united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

SMR/1438 - 10

JOINT ICTP-INFM SCHOOL/WORKSHOP ON "ENTANGLEMENT AT THE NANOSCALE"

(28 October – 8 November 2002)

"Adiabatic charge transport in arrays of Josephson junctions and the Cooper pair pump"

presented by:

J. Pekola
Helsinki University of Technology
Finland

Adiabatic charge transport in arrays of Josephson junctions and the Cooper pair pump

Jukka Pekola, Helsinki University of Technology, Finland

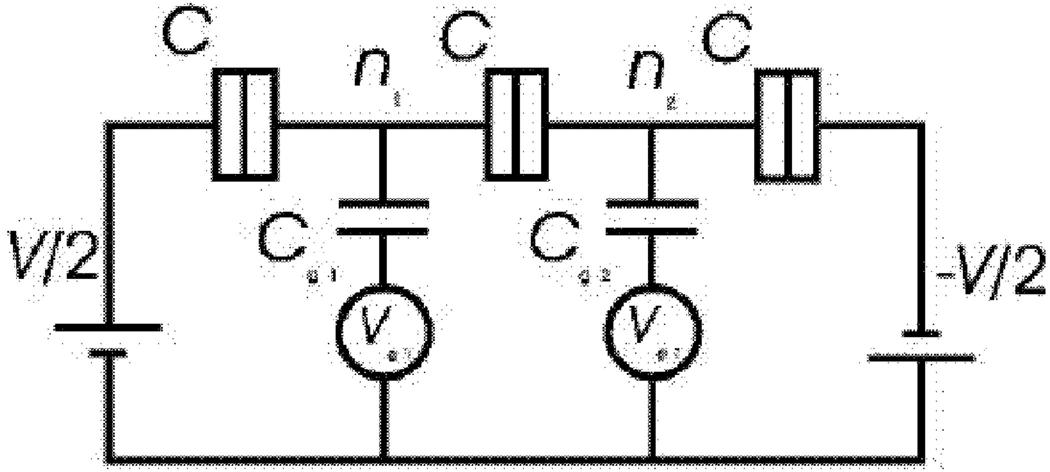
with Jussi Toppari and Matias Aunola, University of Jyväskylä, Finland

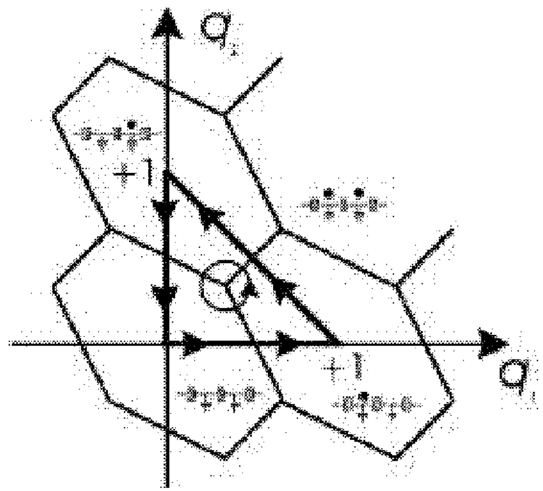
Dmitri Averin (SUNY), Rosario Fazio (Pisa), Frank Hekking (UJF Grenoble)

Contents

1. Controlled charge transport in various systems
2. Focus on Josephson arrays and pumps
3. Adiabatic transport
4. Measurement of current
5. Experimental issues

Pumping of single electrons in a 3-junction pump





$$I \sim 1\mathrm{pA}$$

$$(f \sim 10\mathrm{MHz})$$

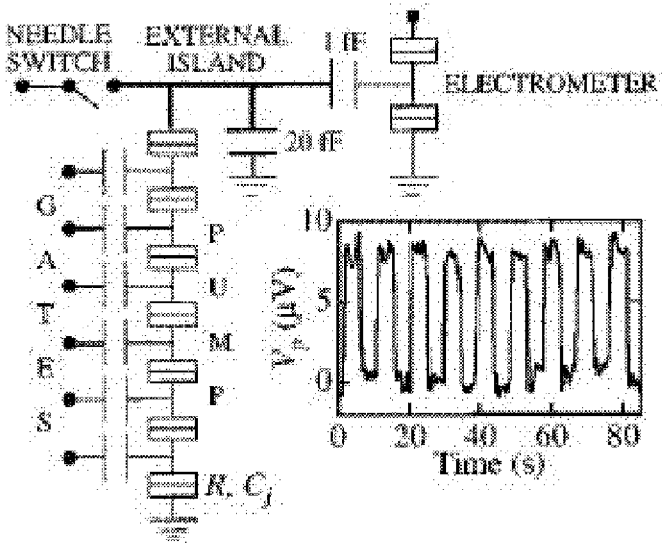
$$\delta I / I \sim 0.01$$

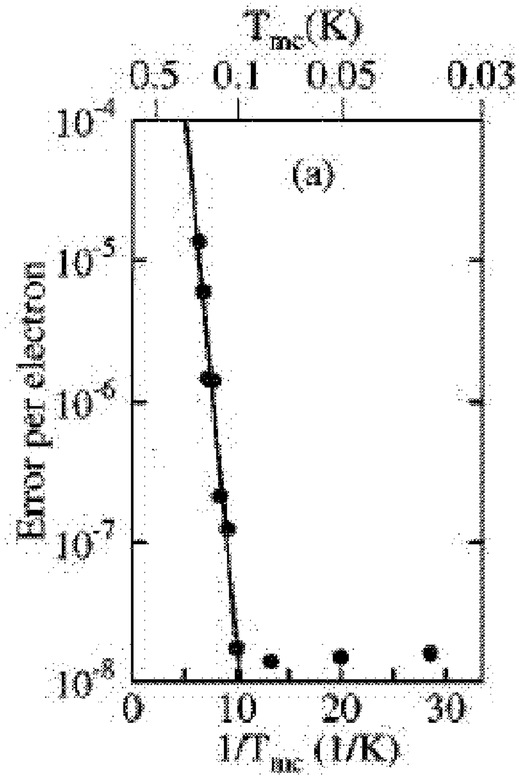
H. Pothier, P. Lafarge, C. Urbina, D. Esteve, M. Devoret, EPL 17, 249 (1992).

Metrological charge pump

Accuracy of electron counting using a 7-junction electron pump

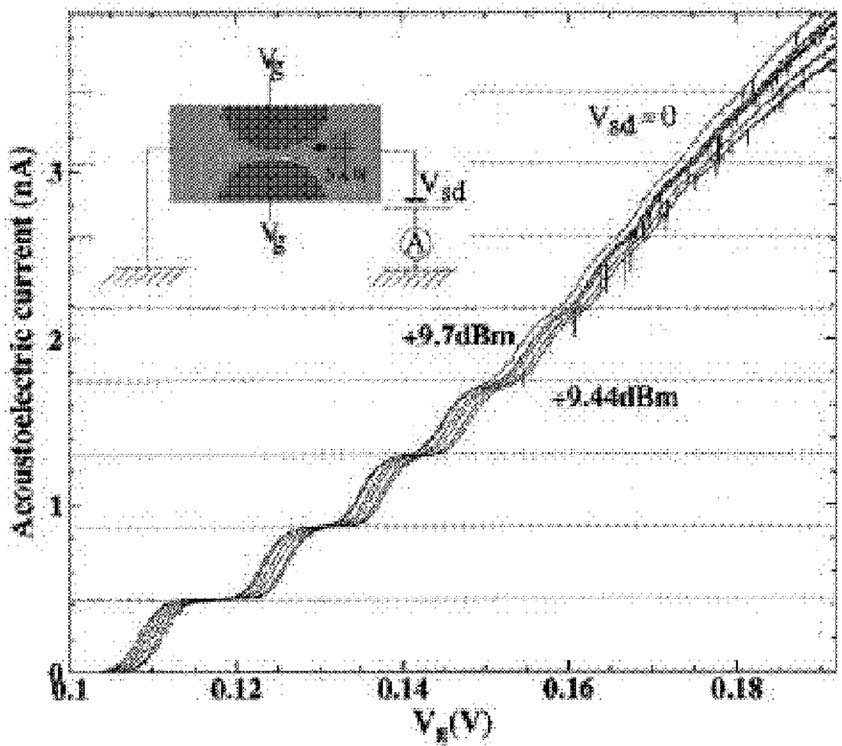
Mark W. Keller[a] and John M. Martinis
National Institute of Standards and Technology, Boulder, Colorado 80303
Neil M. Zimmerman
National Institute of Standards and Technology, Gaithersburg, Maryland 20899
Andrew H. Steinbach[b]
National Institute of Standards and Technology, Boulder, Colorado 80303
(Received 29 April 1996; accepted for publication 22 July 1996)

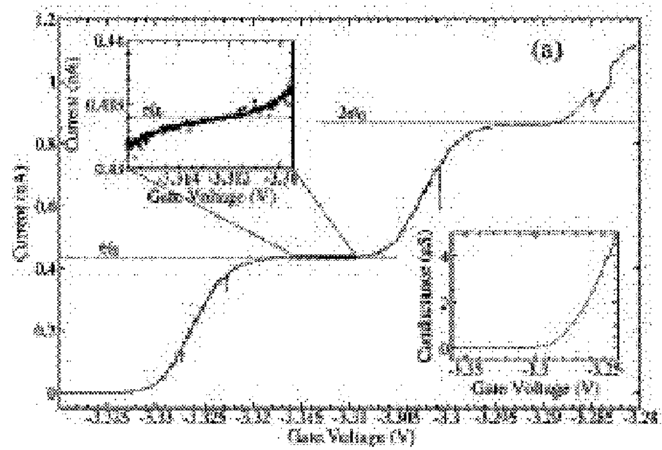




Appl. Phys. Lett. 69, 1804 (1996).

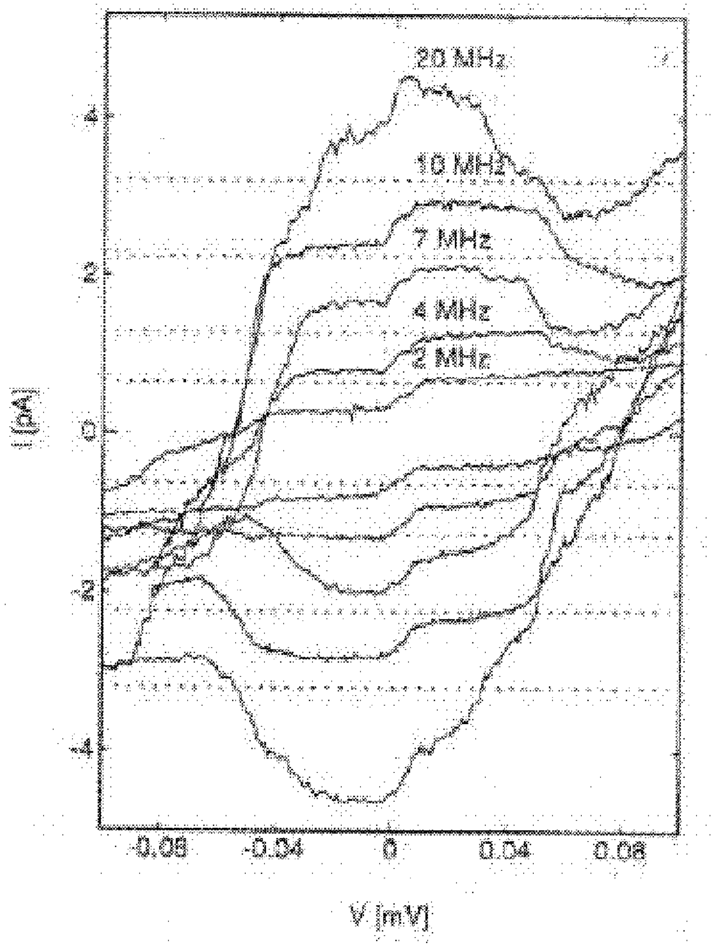
Surface acoustic wave (SAW) driven $I = ef$

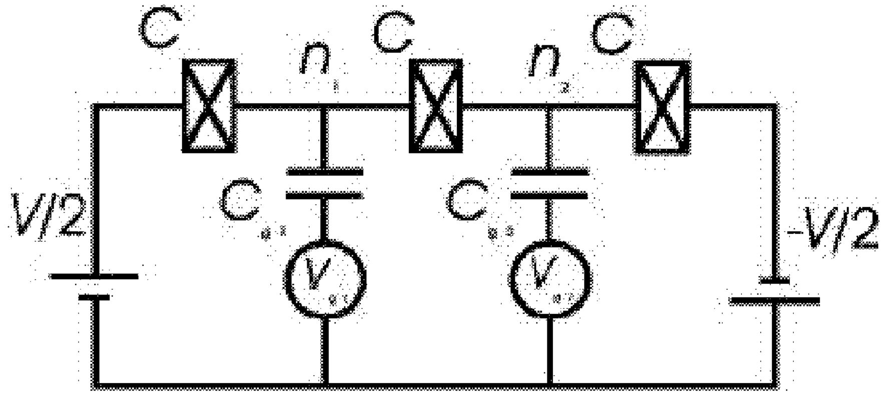




J. Shilton et al., J. Phys. C 8, L531 (1996).
V. Talyanskii et al., PRB 56, 15180 (1997).
J. Cunningham et al., PRB 62, 1654 (2000).
A. Robinson et al., PRB 65, 045313 (2002).
J. Pekola et al., PRB 50, 11255 (1994).

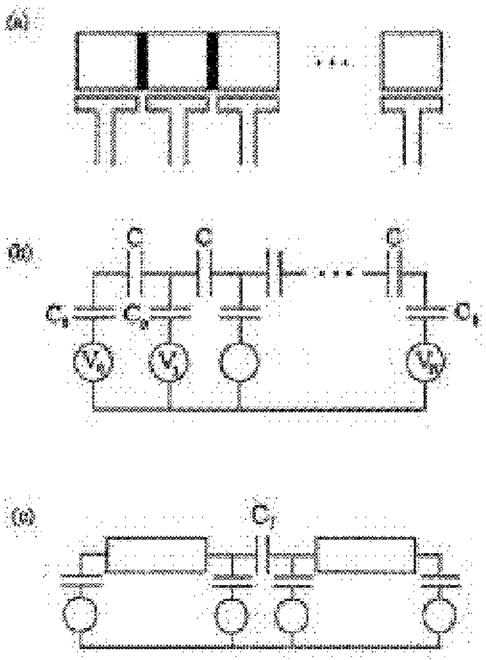
3 junction CPP





L. Geerligs et al., Z. Phys. B: Condensed Matter 85, 349 (1991).

Adiabatic manipulation of Cooper pairs in arrays of JJs



Adiabatic quantum computing, D. Averin (1998).

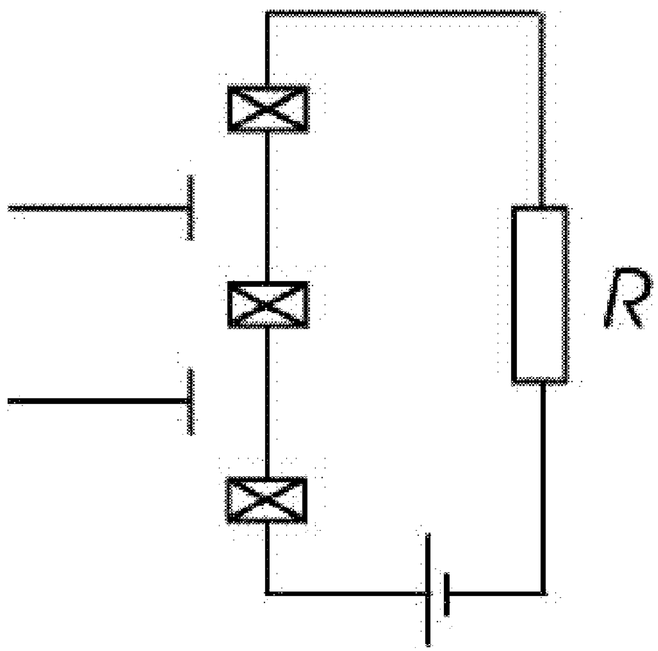
Topologically stable Josephson qubits, Ioffe, Feigelman (2002).

Cooper pair manipulations in geometric qubits, Catania group (2000-).

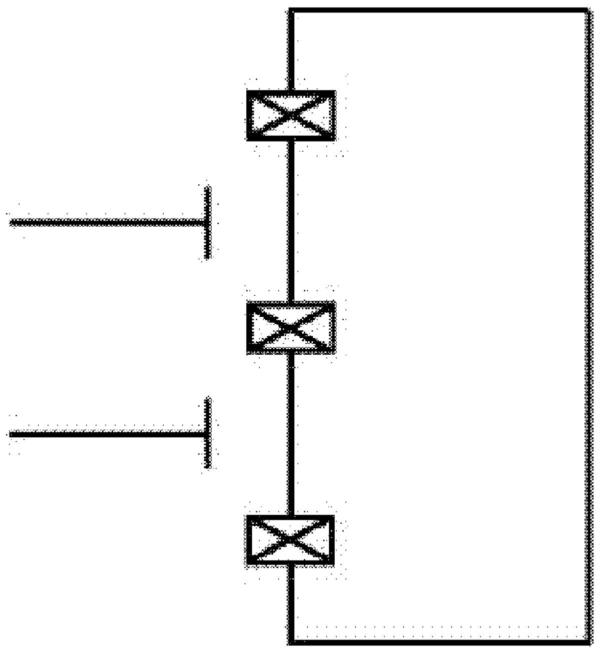
Coherent and incoherent Cooper pair pumping

1. Ideal coherent and incoherent (adiabatic) pumping
2. Phase fluctuations in dissipative environment
3. Inductance limited phase fluctuations

Coherent vs incoherent Cooper pair pumping



R-pump, $R >> R_Q$



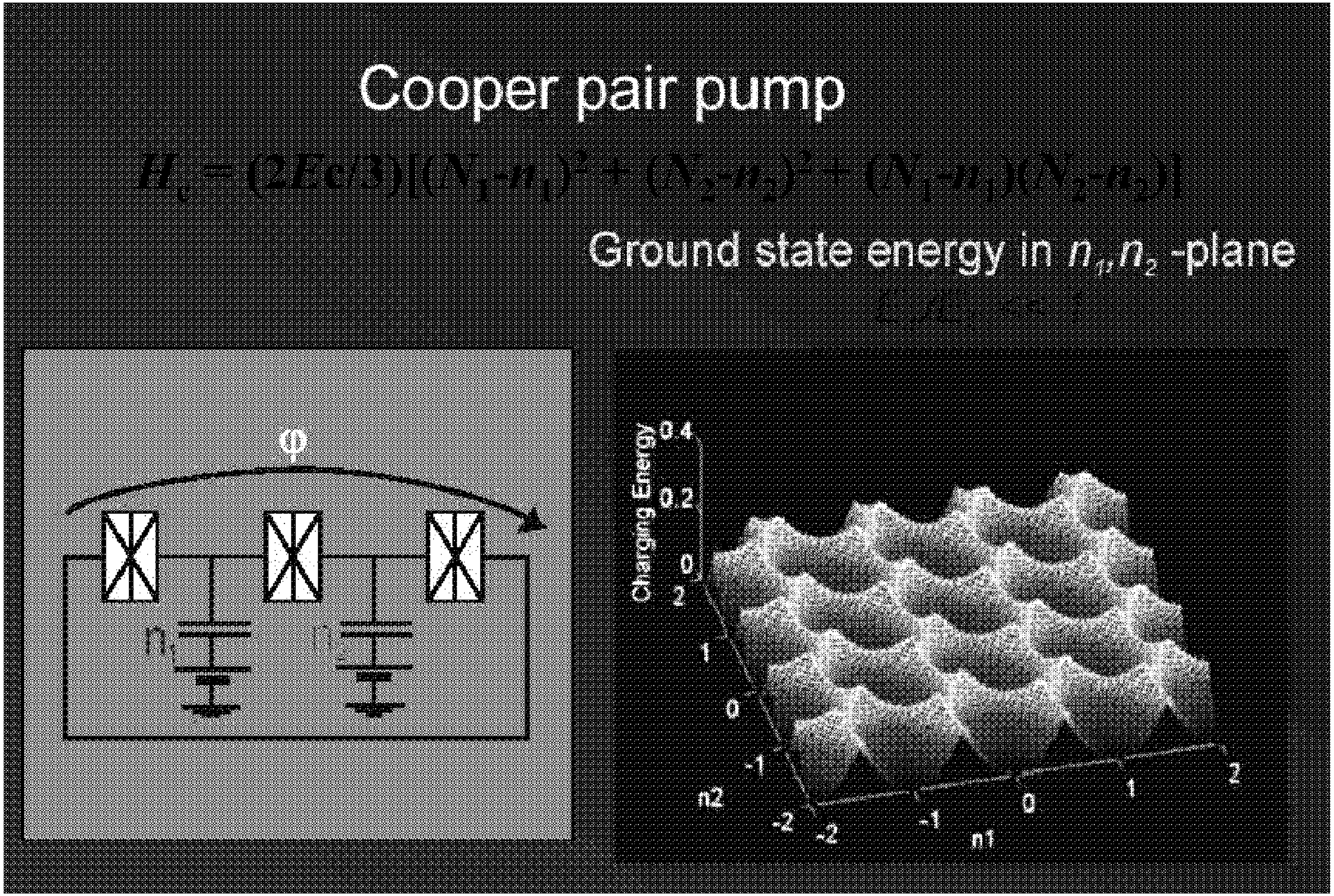
Coherent pump

S. Lotkhov, S. Bogoslovsky, A. Zorin, J. Niemeyer, APL 78, 946 (2001).

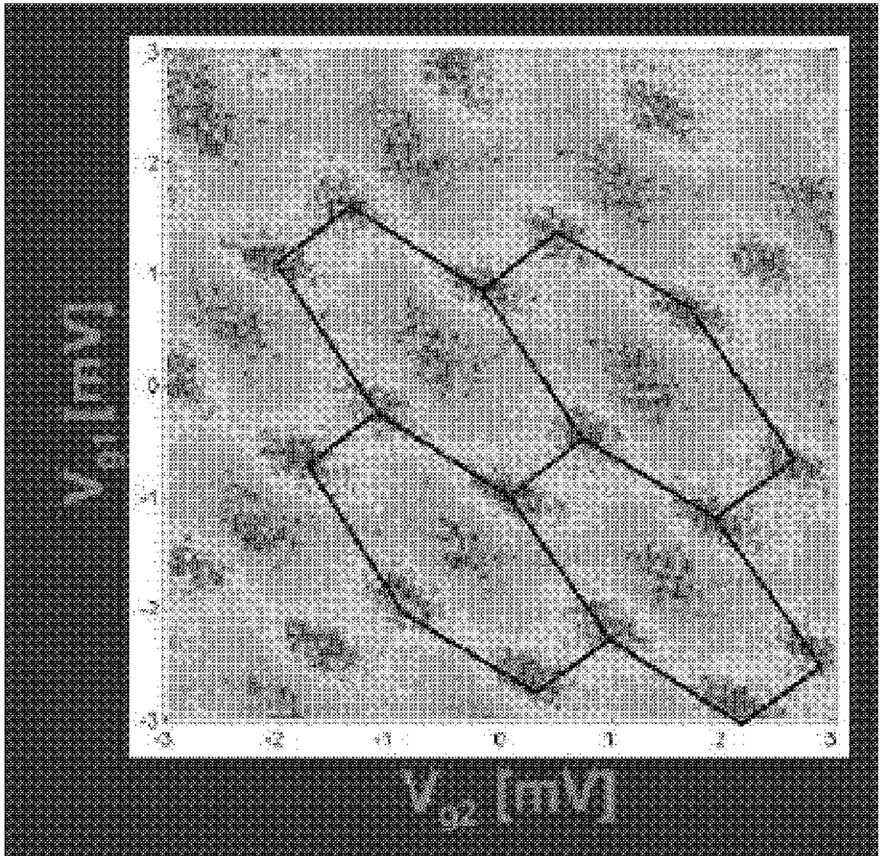
Why Cooper pair pump?

1. New experimental method to measure dissipation and decoherence
2. Multi-gate control of multi-junction qubits
3. Metrological applications

Charging energy



Experimental determination of the gate dependences



Switching current as a function of two gate voltages V_{g1} and V_{g2}

J. Toppari et al., unpublished

Adiabatic transport of Cooper pairs

If the Hamiltonian of the system varies slowly enough, we may study its behaviour using the adiabatic approximation of quantum mechanics.

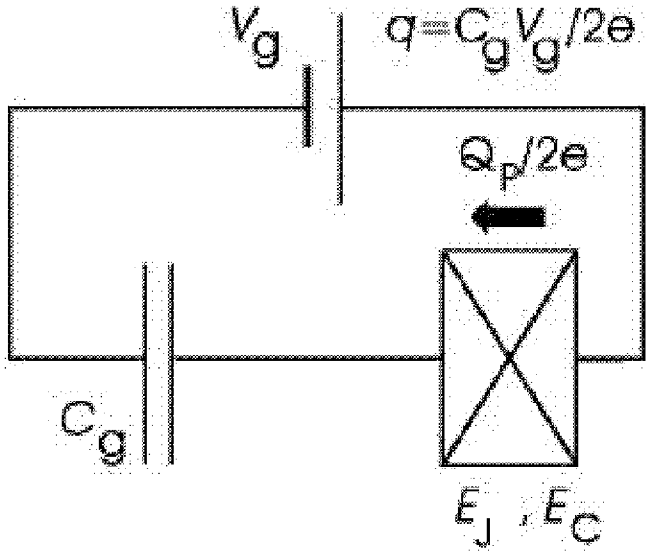
$$\hat{H} = \hat{H}_C + \hat{H}_J$$ varies due to gate operations

$$Q_P = 2\hbar \Im\mathrm{m} \left[\sum_{n \neq m} \oint \frac{(\hat{I}_l)_{mn}}{E_m - E_n} \langle n | \partial_{\vec{q}} m \rangle \cdot d\vec{q} \right]$$

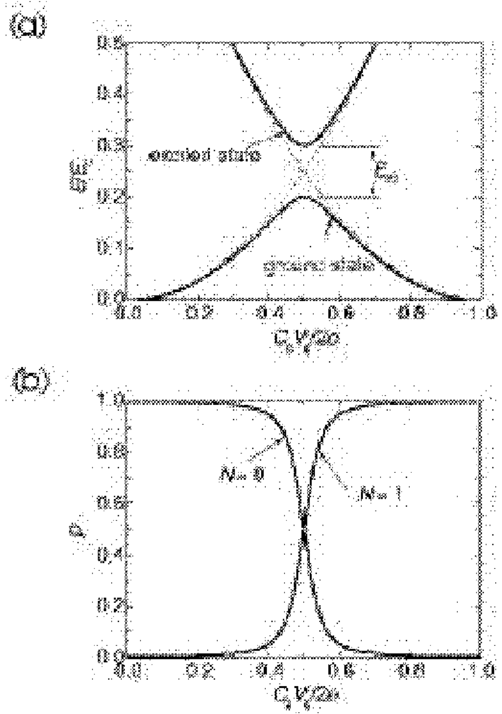
(m = 0 for transport in the ground state)

J. Pekola, J. Toppari, M. Aunola, M. Savolainen, D. Averin, PRB 60, 9931 (1999).

Adiabatic transport in a Cooper pair box



$$Q_P = 2\hbar \Im \left[\sum_{n \neq m} \oint \frac{(\dot{I}_\ell)_{mn}}{E_m - E_n} \langle n | \partial_{\vec{q}} m \rangle \cdot d\vec{q} \right]$$

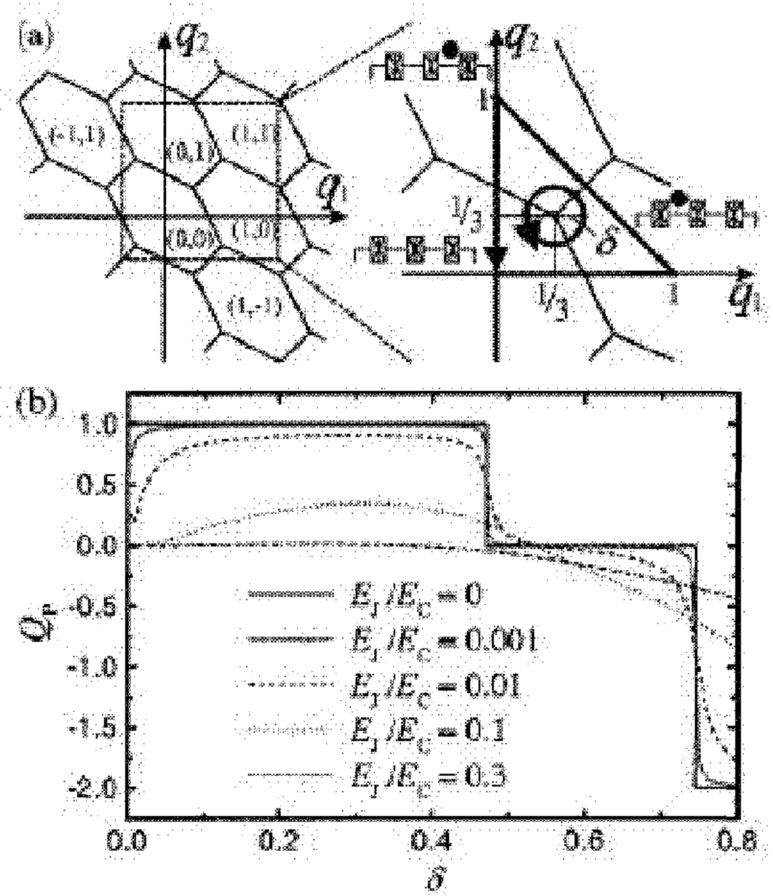


$$Q_{\rm P}/(2e) = [\eta_f/\sqrt{1+\eta_f^2} - \eta_i/\sqrt{1+\eta_i^2}]/2$$

$$\eta_{i,f} = (E_1 - E_2)_{i,f}/E_{\rm J}$$

(The same result can be seen directly from the composition of the ground state!)

Coherent adiabatic CPP, basic results

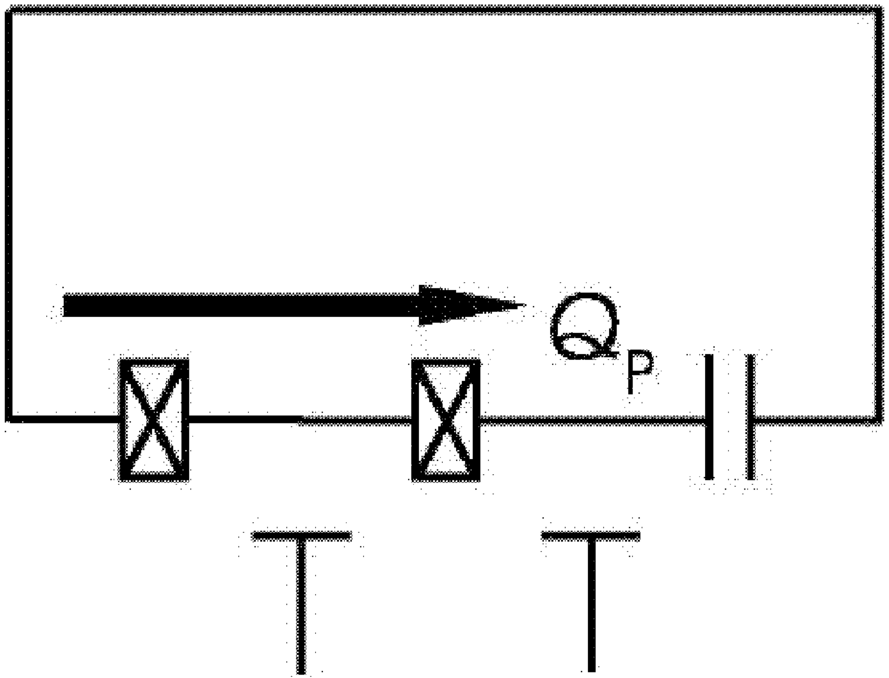


$$Q_P = 2\hbar\Im\mathrm{m}\left[\sum_{n\neq m}\oint \frac{(\tilde{I}_l)_{mn}}{E_m - E_n}\langle n|\partial_{\vec{q}} m\rangle \cdot d\vec{q}\right]$$

$$\boldsymbol{I_p/(2ef) = 1 - 9E_J/E_C\cos\varphi}$$

(triangular path)

Cooper pair trap



As a CPP, but instead of the third JJ there is a (classical) capacitor

$$\frac{Q_P}{2e} = 1$$

Adiabatic transport vs. Landau-Zener band-crossing

$H = H_J + H_C$

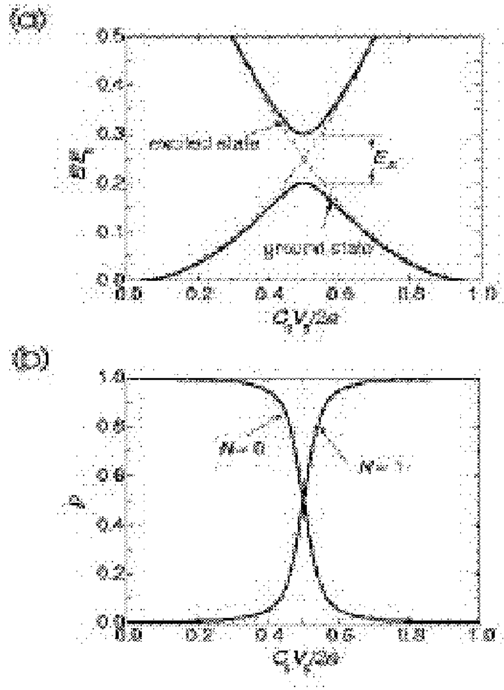
Adiabatic approximation is valid, if

$$|\langle 1|\dot{0}\rangle| << (E_1 - E_0)/\hbar$$

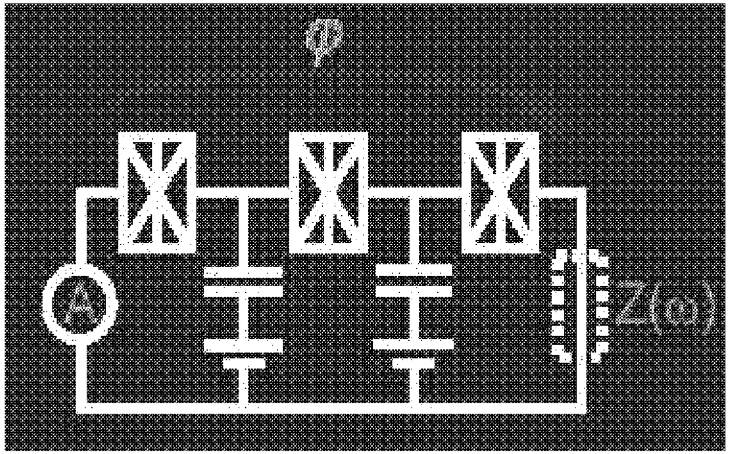
Band-crossing (LZ) becomes important, if this condition is violated.

For periodic gate operation this happens at

$$f_{LZ} \sim \frac{E_J^2}{\hbar E_C}$$



Phase fluctuations due to environment



J. Pekola and J. Toppari, PRB 64, 172509 (2001).

Simple idea:

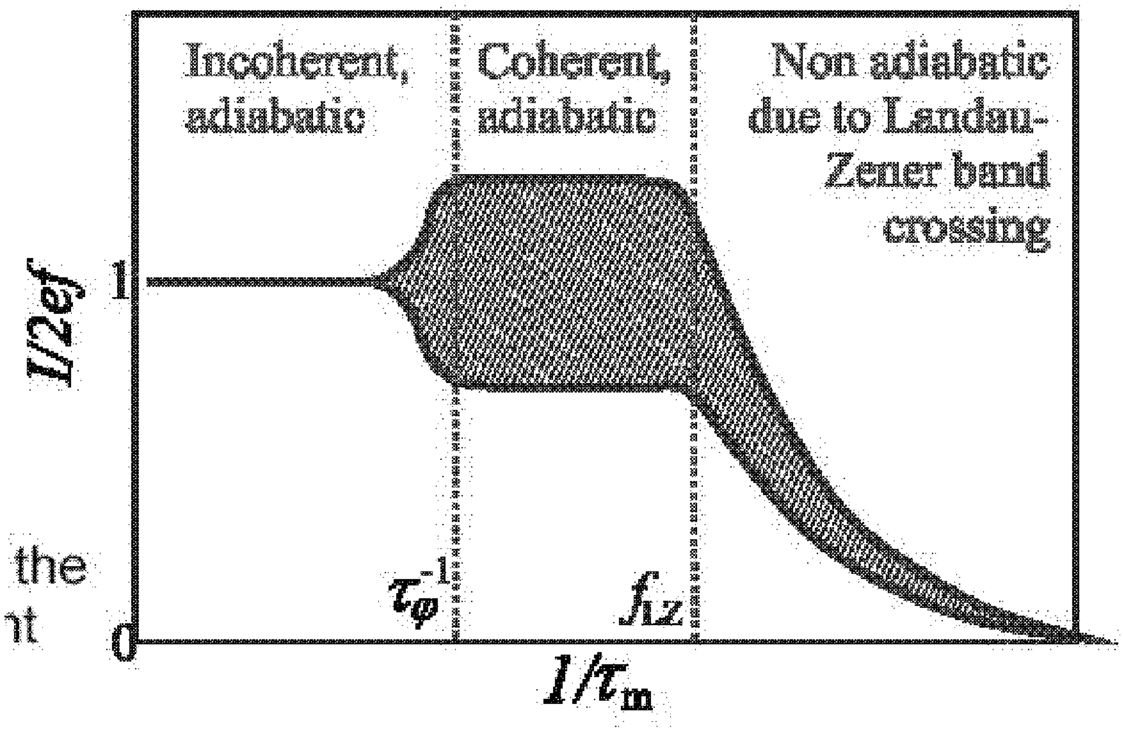
Determine the fluctuations of φ (in real time).

If $\langle(\Delta\varphi)^2\rangle \ll (\pi/2)^2$, pumping is coherent

If $\langle(\Delta\varphi)^2\rangle \gg (\pi/2)^2$, pumping is incoherent

In the latter case: $Q_P/2e = 1 - 9E_J/E_C\langle\cos\varphi\rangle \rightarrow 1$

Pumping regimes determined by Landau-Zener band-crossing and decoherence

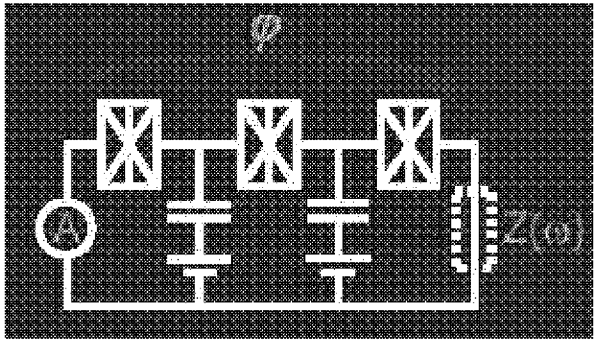


Phase fluctuations due to environment

FDT: $$J(t) = 2\int_0^\infty \frac{d\omega}{\omega}\frac{\mathrm{Re}\, Z_t(\omega)}{R_K} \times \left\{ \coth\left(\frac{\hbar\omega}{2k_B T}\right)[\cos(\omega t) - 1] - i\sin(\omega t) \right\}$$

$$\Delta\varphi \equiv \varphi(t) - \varphi(0)$$

$$\langle(\Delta\varphi)^2\rangle = -2\,\mathrm{Re}\, J(t)$$



Phase fluctuations: results in resistive environment

$T = 0$

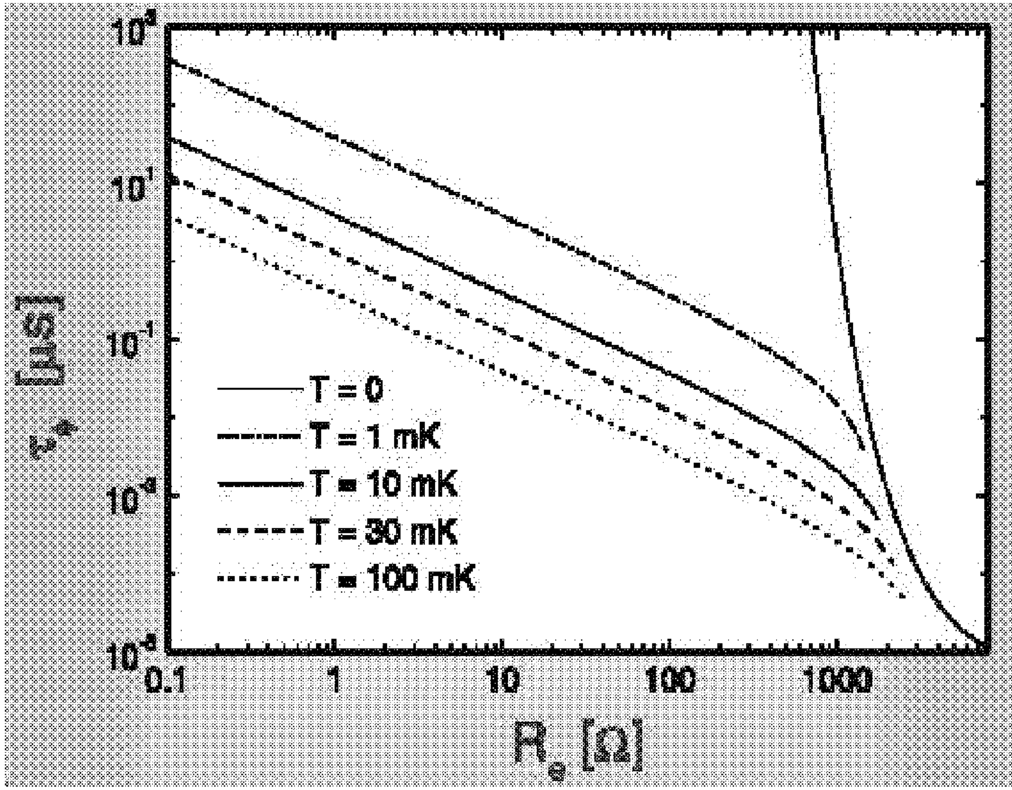
$$\langle (\Delta\varphi)^2 \rangle = 4 \frac{R_e}{R_K} [\ln(t/\tau) + \gamma]$$

$T > 0$

$$\langle (\Delta\varphi)^2 \rangle \simeq 4 \frac{R_e}{R_K} \left[\frac{\pi k_B T}{\hbar} t - \ln\left(\frac{2\pi k_B T \tau}{\hbar} \right) + \gamma \right]$$

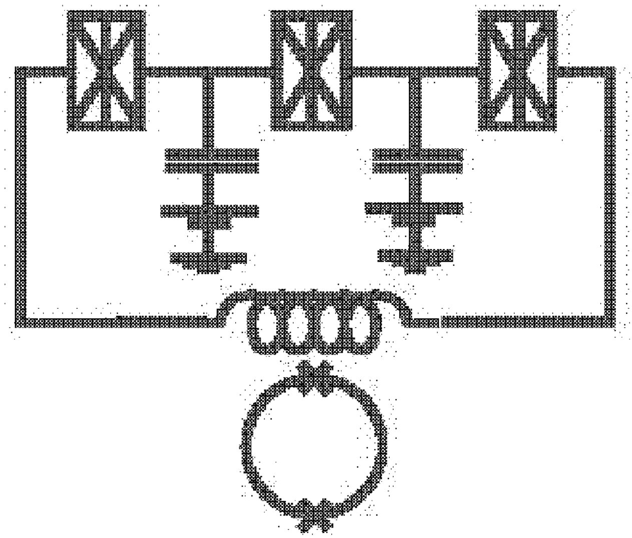
$$\tau_\varphi = \tau \exp\left(\frac{\pi^2}{16} \frac{R_K}{R_e} - \gamma \right) \qquad (T = 0)$$

$$\tau_\varphi \simeq \frac{\pi}{16} \frac{\hbar}{k_B T} \frac{R_K}{R_e} \qquad (T > 0)$$



$\langle (\Delta\varphi)^2 \rangle = (\pi/2)^2$ at $t = \tau_\varphi$

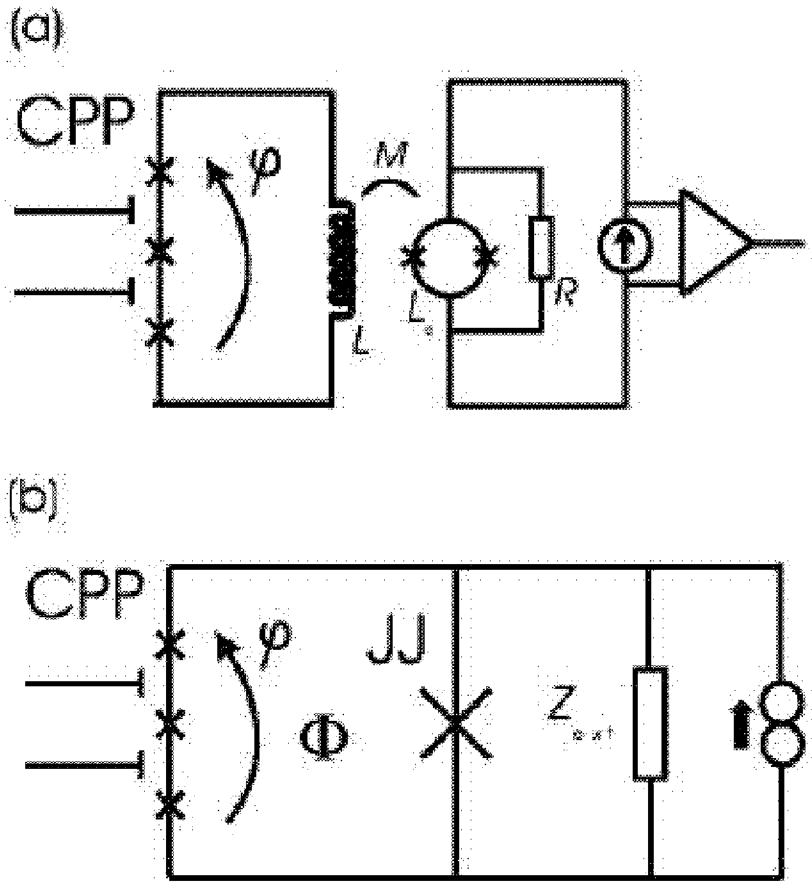
Measurement schemes to avoid phase fluctuations?



Measuring current with
SQUID ammeter ?

$$Q_{\mathrm{P}}/(2e) = 1 - [9E_{\mathrm{J}}/E_{\mathrm{C}} - (2\pi^2/3)LE_{\mathrm{J}}/\Phi_0^2]\cos\varphi$$

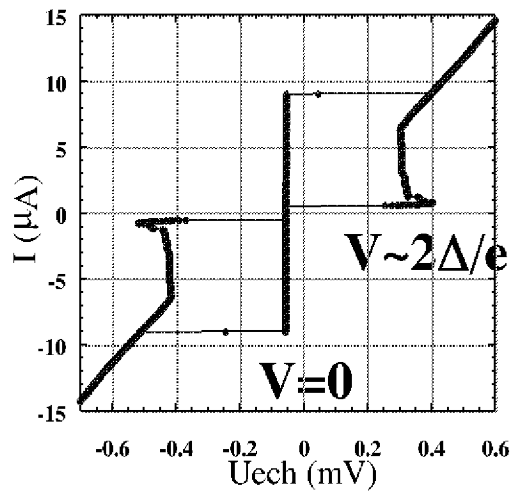
SQUID amplifier or escape junction



Current measurement by:

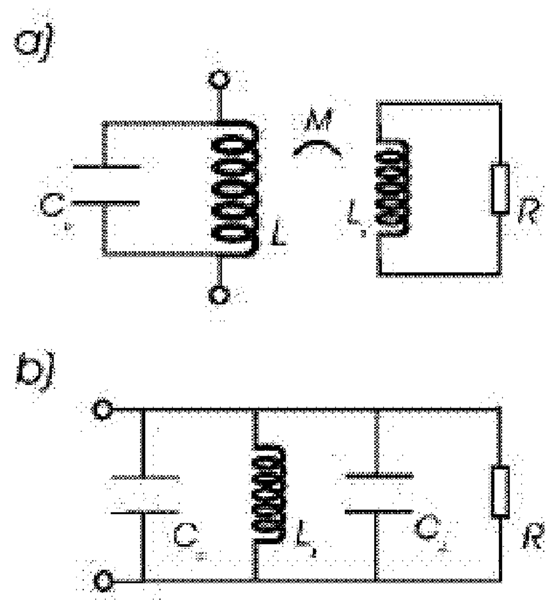
(a) SQUID amplifier

(b) Biased Josephson junction



F. Balestro, O. Buisson et al., Grenoble

Circuit models of SQUID amplifier and escape measurement

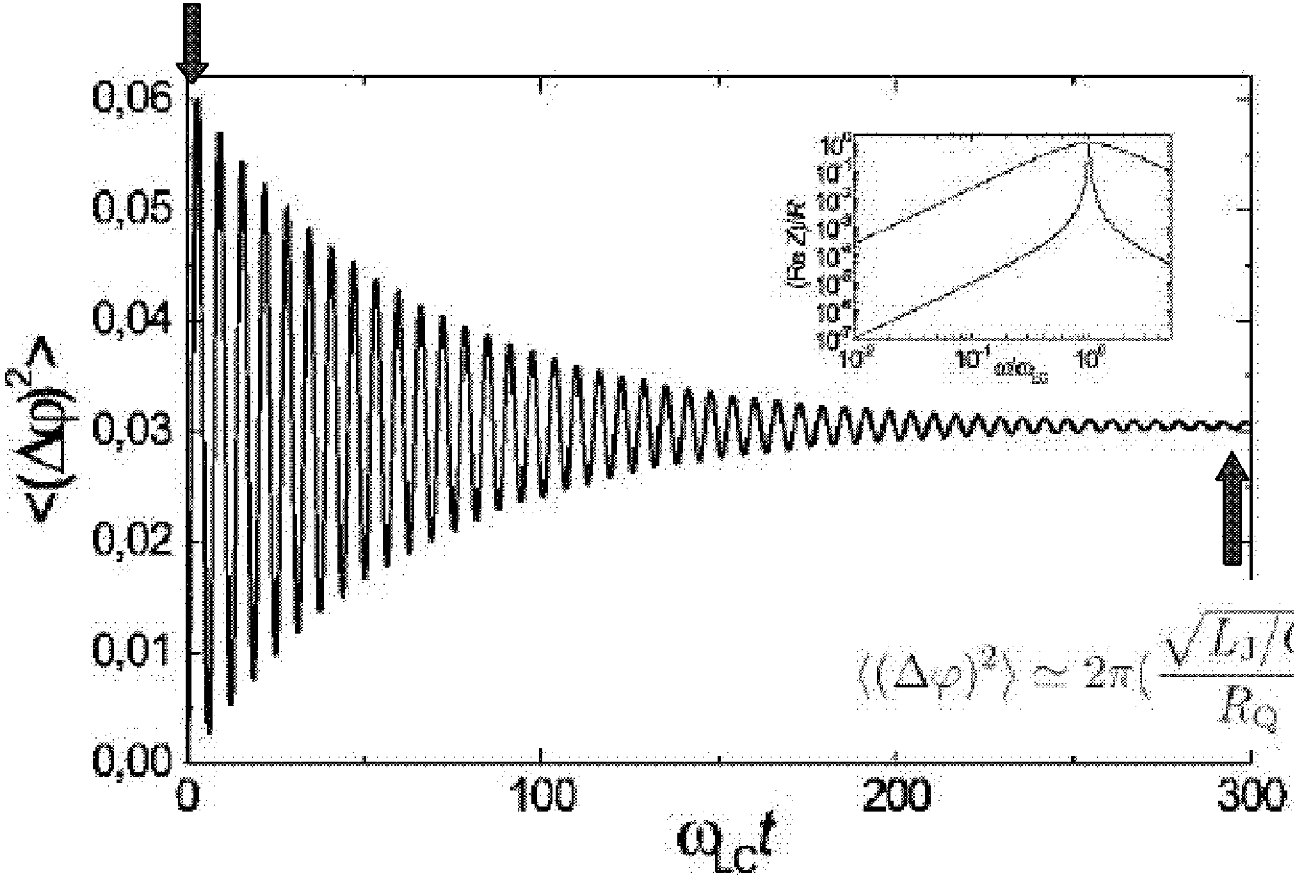


Inductance limited dephasing (underdamped case)

$$\sqrt{L_J/C_J^*}/R \ll 1$$

$$\langle(\Delta\varphi)^2\rangle \simeq 2\pi(\frac{\sqrt{L_J/C_J^*}}{R_Q})\coth(\frac{\hbar\omega_{LC}}{2k_BT})[1-\cos(\omega_{LC}t)]$$

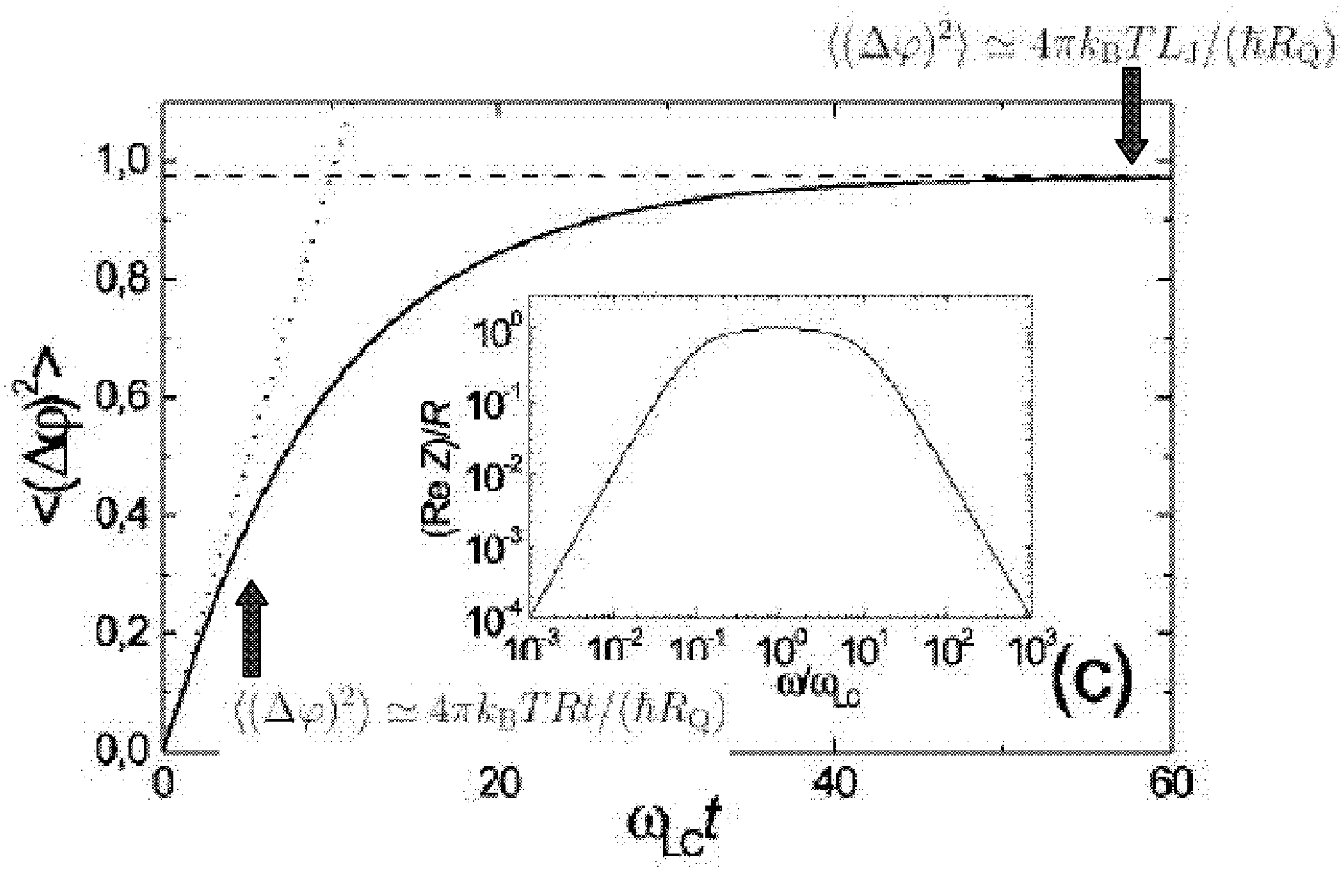
$$t_{dec} = 2RC_J^*$$



$$\langle(\Delta\varphi)^2\rangle \simeq 2\pi(\frac{\sqrt{L_J/C_J^*}}{R_Q})\coth(\frac{\hbar\omega_{LC}}{2k_BT})$$

Fazio, Hekking, Pekola, unpublished (2002)

Inductance limited dephasing (overdamped case)

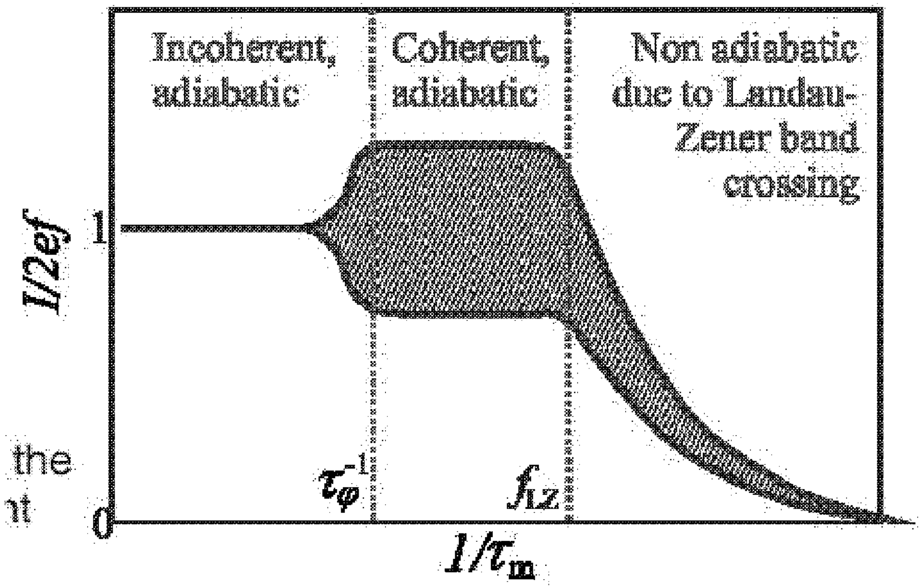


Parameters of the planned measurement

Pumping frequency <100 MHz, current <30 pA (aluminium)

Niobium would allow > 1 GHz and > 0.3 nA (?)

Measurement bandwidth > τ_φ^{-1} ~ 1 MHz



Experiments on Nb structures

N. Kim, J. Toppari, L. Taskinen, S. Paraoanu, K. Hansen, J. P.

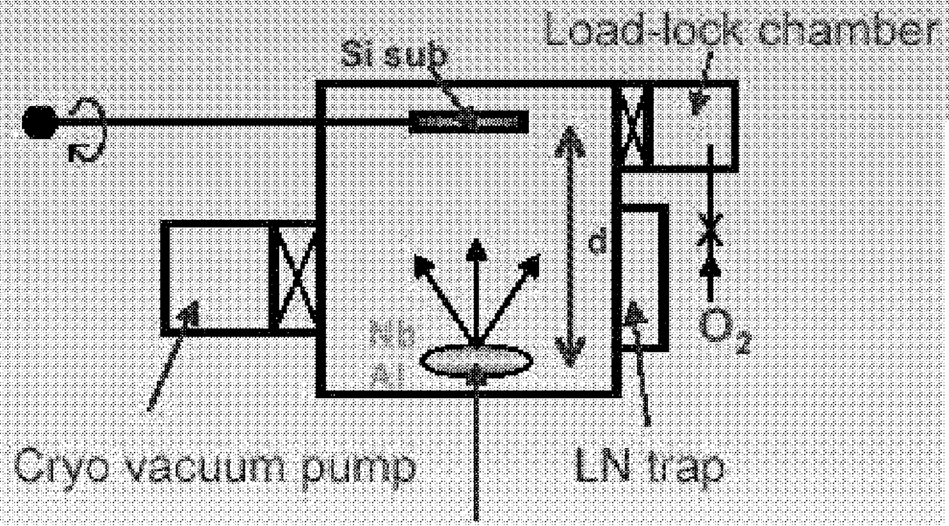
$$E_J \sim (R_Q/R)\cdot(\Delta/2)$$

$$\Delta(Nb) = 1.5\ meV \approx 7.5\Delta(Al)$$

- multilayer technique
  - Nb/(Al-)AlO_x/Nb tri-layers,
    Pavolotsky *et al.* JVSTB(1994)
- two angle evaporation technique
  - Nb/AlO_x/Al, Harada *et al.* APL(1994)
  - Nb/AlO_x/Al, Dolata *et al.* APL(2002)

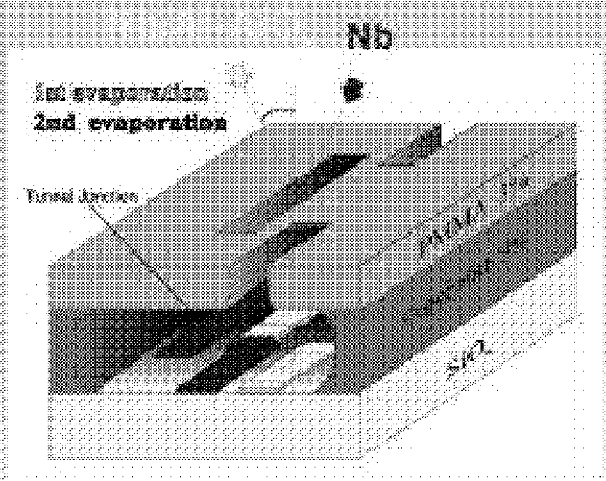
Metallisation set-up

UHV chamber



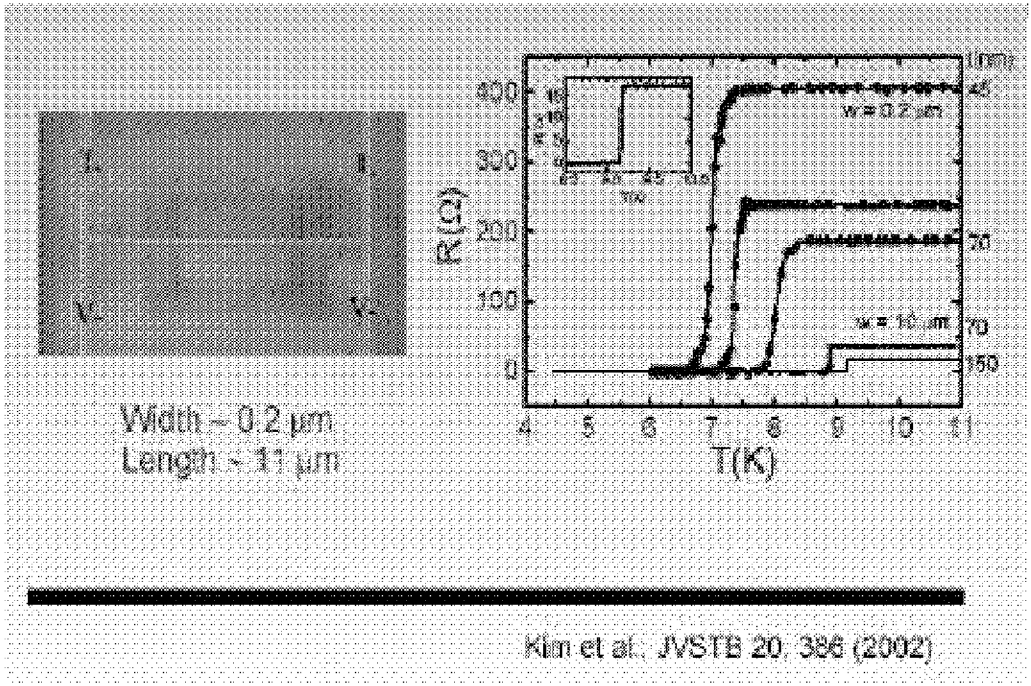
E-gun heated
Pressure ~10^{-8} mbar
d ~ 40 cm

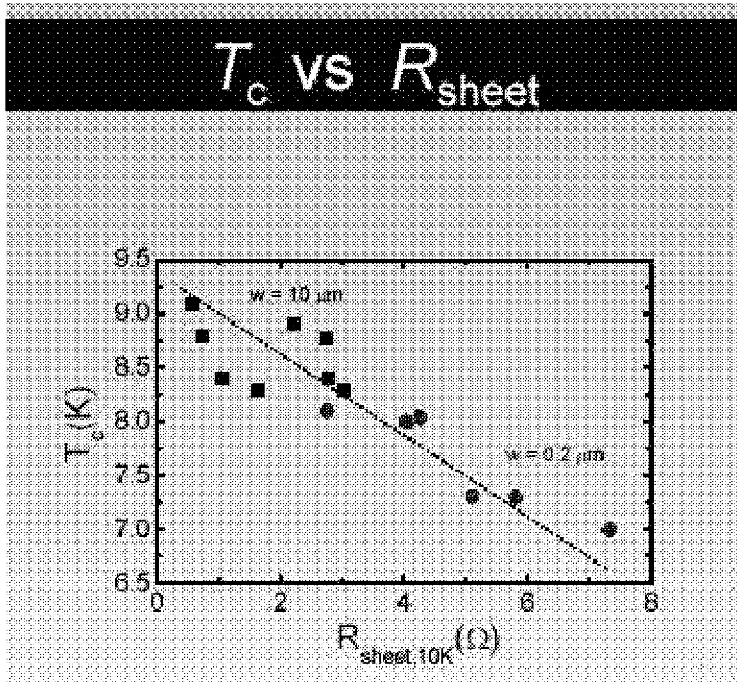
Two angle evaporation



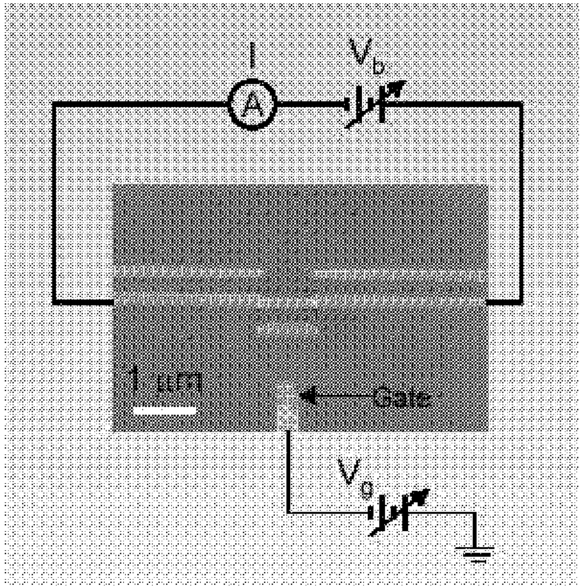
t_{Nb}~ 50nm
t_{Al} ~ 20nm

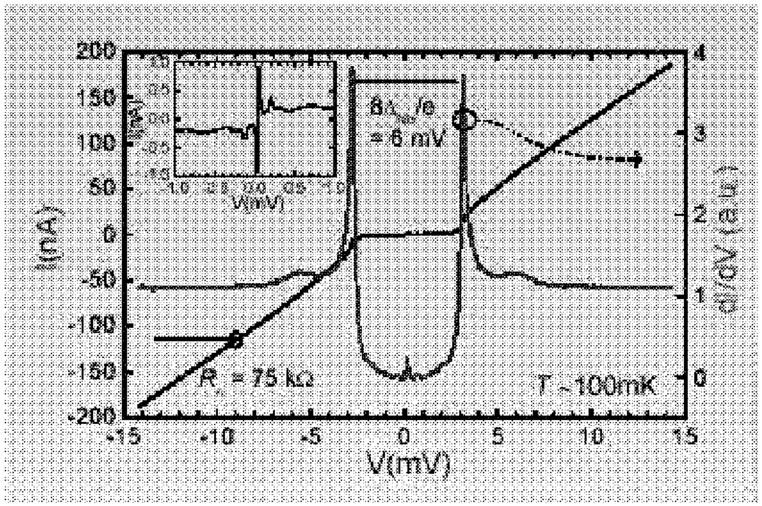
Nb-wires

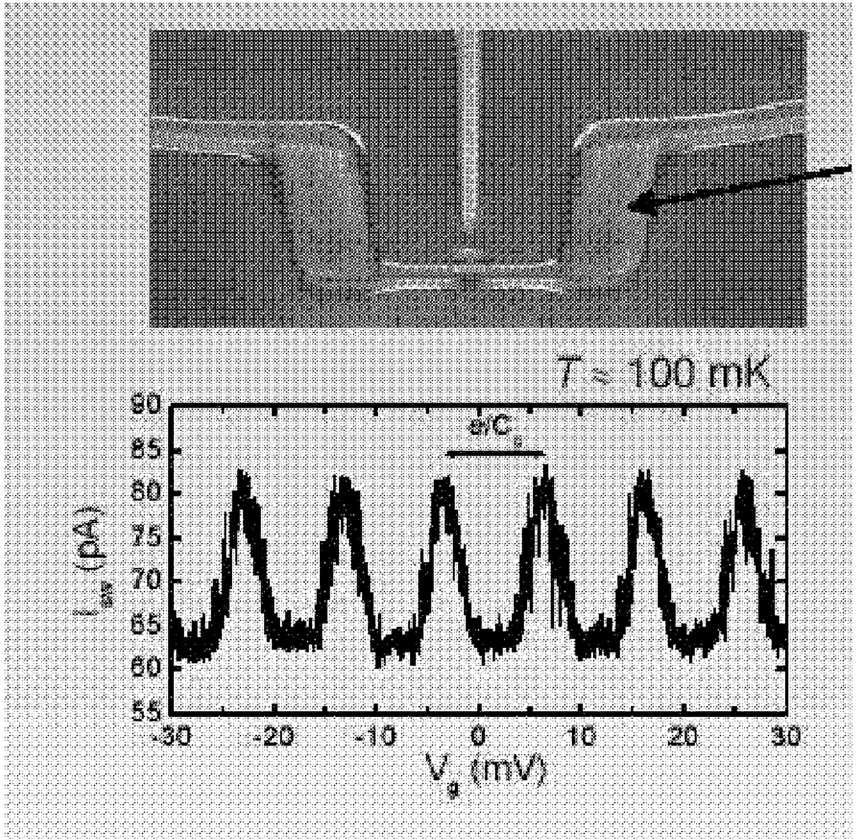

Width ~ 0.2 µm
Length ~ 11 µm
R(Ω)
T(K)
w = 0.2 µm
w = 10 µm
Kim et al., JVSTB 20, 386 (2002)


Tc vs Rsheet
w = 10 µm
w = 0.2 µm
Tc(K)
Rsheet,10K(Ω)

Nb-SSETs


I
V_b
A
1 μm
Gate
V_g


8Δ_Nb/e = 6 mV
R_n = 75 kΩ
T ~100mK
I(nA)
dI/dV (a.u.)
V(mV)


T ≈ 100 mK
e/C_g
I_av (pA)
V_g (mV)