IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), April 2017.
Oral presentation at IWSSD 2016. No manuscript was submitted for hardcopy journal publication.

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IWSSD 2016 14-17 Nov. 2016 TUKUBA

Phase slips and Superconductor-Insulator transition in Nitride nanowire

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Scientific Reports **4**, (2014) 5740

NICT National Institute of Information and Communications Technology

Outline

Background and Motivation

Phase slips (Quantum and Thermal Activation)

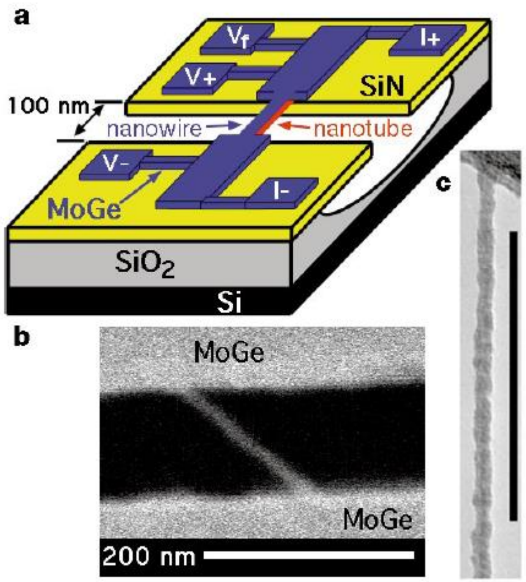
Superconductor-Insulator transition(SIT)

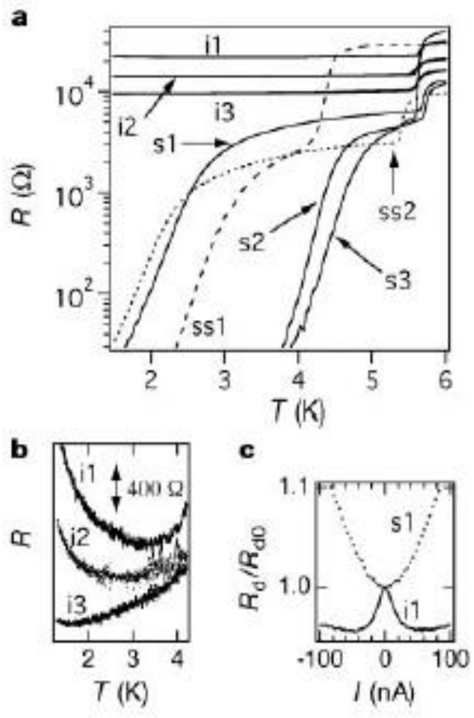
Duality analysis

Future work and summary

Background

Quantum suppression of superconductivity (quantum phase slips)



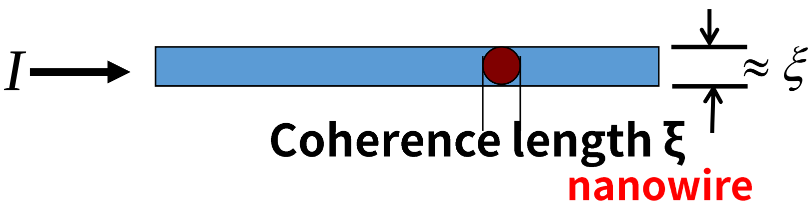


A. Bezryadin, Lau, Tinkham
Nature 404 971 (2000)

Phase slips

T<Tc

Normal conducting core due to fluctuations

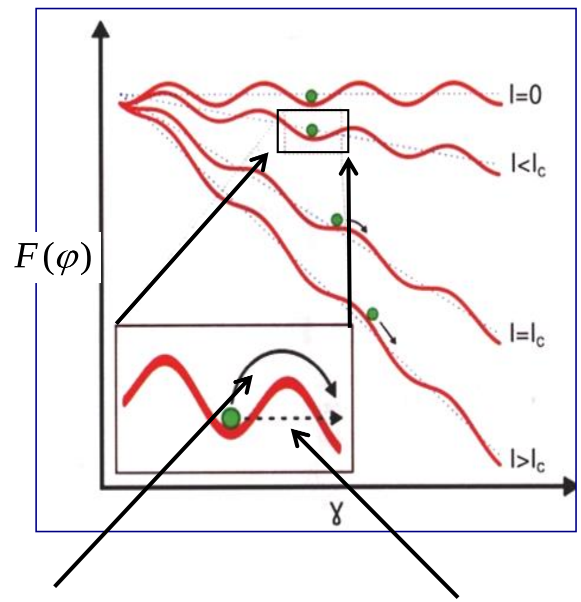


Potential barrier ΔF for Cooper pairs

Phase ϕ shifts occurs passing over ΔF

$$V = \left(\frac{\hbar}{2e}\right)\frac{d\varphi}{dt}; \quad Josephson \quad equation$$

$$R(T=0) \neq 0$$

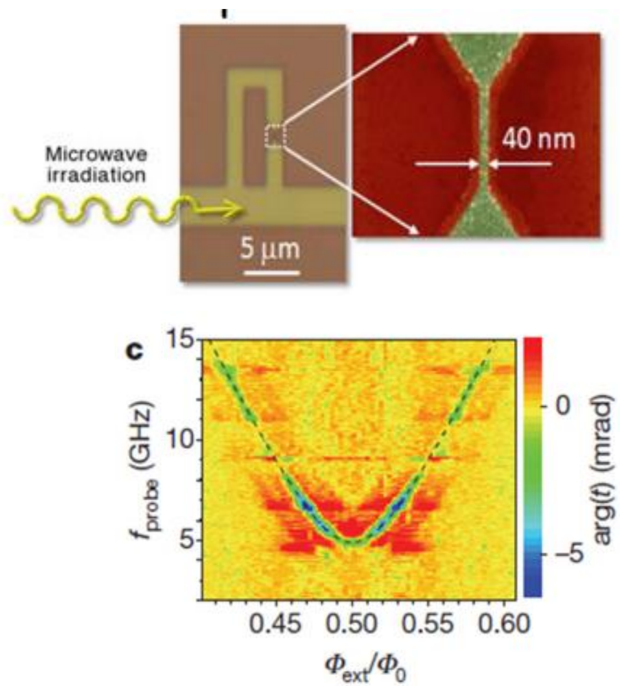


Thermal Activation
→TA Phase Slip TAPS

Quantum Tunneling
→Q Phase Slip QPS

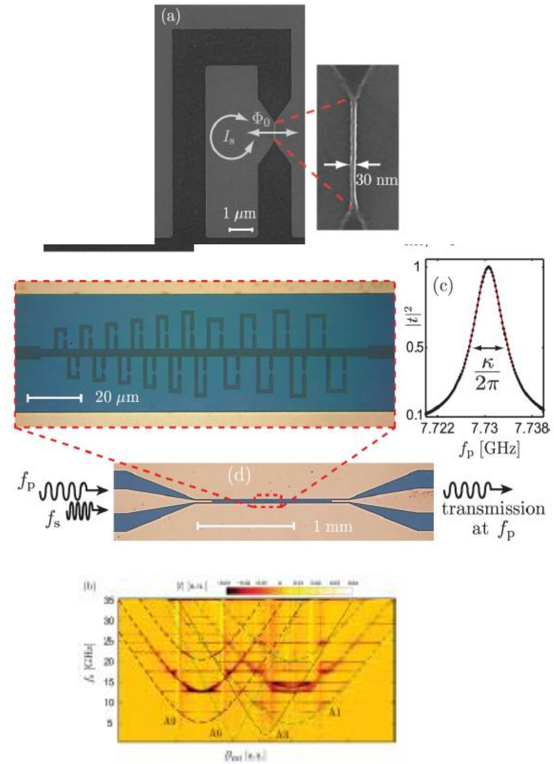
Coherent Quantum Phase slips

InOx nanowire



Astafiev et al.
Nature 484 355-358 (2012)

NbN nanowire



Peltonen et al.
Phys. Rev. B (2013)

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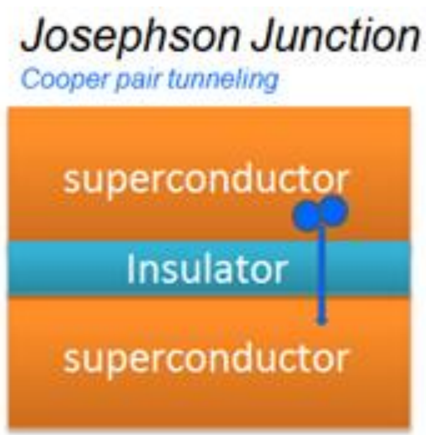
Dualitiy



$$H_{JJ} = E_C(n - n_c)^2 - \left(\frac{E_J}{2}\sum_n |n+1\rangle\langle n| + h.c\right)$$

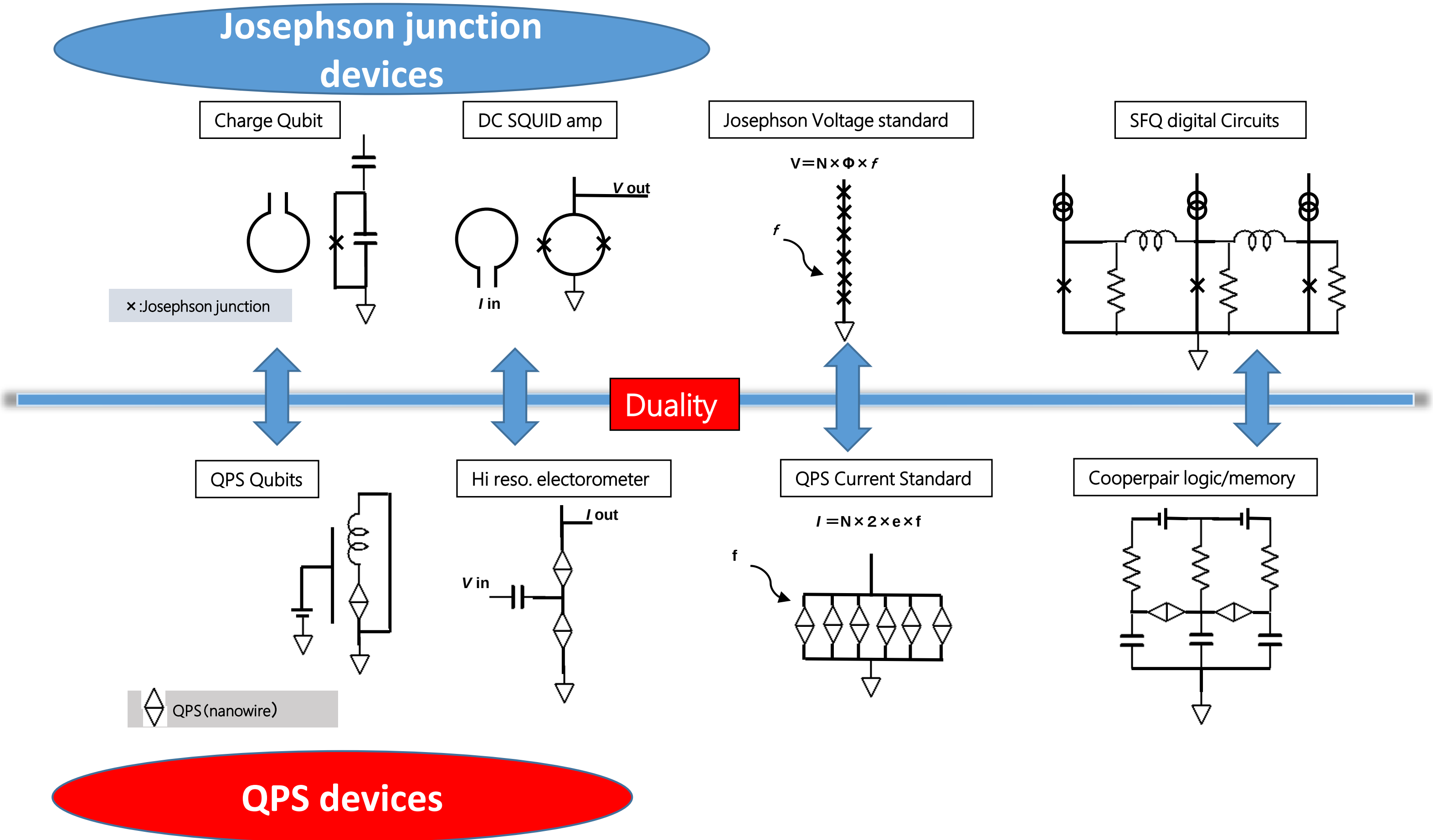
$$H_{QPS} = E_L(n - f)^2 - \left(\frac{E_S}{2}\sum_n |n+1\rangle\langle n| + h.c\right)$$

Josephson junction
Charging energy E_C
Josephson energy:E_J
Phase : Φ
Voltage :*V*

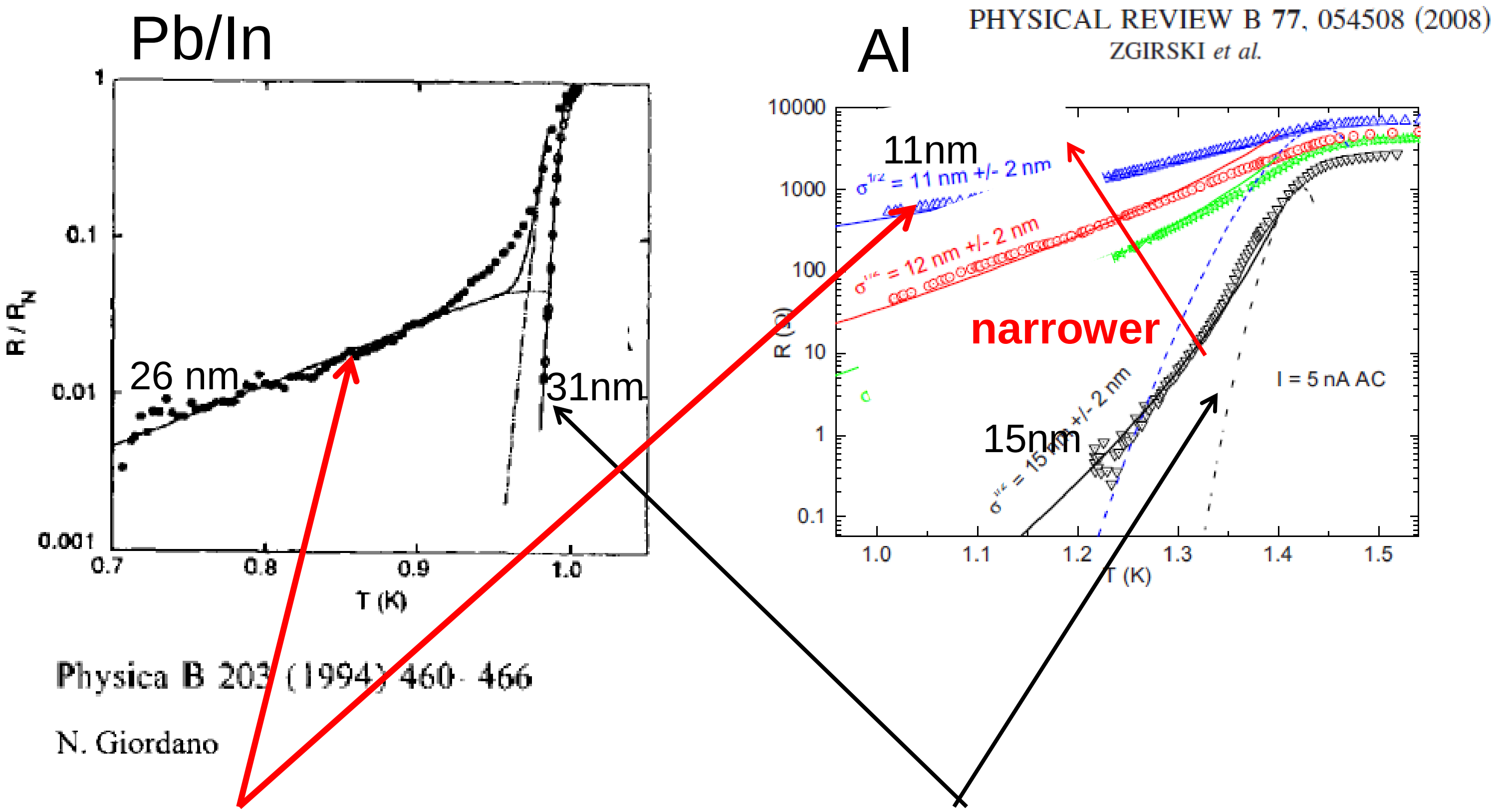
QPS nanowire
Inductance energy E_L
QPS energy:E_S
Charge :2 e
Current :*I*

Some devices(ex. Qubits) without Josephson junction

Duality devices



Phase Slip (R-T)



Quantum phase slip(QPS)
- **Schon and Zaikin(1990)**

Thermal Activated phase slip(TAPS)
- Langer, Ambegaokar (1967)
- McCumber, Halperin(1970)

TA model & MQT model

J. S. Langer and V. Ambegaokar, Phys. Rev. **164**, 498 (1967); D. E. McCumber and B. I. Halperin, Phys. Rev. B 1, 1054 (1970). LAMH theory

- thermal activation ;

$$R_{\mathrm{TA}} = \frac{\phi_0 \Omega}{k_{\mathrm{B}} T / \phi_0} \exp[-\Delta F / k_{\mathrm{B}} T]$$

magnetic barrier

$$\Delta F = \sqrt{2}\sigma H_c^{\,2} \xi / 3\pi$$

asociated attept frequency

$$\Omega = \frac{L}{2\pi^2 \xi \tau_{\mathrm{GL}}} [\frac{3\pi \Delta F}{k_{\mathrm{B}} T}]^{1/2}$$

GL relaxzation time

$$\tau_{\mathrm{GL}} = \frac{\pi \hbar}{8 k_{\mathrm{B}} (T_c - T)}$$

N. Giordano, Physica (Amsterdam) **203B**, 460 (1994)

D. S. Golubev and A. D. Zaikin, Phys. Rev. B **64**, 014504 (2001).

change of enrgy scale $k_{\mathrm{B}} T$ to $\hbar / \tau_{\mathrm{GL}}$

$$R_{\mathrm{MQT}} = \left(\frac{h}{4e^2}\right)\left(\frac{\hbar\Omega}{\hbar/\alpha\tau_{GL}}\right) exp\left(-\frac{\Delta F}{\hbar/\alpha\tau_{GL}}\right)$$

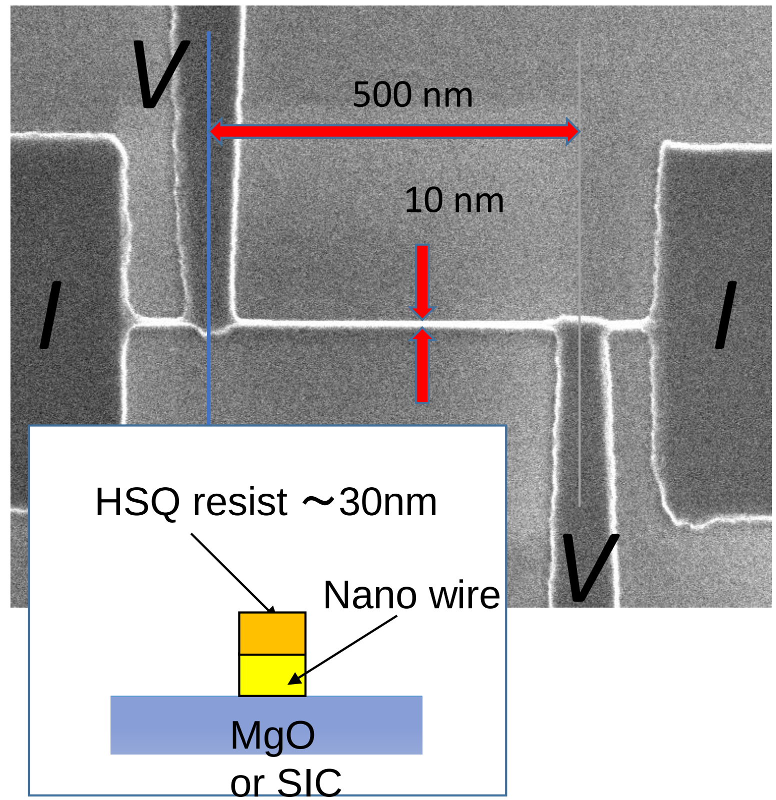
$$= \alpha R_{\mathrm{Q}} \left(\frac{8\sqrt{3}L}{2\pi^{5/2}\xi_0}\right) 0.83 \left(\frac{L R_{\mathrm{Q}}}{\xi_0 R_{\mathrm{N}}}\right)^{1/2} \left[\left(1-\frac{T}{T_{\mathrm{C}}}\right)^{7/4} \frac{T_{\mathrm{C}}}{T}\right] \; exp\left[-0.83\left(\frac{L R_{\mathrm{Q}}}{\xi_0 R_{\mathrm{N}}}\right)\left[\left(1-\frac{T}{T_{\mathrm{C}}}\right)^{1/2}\right]\right]$$

,where R_Q=h/4e^2

Experimental details

- **Niobium Nitride (NbN), Niobium Titanium Nitride(NbTiN),**
  Titanium Nitride(TiN)
  Molybdenum Nitride (MoN)
  MgO (100) substrate
  3C-SiC/Si (100) substrate
- **DC reactive magnetron sputtering method**

- **Reactive Ion Etching**
- **d=2-10 nm, L = 250-1000nm**
- **w = 10-300nm**
- **R(T), R(H), I-V measurement**



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Nitride nanowire (NbN)

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Epitaxial NbNnanowire

	Lattice Type	Lattice Constants (nm)
MgO	NaCl-cubic	0.439
3C-SIC	NaCl-cubic	0.421
NbN	NaCl-cubic	0.436
NbTiN	NaCl-cubic	0.440

Lattice mismatch

$$_{NbN-MgO} = \frac{a_{MgO} - a_{NbN}}{a_{NbN}}$$

1 %

$$E_{NbN-SiC} = \frac{a_{SiC} -}{a_{N}}$$

=-0.7 %

Lattice mismatch between NbN and 3C-SiC/Si is smaller.

Sample preparation

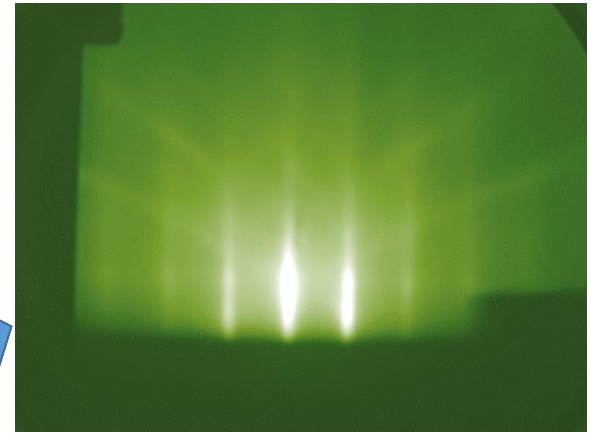
$H_2SO_4+H_2O_2$ 85 °C 10 min Remove organic contamination

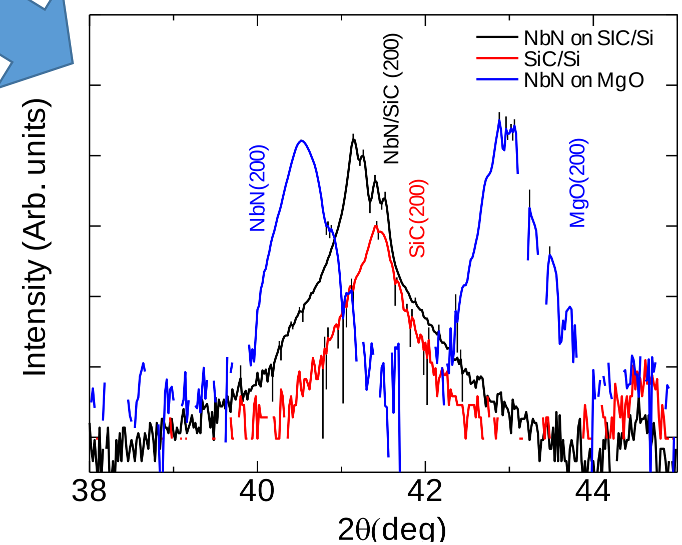
Dipped into a buffered HF solution Remove any native oxide.

NbN thin film deposition

EB lithography

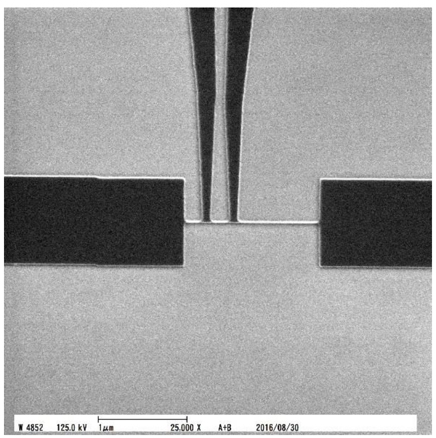
Etcing (DRY:RIE)



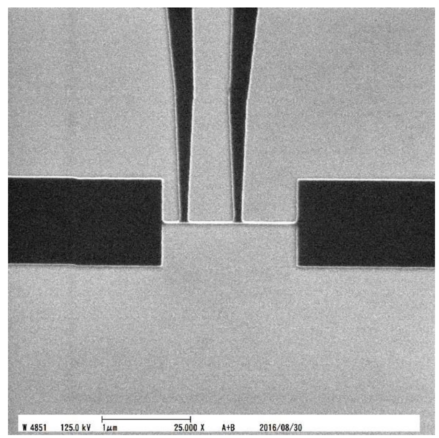


Nitride nanowire (NbN)

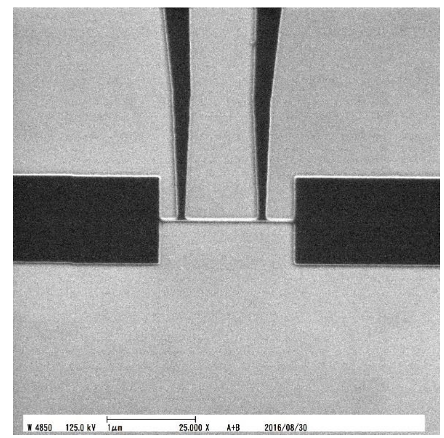
Using four-probe method to eliminate the contact resistance.



L = 300 nm

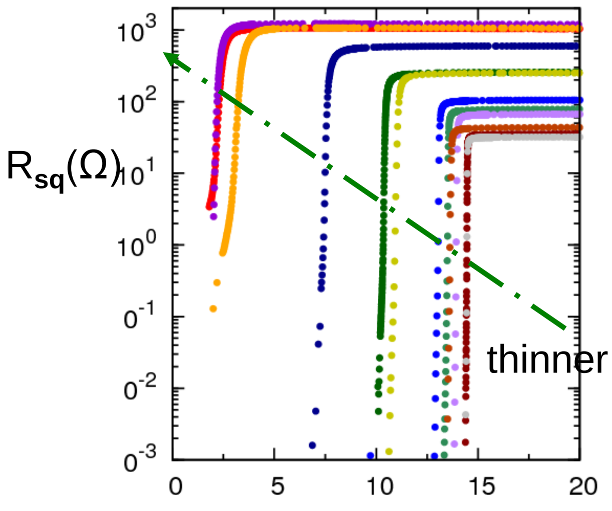


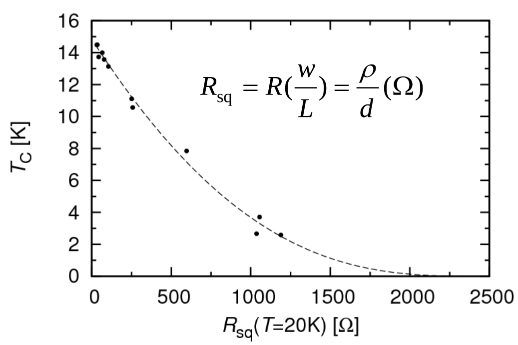
L = 600 nm



L = 900 nm

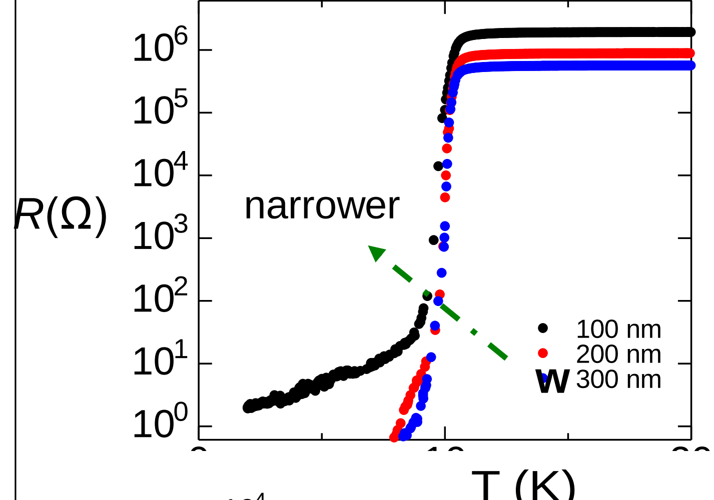
Size dependence

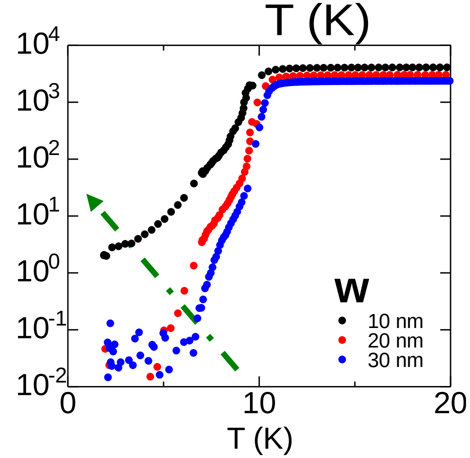




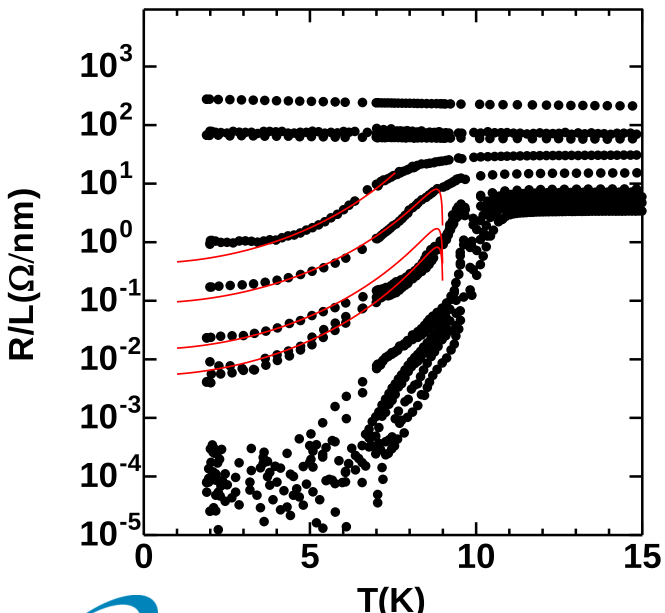
NbTiN 2D film **w=100μm**

Nano wire





QPS fitting



$$R_{\mathrm{QPS}}(T) = \left(\frac{h}{4e^2}\right)\left(\frac{\hbar\Omega}{\hbar/\alpha\tau_{GL}}\right) exp\left(-\frac{\Delta F}{\hbar/\alpha\tau_{GL}}\right)$$

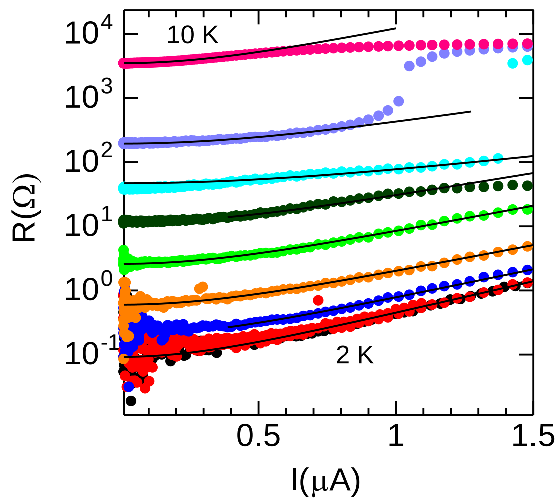
$$R_{\mathrm{QPS}}(T)$$
$$= \alpha R_{\mathrm{Q}}\left(\frac{8\sqrt{3}L}{2\pi^{5/2}\xi_0}\right)0.83\left(\frac{LR_{\mathrm{Q}}}{\xi_0 R_{\mathrm{N}}}\right)^{1/2}\left[\left(1-\frac{T}{T_{\mathrm{C}}}\right)^{7/4}\frac{T_{\mathrm{C}}}{T}\right]$$
$$exp\left[-0.83\left(\frac{LR_{\mathrm{Q}}}{\xi_0 R_{\mathrm{N}}}\right)\left[\left(1-\frac{T}{T_{\mathrm{C}}}\right)^{1/2}\right]\right]$$

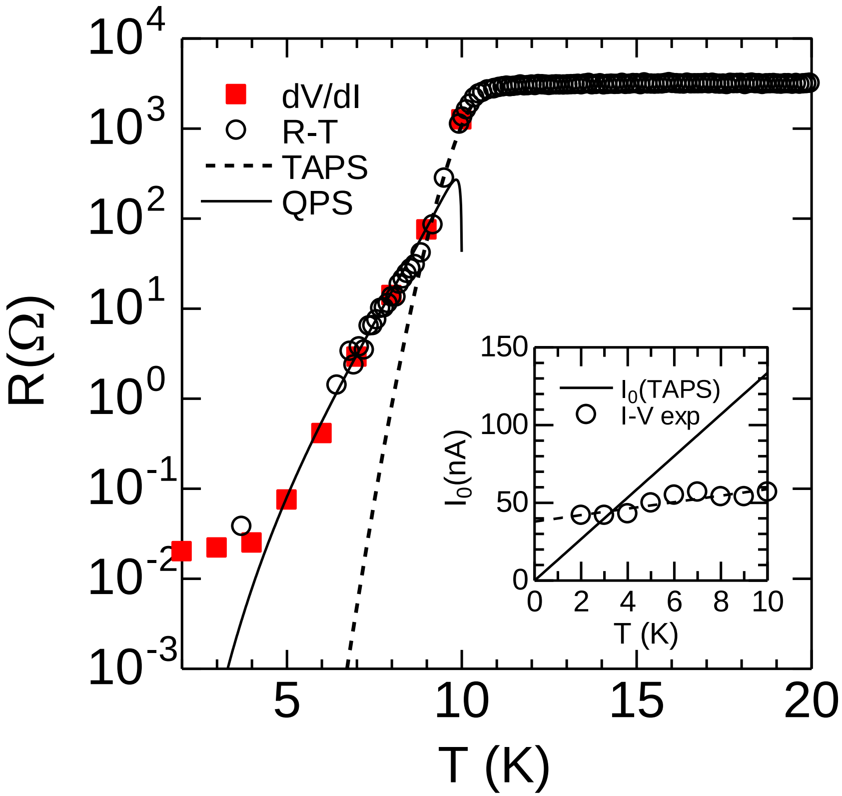
$$I_{QPS} = \left(\frac{2e}{\beta\pi\tau_{GL}}\right)$$

$$V_{QPS} = I_{QPS}R_{\mathrm{QPS}} sinh\left(\frac{I}{I_{QPS}}\right)$$

Zaikin et al., Phys. Rev. Lett. 78, 1552 (1997); D. S.Golubev and A. D. Zaikin, Phys. Rev. B 64, 014504(2001).

TAPS fitting (I-V & R-T Curve)





dV/dI =R_{TAPS}(T)cosh(I/I_0)

I_0 (T)=4ek*T*/h (By TAPS, I_0 depend on only Temperature.)

Switching Current

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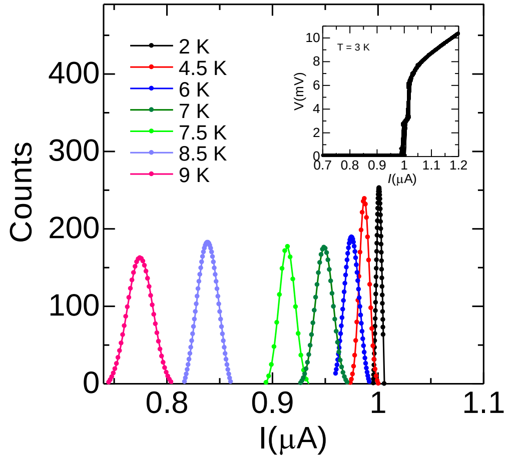
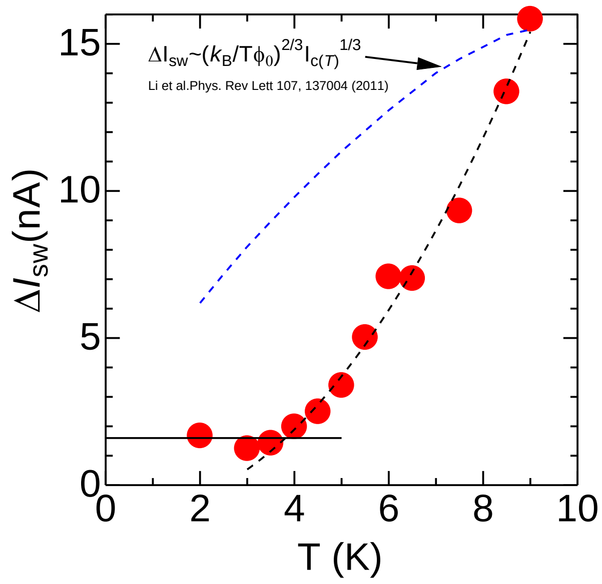
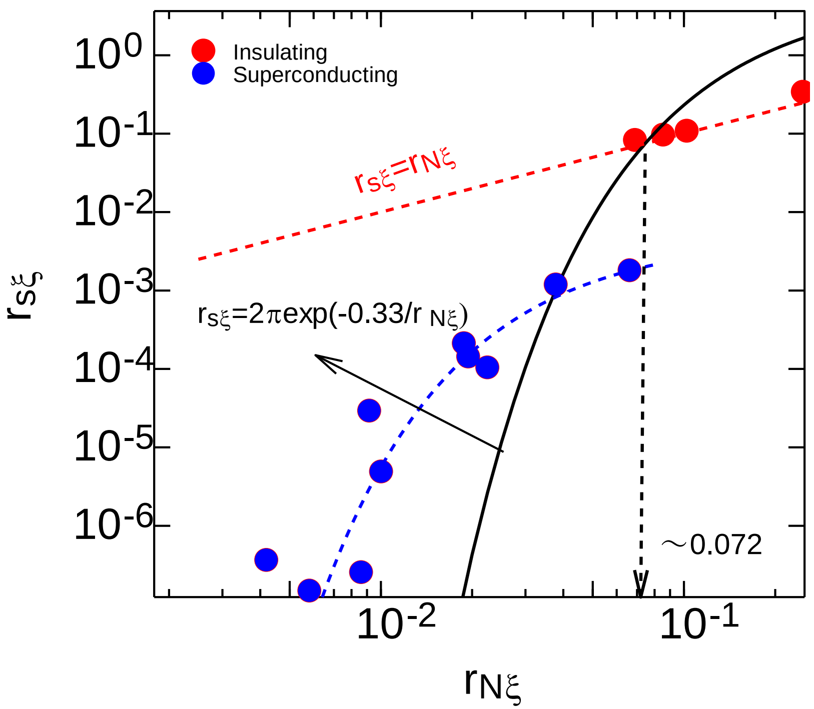
I_{sw} distribution at different temperature





Estimation of Cross over for SIT based on QPS model



superconducting state resistance R_s measured in units of R_Q for length in units of ξ

$(R_{QPS} = R_S)$

$$(R_s / R_Q)(\xi / L) \equiv r_{S\xi}$$

$$= 2\pi \exp[-0.33(R_Q / R^N)(L/\xi)]$$

$$= 2\pi \exp[-0.33 / r_{N\xi}] \quad (1)$$

at cross over, $r_{S\xi} = r_{N\xi}$ (2)

$$\Rightarrow \quad r_{N\xi} = 1/13.3 \approx 0.072$$

$$(R^N / L)_{c.o} = R_Q / 13.3\xi \approx 485\Omega / \xi(0)$$

$\xi(0) \approx 9nm$ for presents pecimens

$$(R^N / L)_{c.o} \approx 54\Omega / nm$$

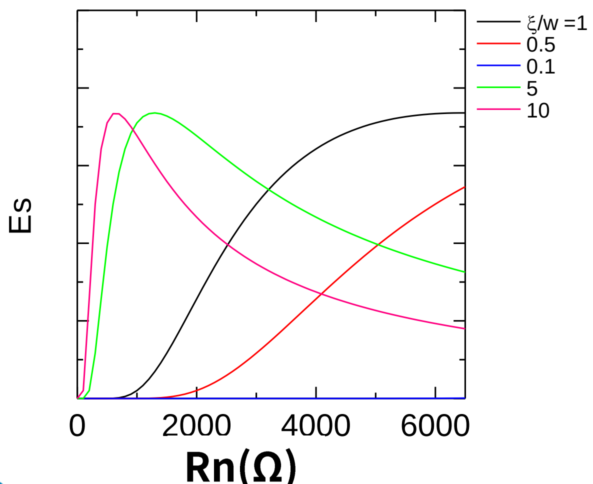
PS & Inductance energy : E_S , E_L

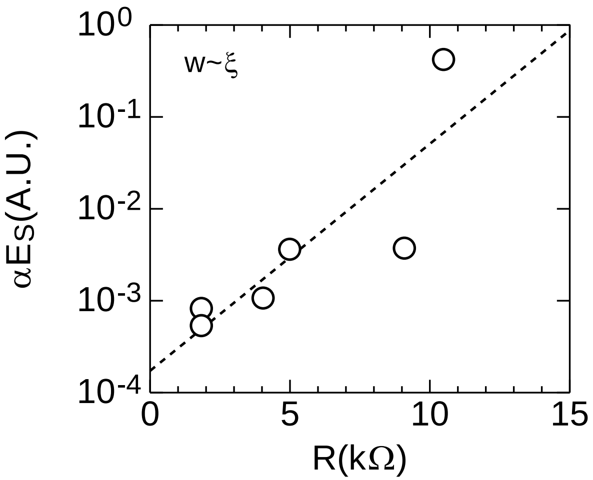
According the theory Quantum phase slip is dependent on sheet resistance.

But it remains unclear whether the characteristics of the QPS depend on disorder

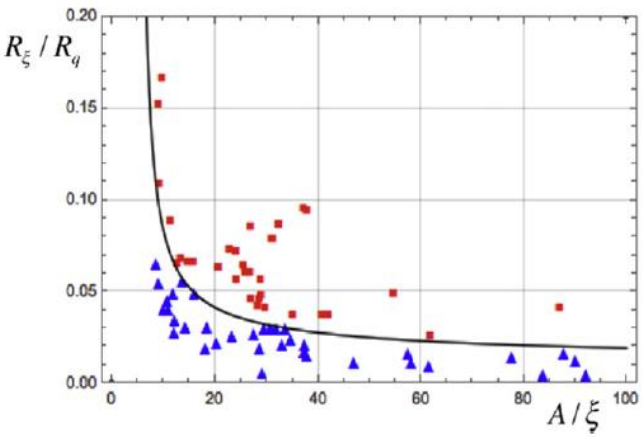
$$E_S = a\frac{A}{\xi}k_B T_C \frac{R_Q}{R_\xi} exp\left(-b\frac{R_Q}{R_\xi}\right) \qquad L = \frac{\hbar R_n}{\pi\Delta}$$

$$R_\xi = R_n \frac{\xi}{w} \qquad E_L = (h/2e)^2/2L$$





Phase diagram of S-I transition



$$E_s / E_{Li} = (a\lambda^2 / 17.4)\exp(-b / r_\xi) = \alpha_c$$

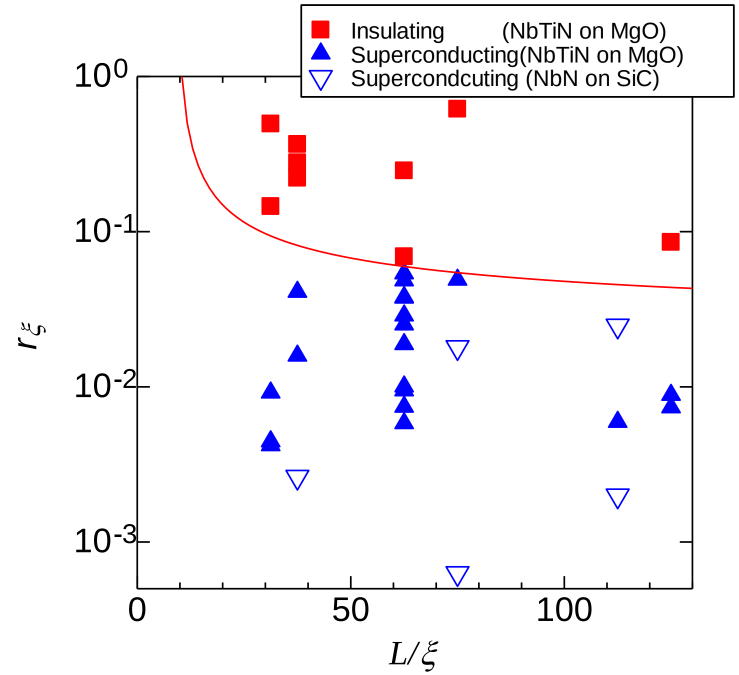
$$r_\xi = (R^N / R_Q)/(L/\xi)$$

$$r_\xi(\lambda) = b / \ln(a\lambda^2 / 17.4\alpha_c)$$

$$\equiv b / \ln(c\lambda^2 / 17.4)$$

MoGe nanowire $E_s/E_L = 0.3$
NbSi nanowire $E_s/E_L = 0.6$

Mooij et al. New J.Phys 17 (2015) 033006.



NbN and NbTiN nanowire
$0.2 < E_s/E_L < 0.5$

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To realize CQPS

Required property of Material

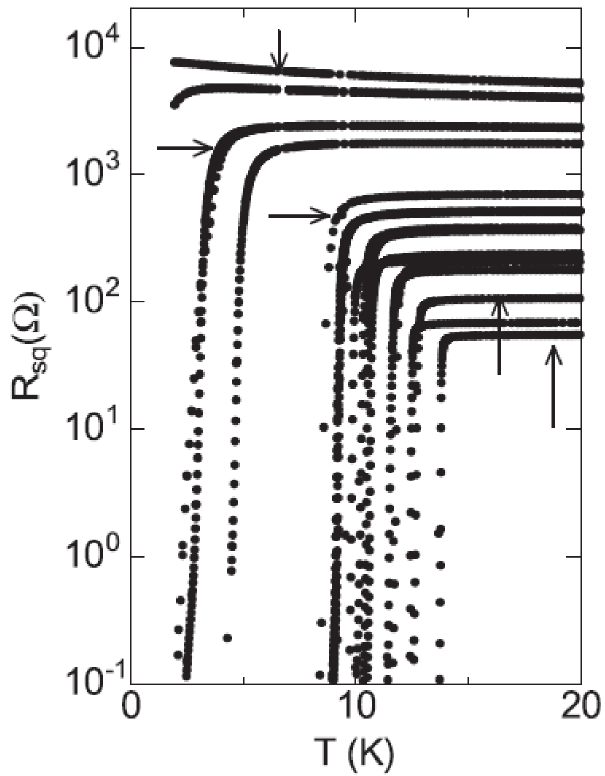
- High degree of disorder
- homogeneous system
- Oxide or Nitride

Phase slips energy(Es)

- Close to SI transition
- narrow wires

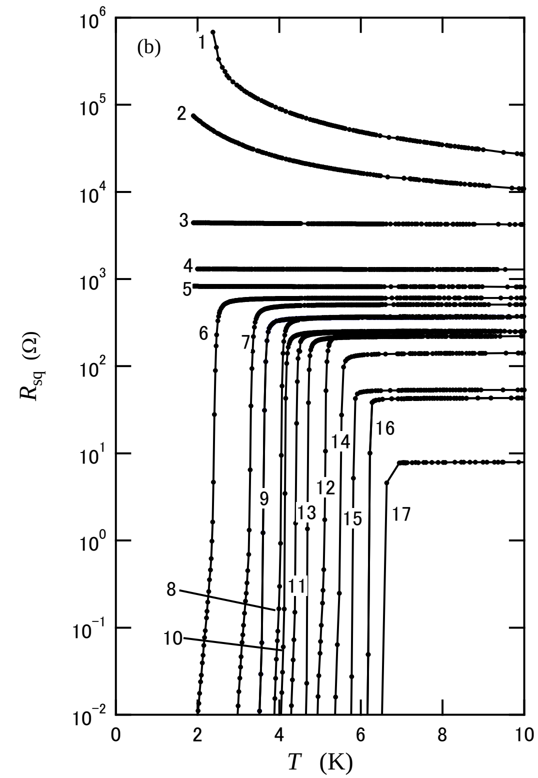
S-I transition for 2D

NbN thin films



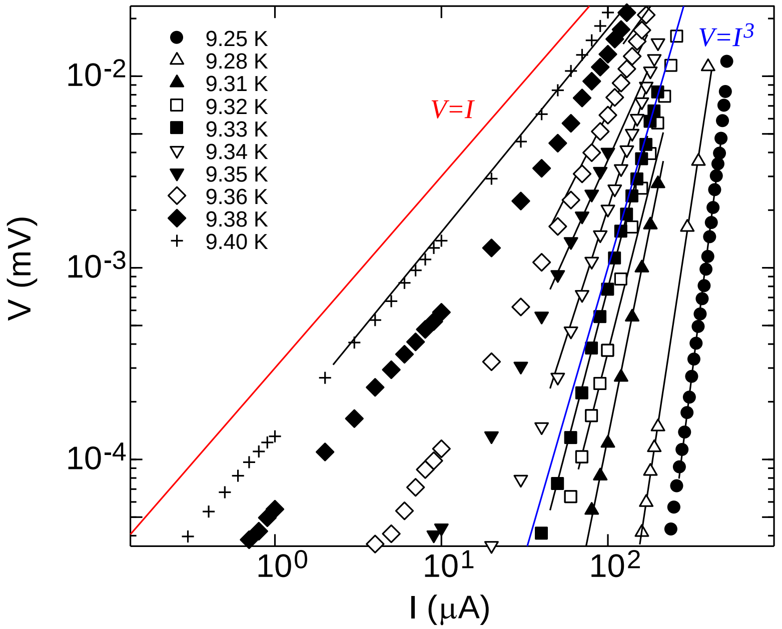
K. Makise et al.Mater. Res. Express 2 (2015) 106001.

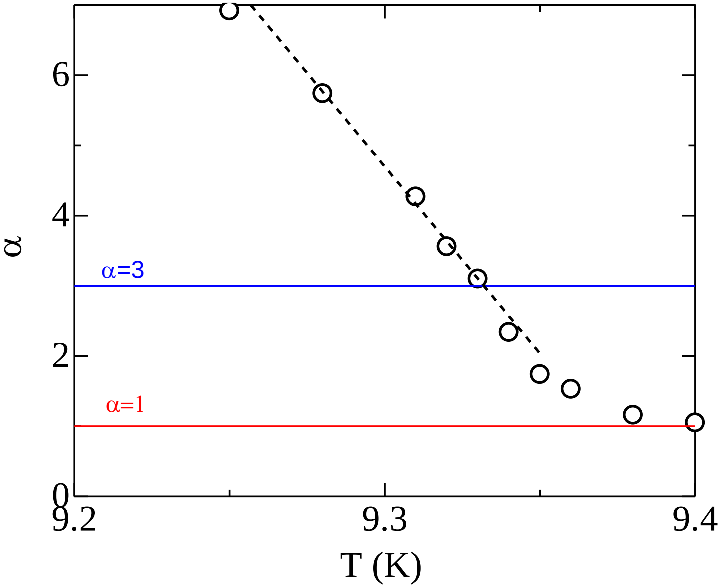
MoN thin films



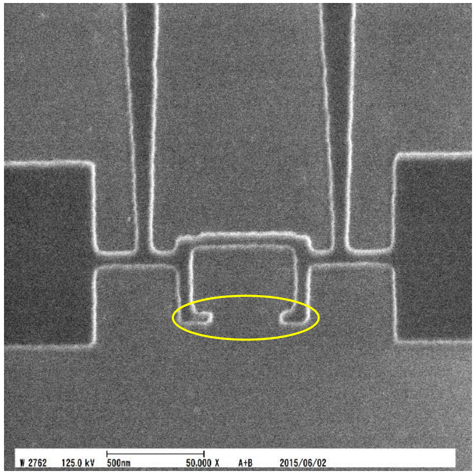
K. Makise et al. J of phys. Cond. Matt. (2016) Accepted.

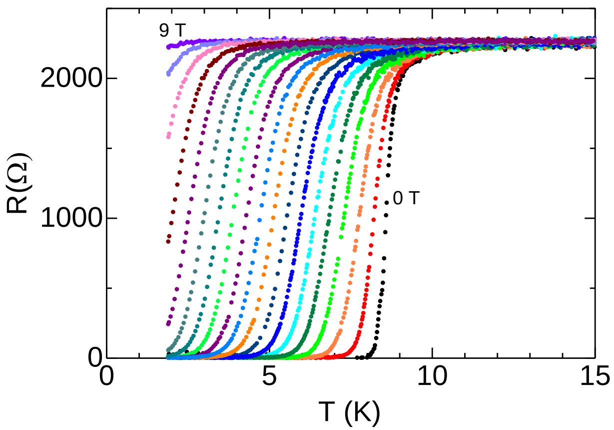
BKT transition (NbTiN films)

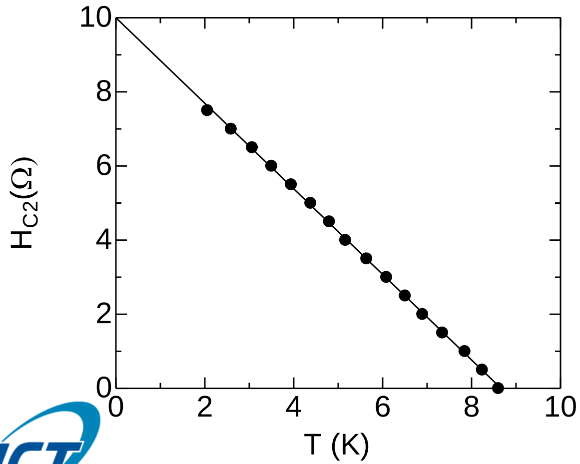


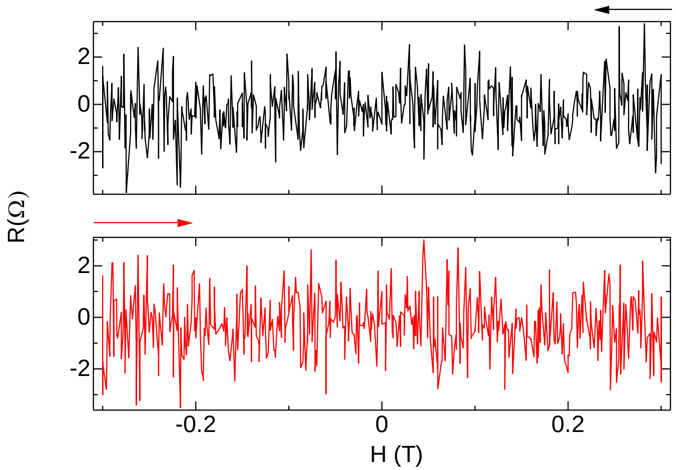


Phase slips ring in Mantic field

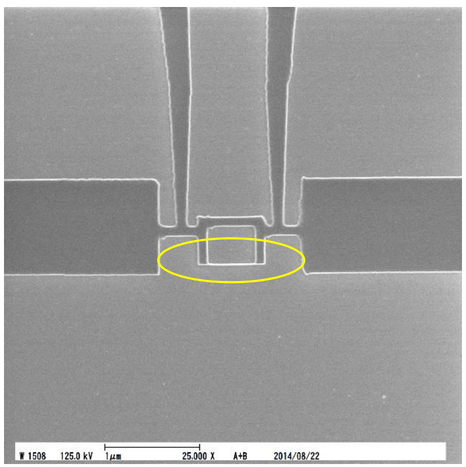


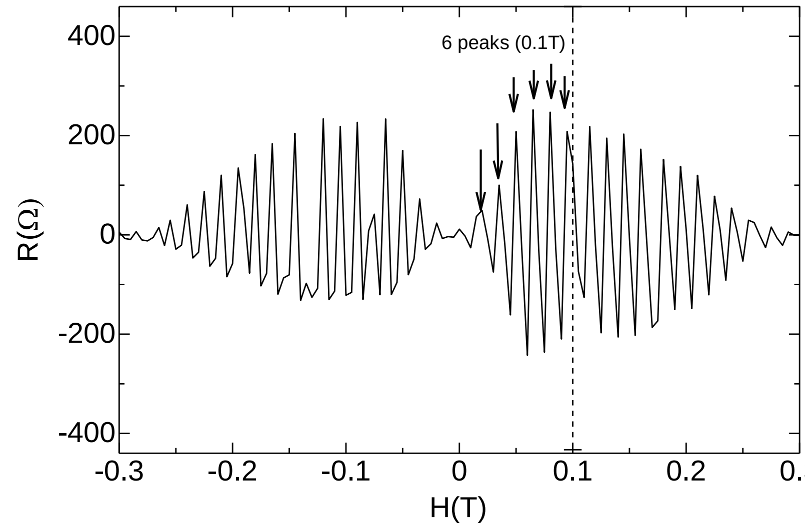






Phase slips ring in Mantic field





Area of Ring
$S = 500 \times 250\ nm^2$

$a_{\square} = (\Phi_0/B)^{1/2} = (2.07\text{x}10^{-15}/0.1)^{1/2}$
$= 143\ nm$
$Vn = S/ (a_{\square}\ \text{x}\ a_{\square}) = 6.11 \backsim 6$

→QPS Qubits

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MoRu and MoRuN films

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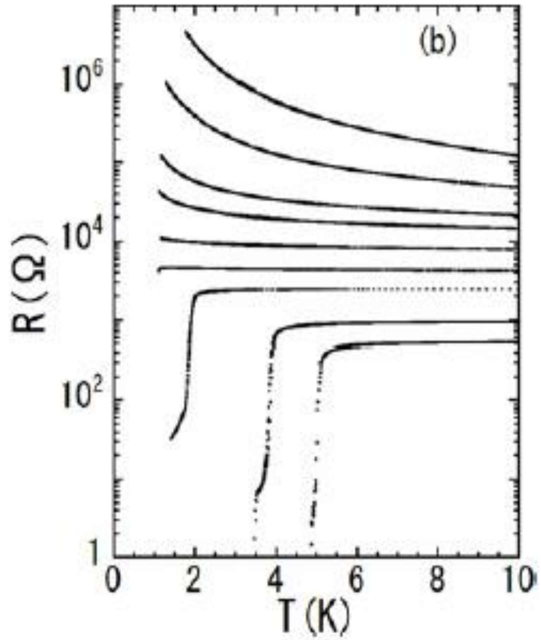
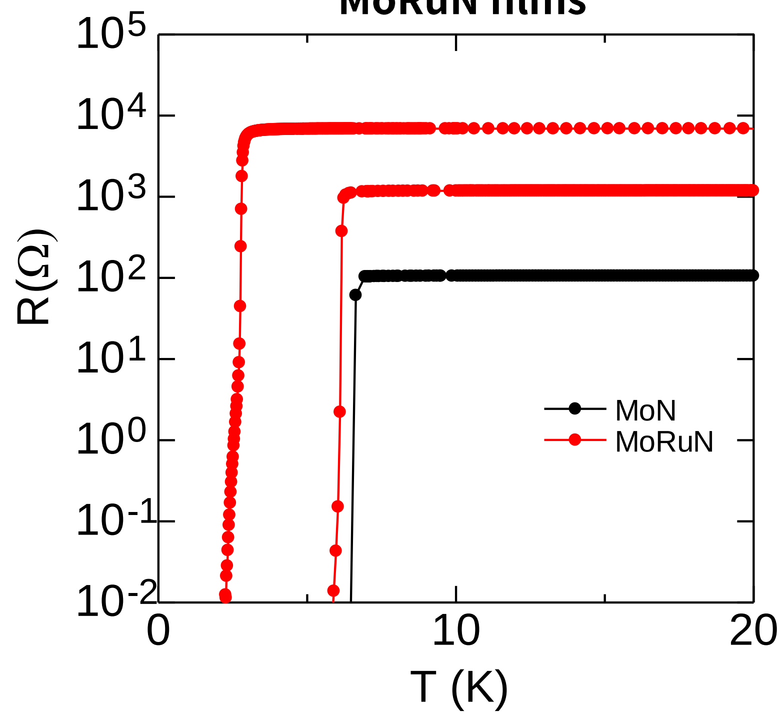
MoRu films



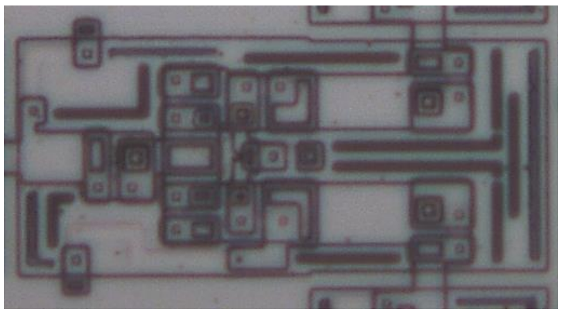
A . Hirakawa, and K. Makise
J. phys. Cond. Matt. 20
(2008)

MoRuN films

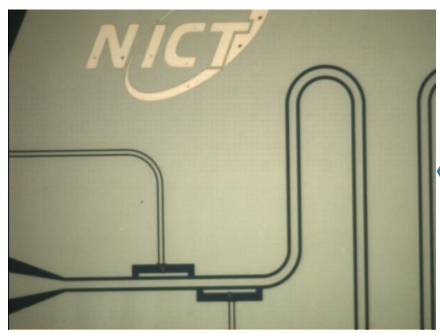


- **High degree of disorder**
- **homogeneous system (amorphous)**
- **Nitride**

Integrated monolithic QPS devices (All Nitride SC)

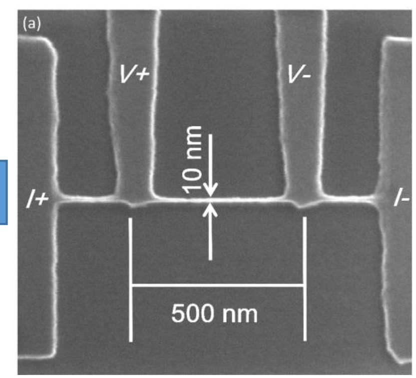


Read out
NbN-SFQ



CPW resonator TIN
MW of Single Photon level
Internal Q above10^6

QPS NbN, NbTiN, TiN, MoRuN
→CQPS



Summary

- We investigated the transport properties of superconducting NbTiN SNW's in a wide range of RN/L using four-probe method to eliminate the contact resistance.
- The characteristic with resistive tail below Tc for SNWs with high values of   can be well explained by the QPS theory.
- The analysis based on the model for the SNW which is being dual element upto Josephson junction, suggests that the separation of the superconducting and insulator phases may be controlled by the ratio of QPS amplitude energy E_S and inductive energy of SNW $E_{l,}$.
- For the present NbTiN series, we observed that SIT may occur at $0.2 < E_S/E_L < 0.5$.