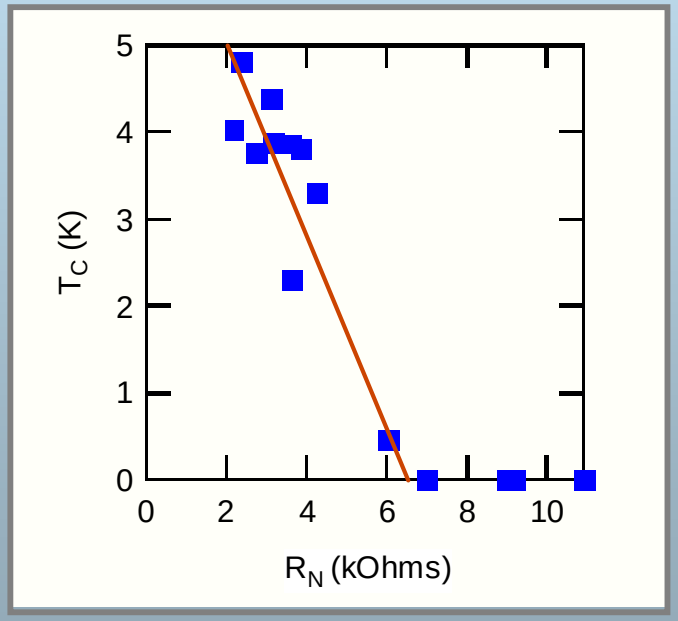
$$\frac{E_C^{0}}{E_C} \propto \exp\left(-\frac{\pi^2 R_Q}{8R_T}\right)$$



Local parameters (fermionic mechanism)

(Resistance per length)

Critical temperature extracted from LAMH fits



Conclusions

- Short insulating-state nanowire behaves as 0-dimensional coherent scatterer.
- R(T) and I(V) dependences are well explained by the theories of week Coulomb blockade.
- Charging energy of CB is set by the capacitance between two film electrodes located on the opposite sides of a nanowire.