Experiments with arrays of Josephson junctions near superconductor-insulator transition

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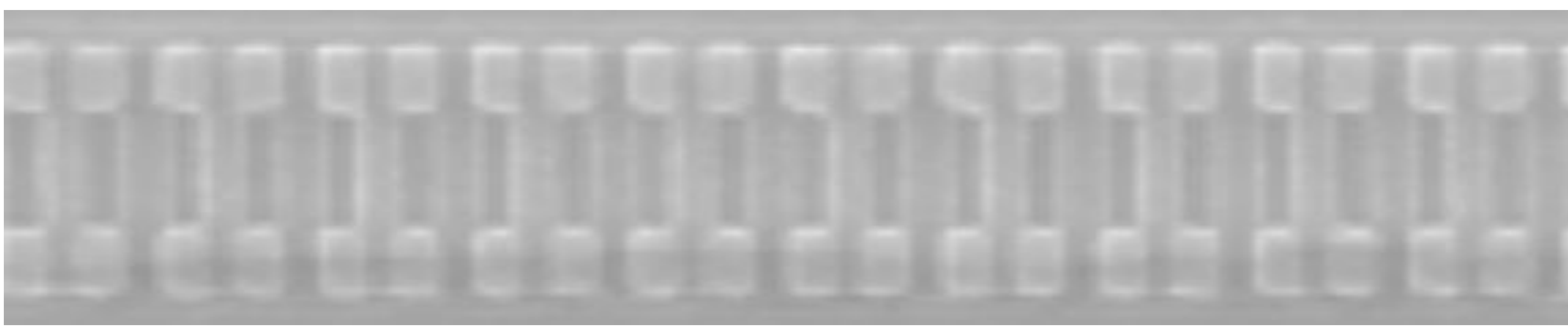
Acknowledgements:
H. Rotzinger, R. Schäfer, A. Shnirman , N. Vogt, J. Zimmer



Outline

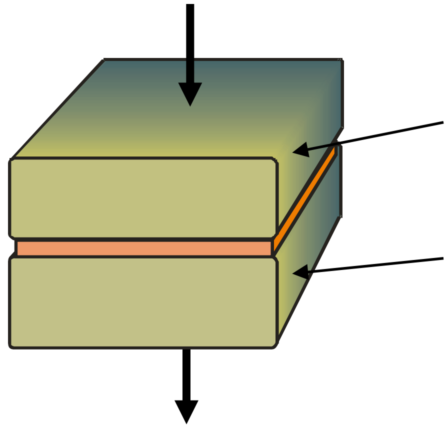
- Josephson junctions and arrays
- Fabrication of Josephson junctions
- Measurement techniques
- Experimental limitations and typical problems
- Brief history of experiments with JJ arrays near S/I transition
  - 2D arrays
  - 1D/2D channels – shooting and localizing quantum vortices
  - 1D arrays – searching for ballistic Cooper pairs
- Our recent experiments with 1D arrays
  - tuning E_J/E_C , dual IV-curves
  - conductance ~ E_J^2, incoherent Cooper pair tunneling
  - thermal activation of charges
  - depinning of charges **=> talk of A. Shnirman today**

Josephson junction

superconductor

tunnel barrier

superconductor



$$\Psi_1 = |\Psi_1| \exp(i\theta_1)$$

$$\Psi_2 = |\Psi_2| \exp(i\theta_2)$$

superconducting phase difference: $\varphi = \theta_1 - \theta_2$

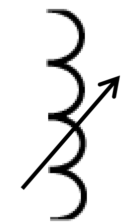
Josephson relations

$$I_S = I_C \sin\varphi$$

$$V = \frac{\hbar}{2e}\frac{\mathrm{d}\varphi}{\mathrm{d}t}$$

Josephson inductance

$$L_J = V \frac{\mathrm{d}I_S}{\mathrm{d}t} = \frac{\Phi_0}{2\pi I_C \cos\varphi}$$



Energy scales

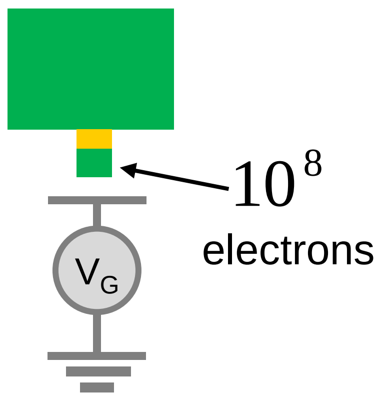
Uncertainty relation for a superconductor: $\Delta n \cdot \Delta \varphi \geq 1$

Charging energy $E_C = \dfrac{e^2}{2C_J}$

Josephson energy $E_J = \dfrac{I_c \Phi_0}{2\pi}$

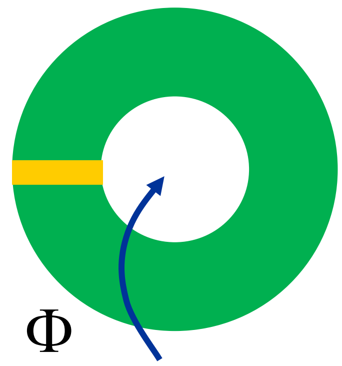
charge limit

$E_C >> E_J$



flux limit

$E_C << E_J$



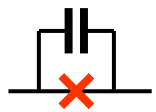
insulating state

superconducting state

Phase-charge duality in Josephson junction circuits

phase inertia

$E_J >> E_C$

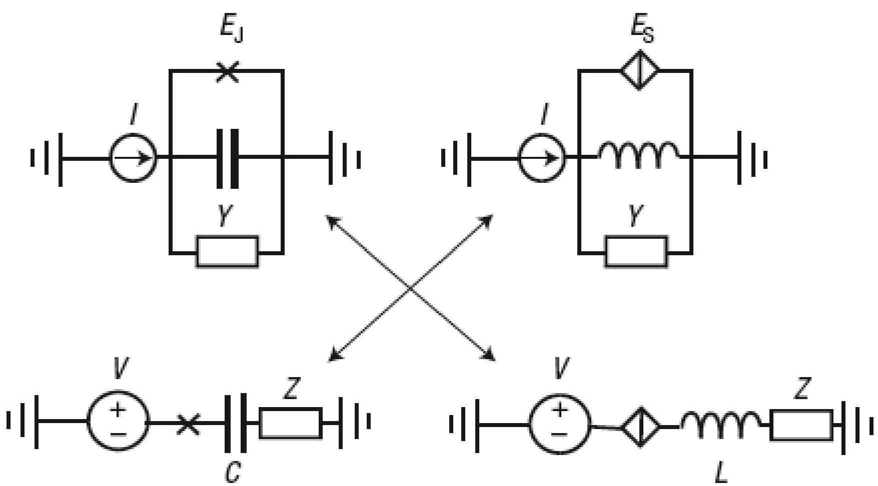


charge inertia

$E_J << E_C$

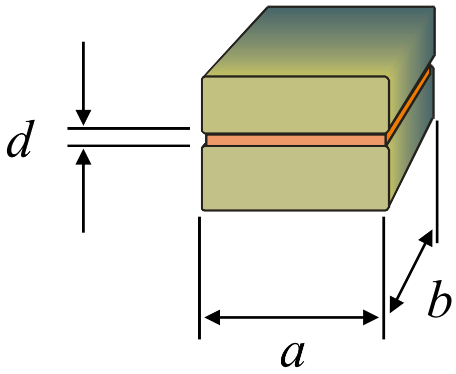
Review of the duality ideas for JJ arrays:
W. Guichard and F. W. J. Hekking, Phys. Rev. B **81**, 064508 (2010)

Duality between Josephson junction and phase slip junction



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

Junction size and energy scales



Josephson energy $E_J = \frac{I_c \Phi_0}{2\pi}$

charging energy $E_C = \frac{e^2}{2C_J}$

$$I_c = \frac{\Phi_0 \Delta}{2R_n} \sim A \exp\left(-\frac{d}{d_0}\right) \qquad C_J \sim \frac{A}{\varepsilon\, d}$$

tunnel barrier thickness d

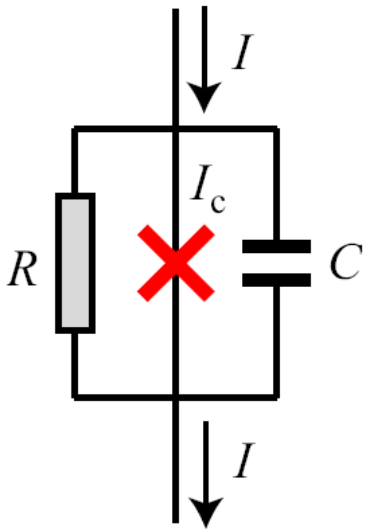
junction area $A = a\,b$

$$\Rightarrow \quad \frac{E_J}{E_C} \sim A^2\, d\, \exp\left(-\frac{d}{d_0}\right)$$

Typically, achieving $\frac{E_J}{E_C} < 1$ requires $A < 0.01\mu\text{m}^2$

Simple estimate of conditions needed for observing quantum effects in a JJ

- A simple estimate for value of the junction resistance above which clear quantum effects become visible

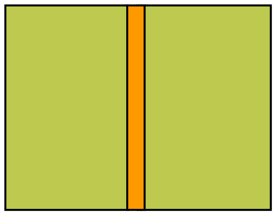


- The Heisenberg relation $\Delta E \, \Delta\tau \geq \hbar$
- taking $\Delta E \approx E_C = \dfrac{e^2}{2C}$ and $\Delta\tau \approx RC$
- the junction resistance should satisfy

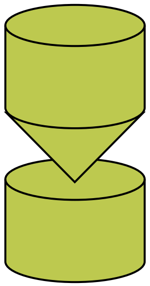
$$R \geq R_Q = \frac{h}{4e^2}$$

for quantum effects to be observable

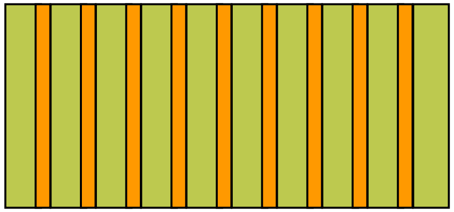
Josephson junctions and weak links



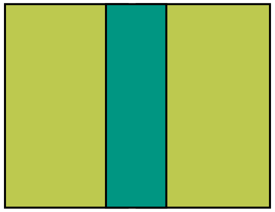
SIS
tunnel junction



point contact

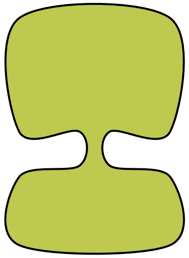


SISISISISISISISISIS
intrinsic junctions
(crystal)

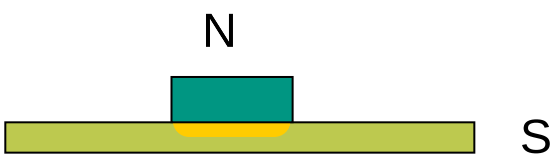


SNS

normal metal

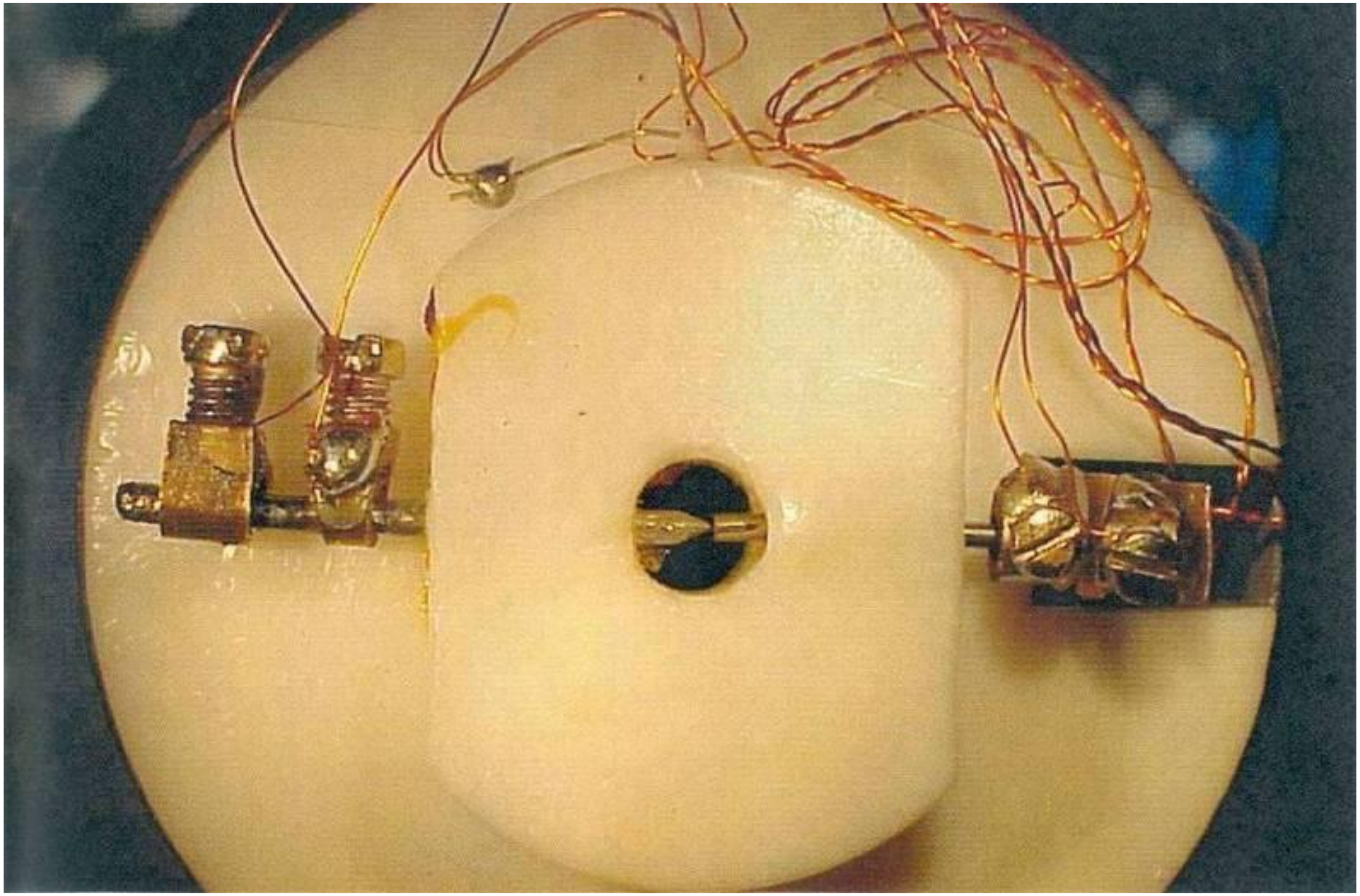


nano-bridge
(constriction)

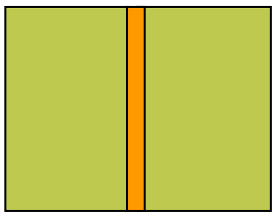


proximity link

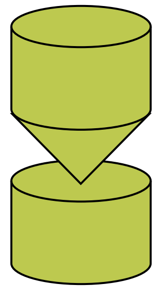
The simplest way of making a Josephson junction



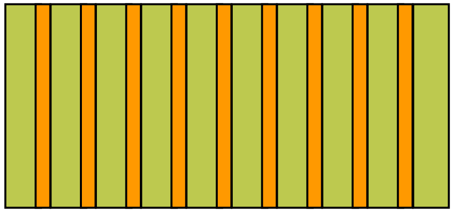
Josephson junctions and weak links



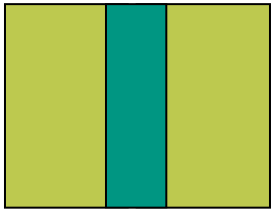
SIS
tunnel junction



point contact

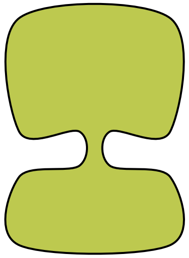


SISISISISISISISISIS
intrinsic junctions
(crystal)

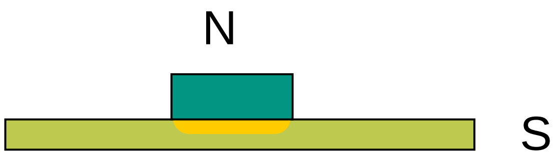


SNS

normal metal

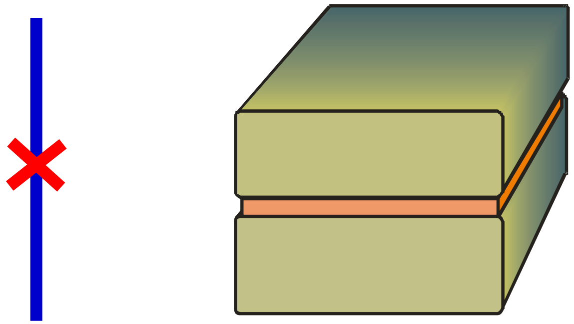


nano-bridge
(constriction)



proximity link

Fabrication of Josephson devices

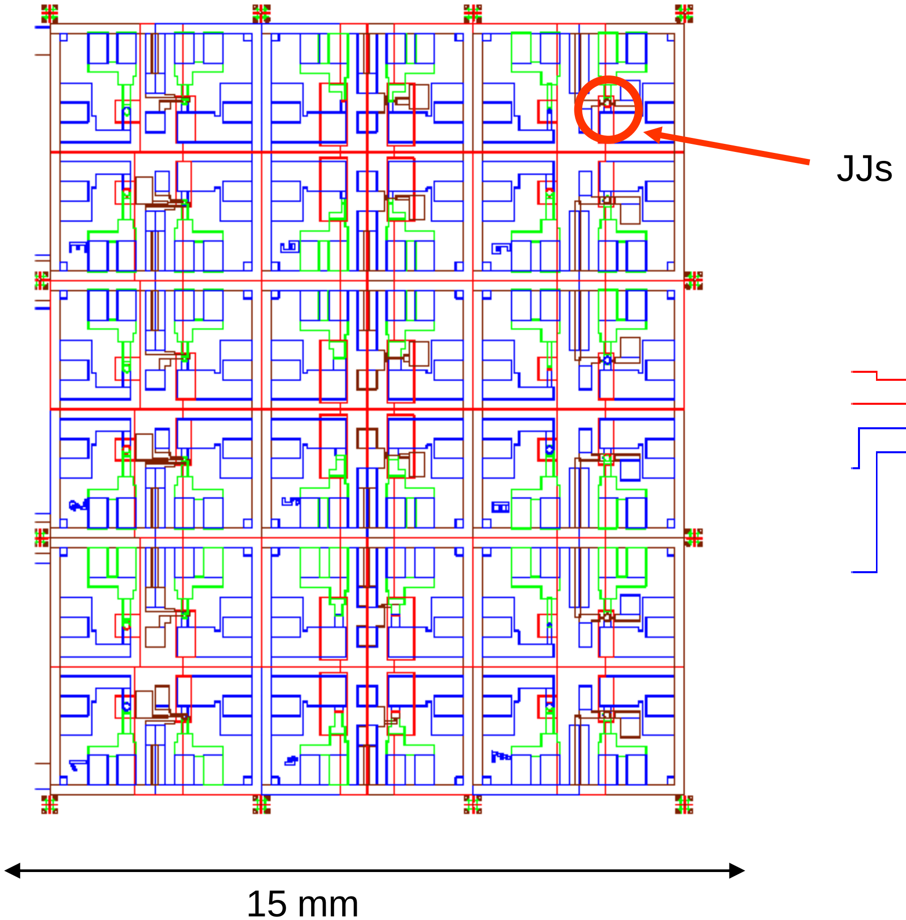


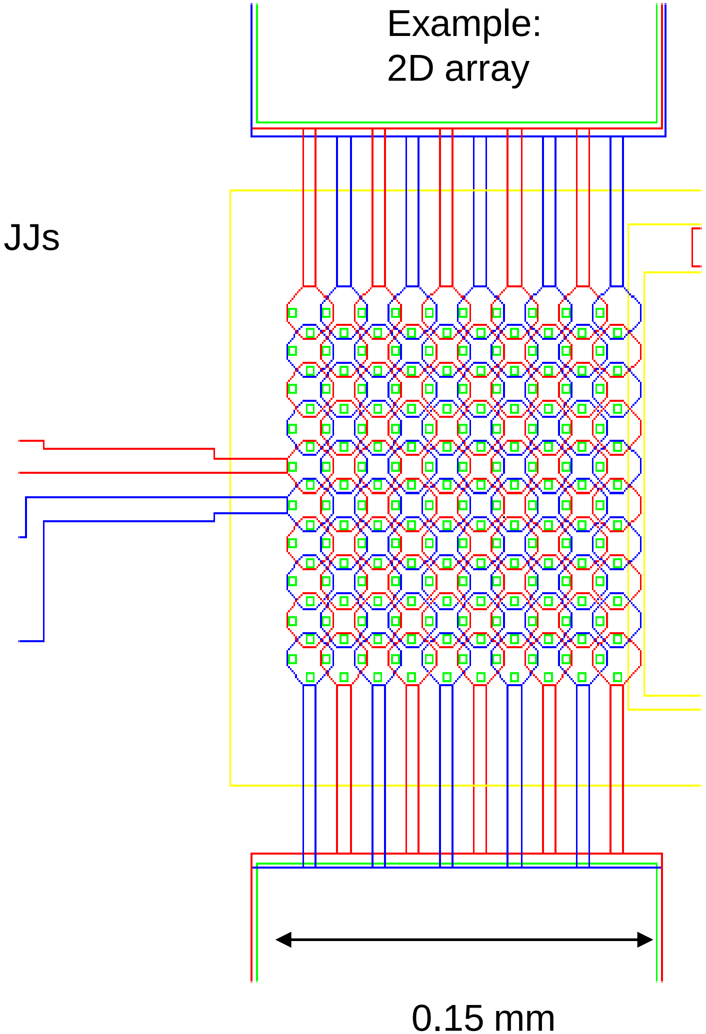
1. circuit layout (CAD)
2. fabrication of photomasks
3. deposition of superconducting and insulating layers on a wafer
4. photo (or e-beam) lithography
5. dicing the wafer into chips

- *Nb-AlO$_x$-Nb*
  - *Nb* sputtering
  - *Al* sputtering and oxidation
  - T_c = 9.2 K
  - J_c from 10^2 to 10^4 A/cm^2
- *Al-AlO$_x$-Al*
  - *Al* evaporation
  - *Al* oxidation
  - T_c = 1.2 K
  - J_c from 1 to 10^2 A/cm^2

Circuit layout

CAD = computer aided design

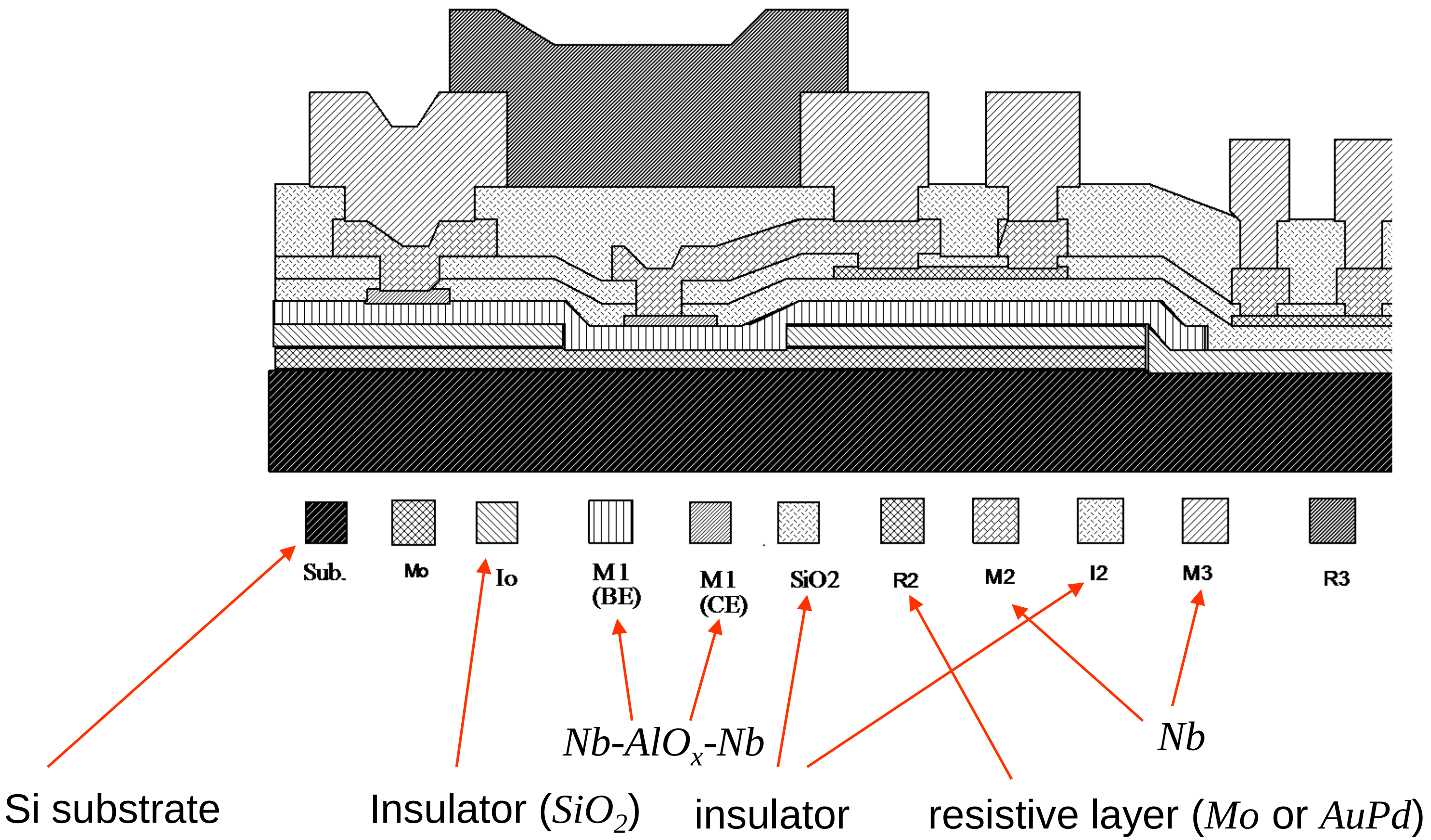




Stacking thin-film layers: Example

design rules of Hypres Inc.

See: http://www.hypres.com



Wafer processing

Photolithography can be used for JJ size down to 1 μm

Clean room

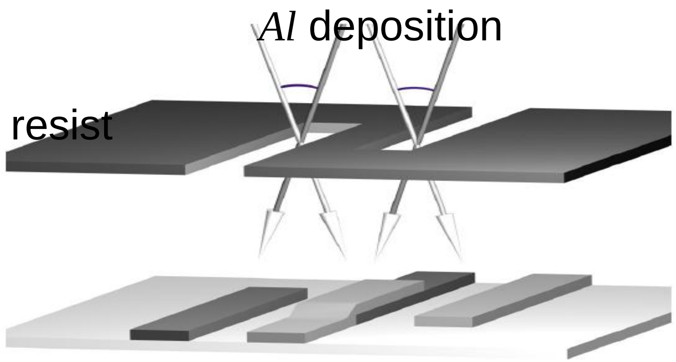
mask alignment

Evaporation of superconducting thin films

PLASSYS electron beam evaporation unit with load lock. The unit is dedicated for fabrication of Josephson junctions and was installed at RQC lab at ISSP Chernogolovka in June 2014

Shadow evaporation technique

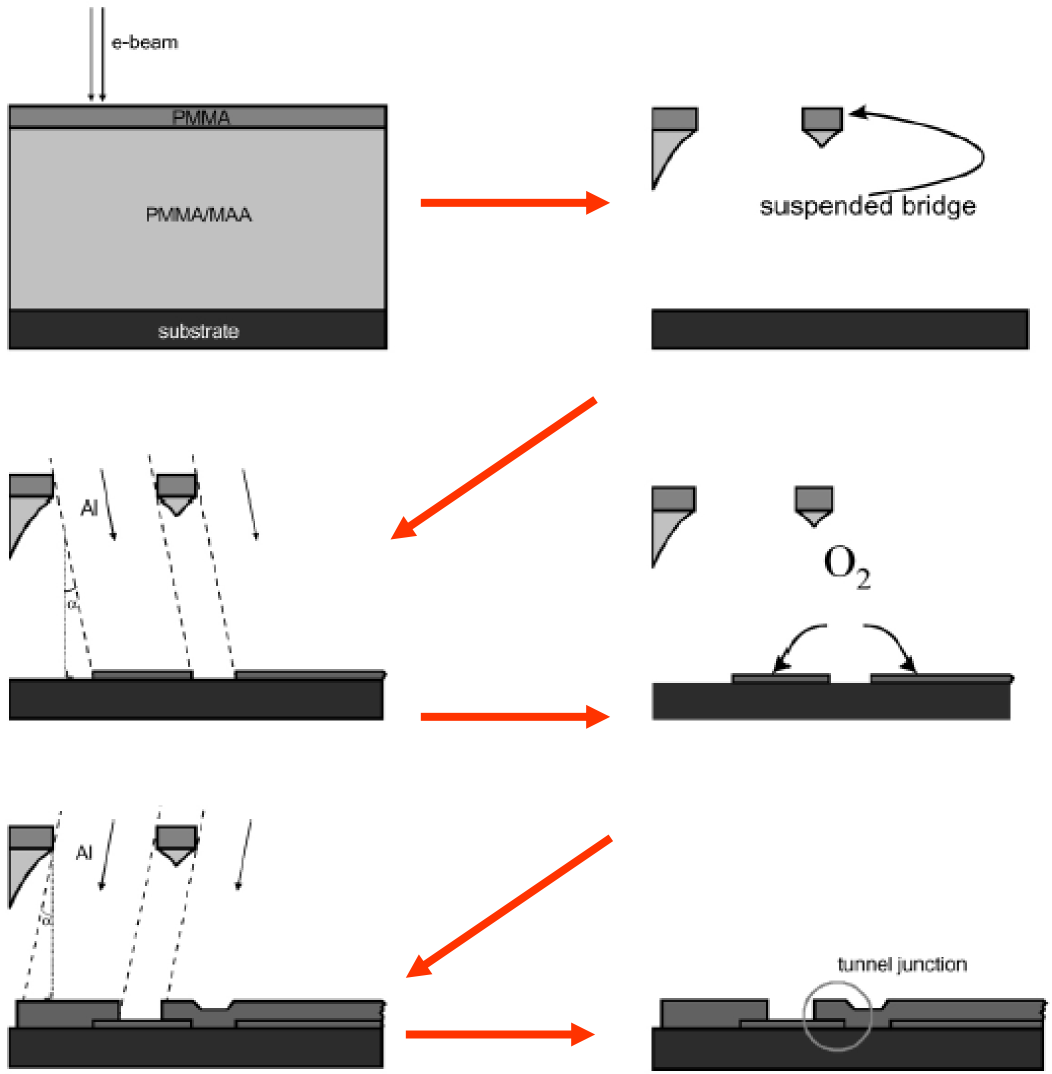
Electron beam lithography can produce JJ size < 0.1 μm



Electrom beam lithography

In a first step metal is evaporated from one angle, indicated by the dark arrows and dark structures on the substrate surface. The evaporation from another angle leads to an overlap of the features in the middle. (Picture by Mattias Urech)

Shadow evaporation of Al-AlO_x-Al junctions



Pattern is written in the resist using an electron beam

After the sample is developed, a suspended resist bridge is left

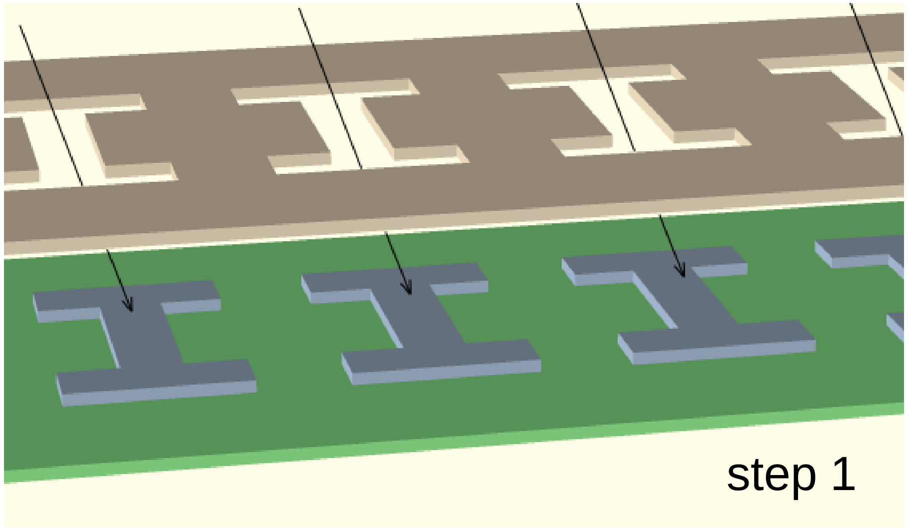
The bottom layer of aluminum is deposited under an angle +α

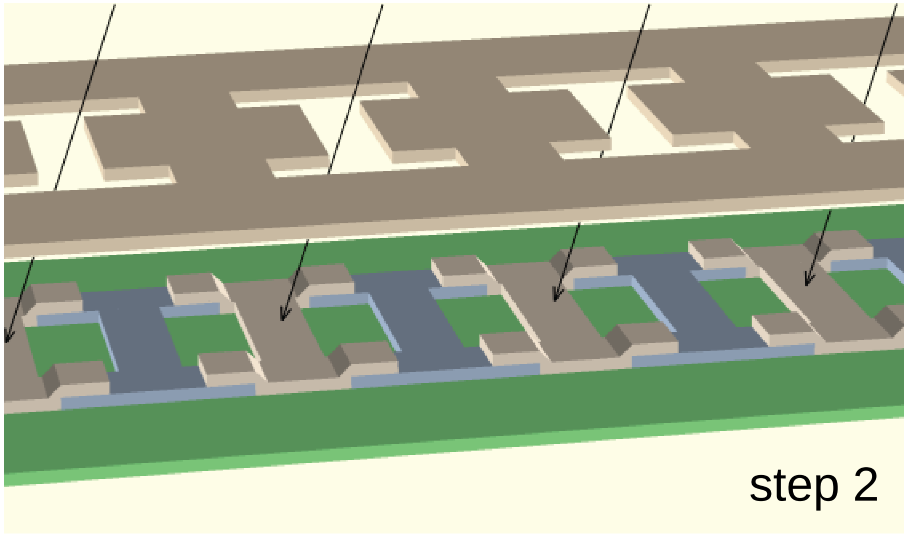
The sample is exposed to O_2 to form the oxide layer

The top layer of aluminum is deposited under an angle -α

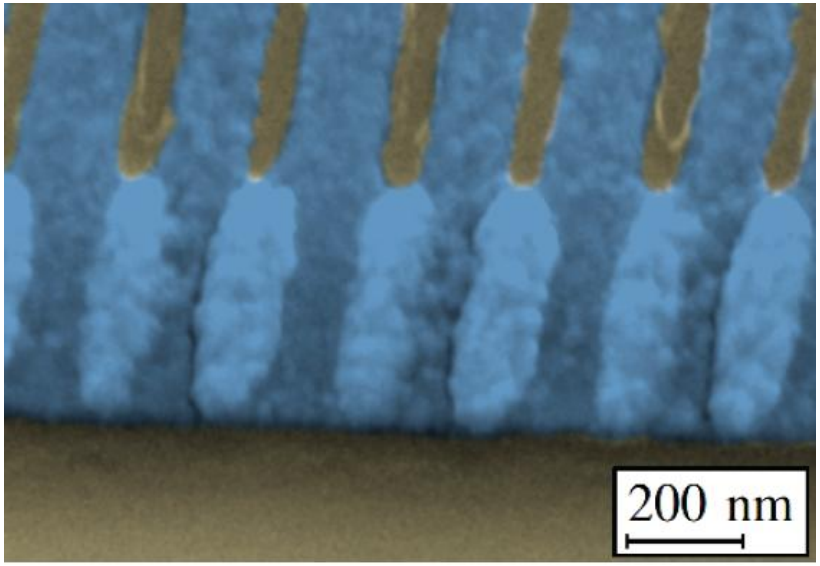
Lift-off in acetone removes the resist and a tunnel junction is left

Shadow evaporation of SQUID arrays

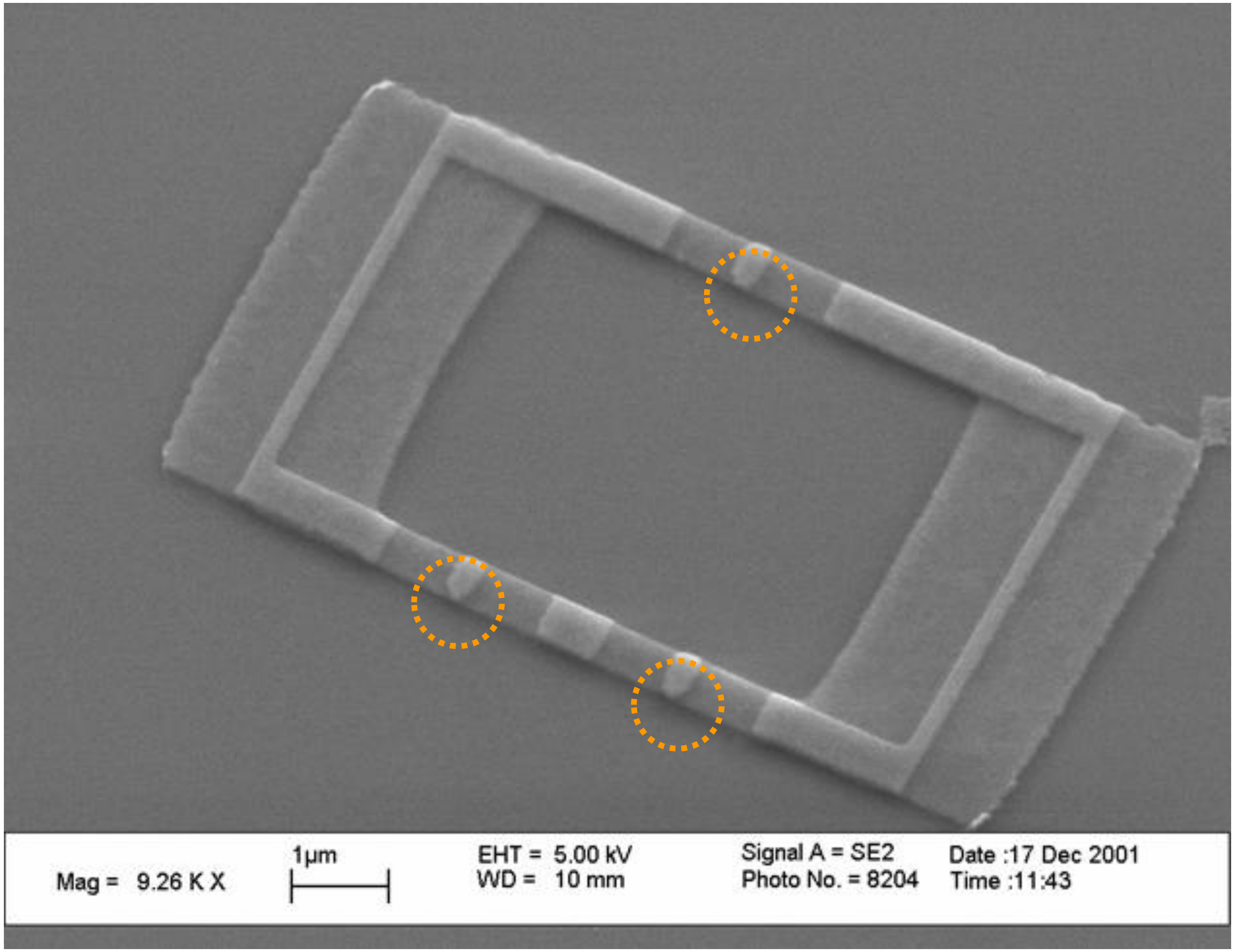


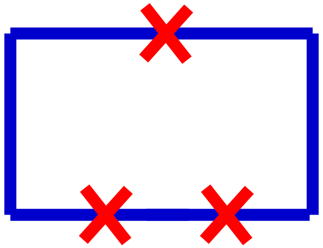


result



Sub-micron Al-AlO_x-Al JJs produced by electron beam lithography

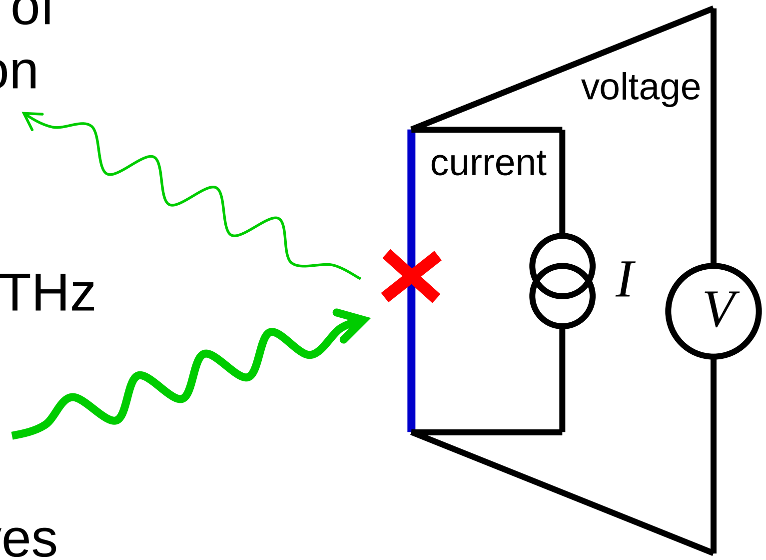




3-JJ flux qubit

Experiments with JJs

detection of Josephson radiation



1 GHz – 1 THz

applying microwaves

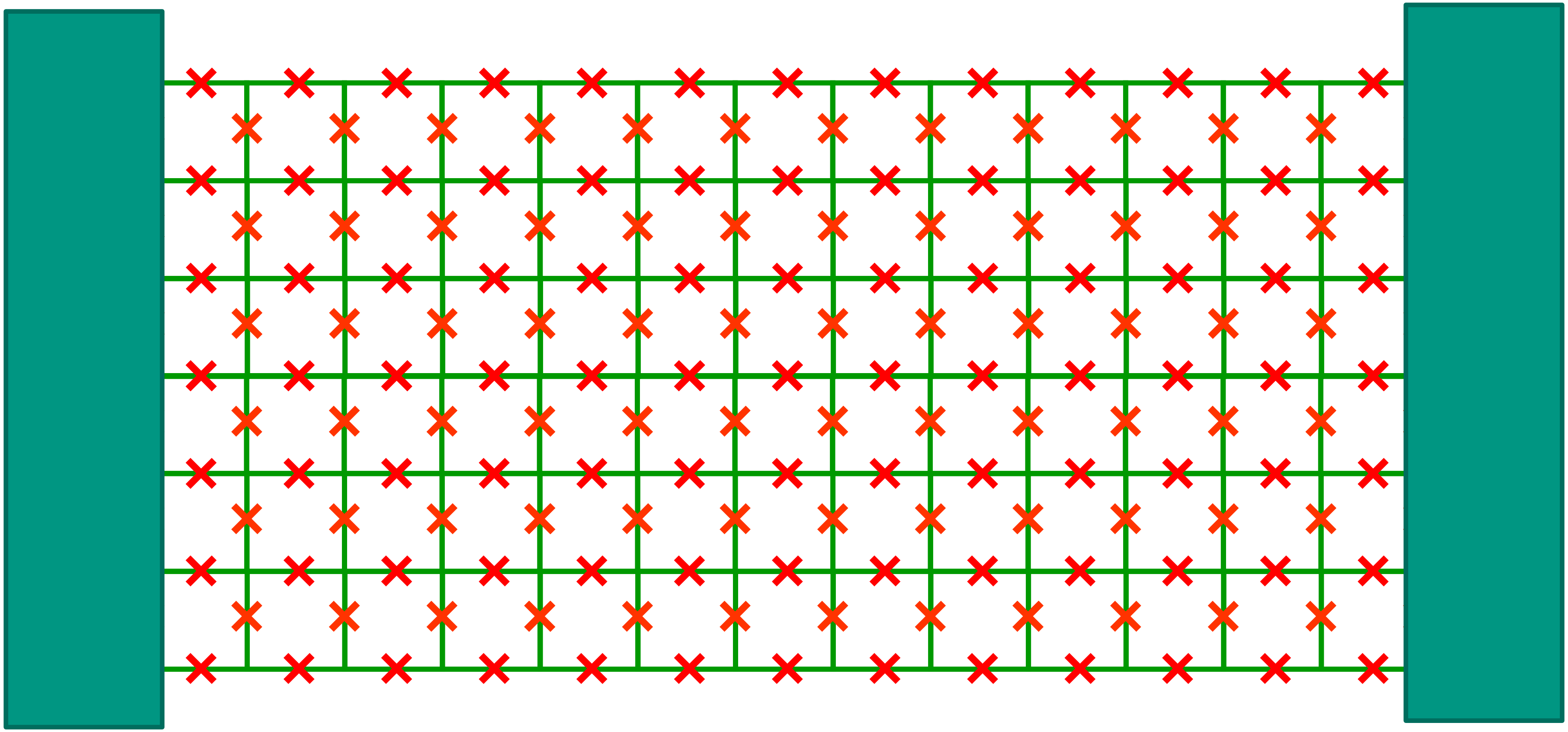
AC techniques

expensive and more difficult

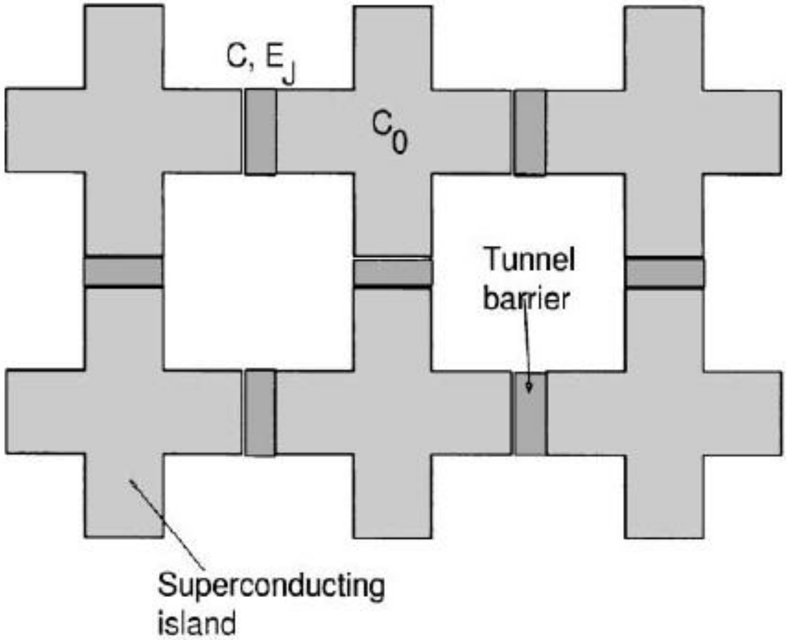
DC techniques

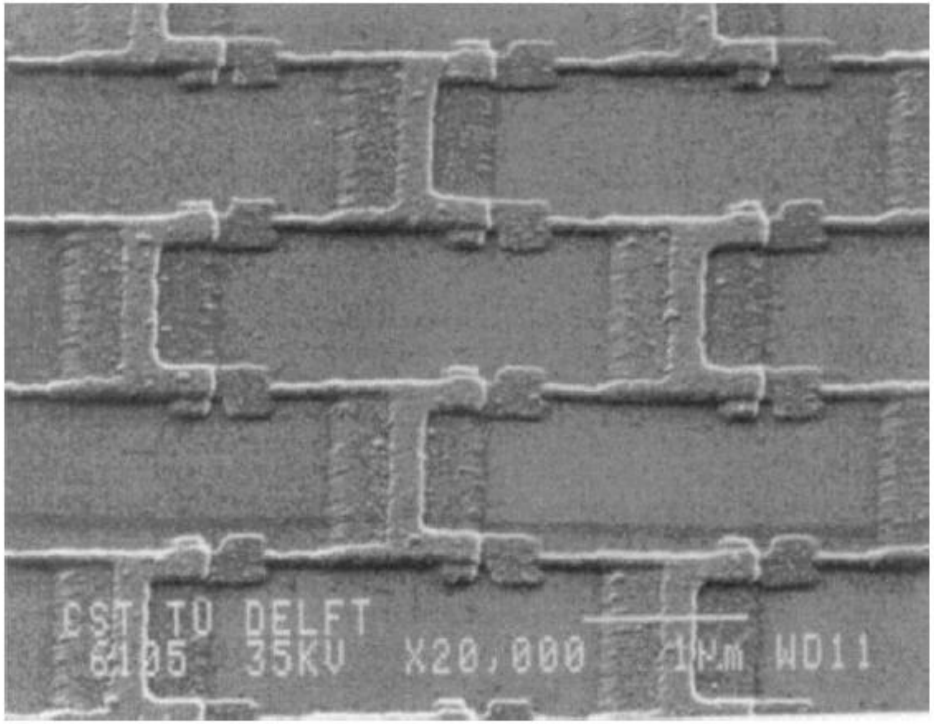
cheap and easy

Experiments with 2D arrays



Early works on 2D Josephson arrays

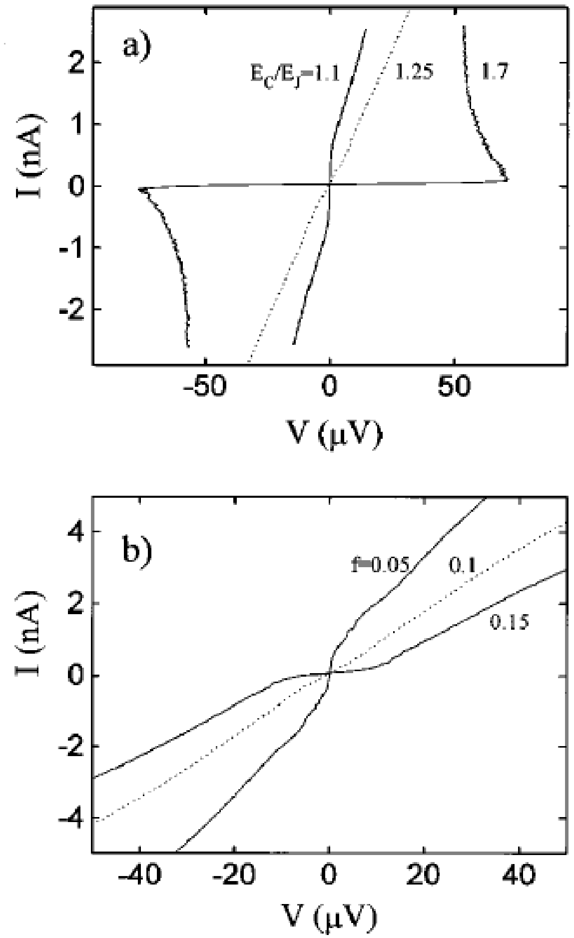


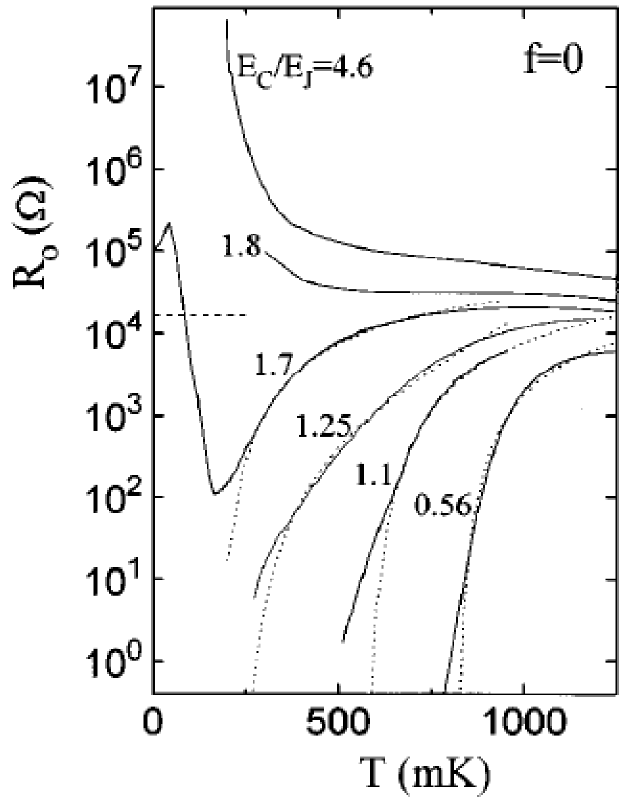


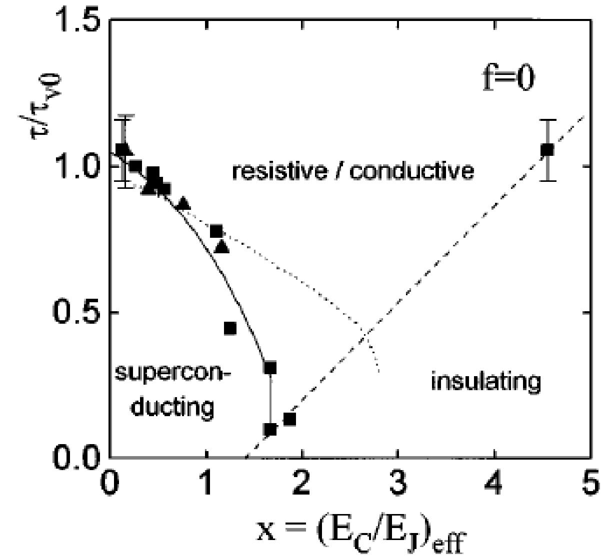
Ph.D. Thesis of L.J. Geerligs, Delft 1990

Review: R. Fazio and H. van der Zant, Phys. Rep. **355**, 235 (2001)

Observation of S/I transition in 2D

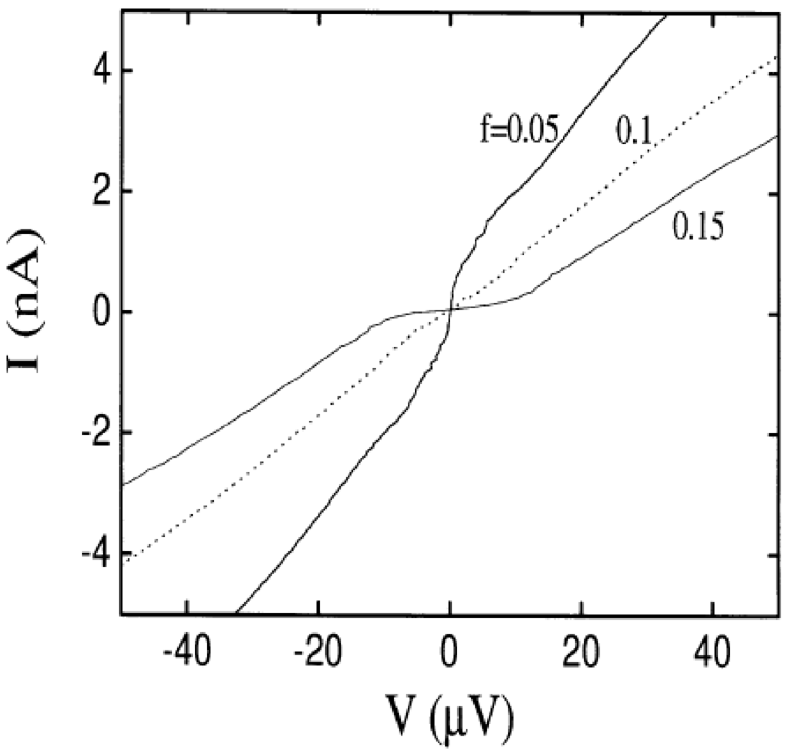


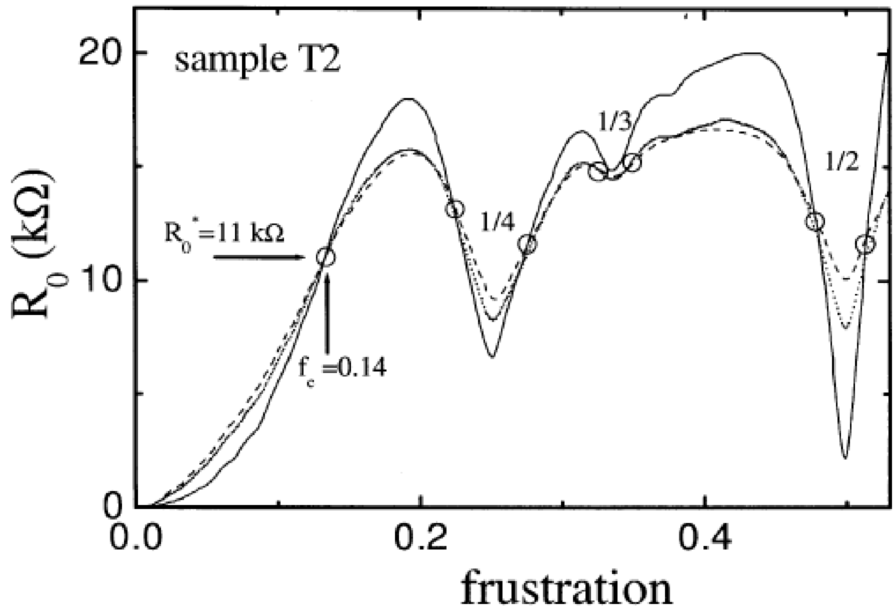




H.S.J. van der Zant, W.J. Elion, L.J. Geerligs, J.E. Mooij, Phys. Rev. B **54**, 10081 (1996)

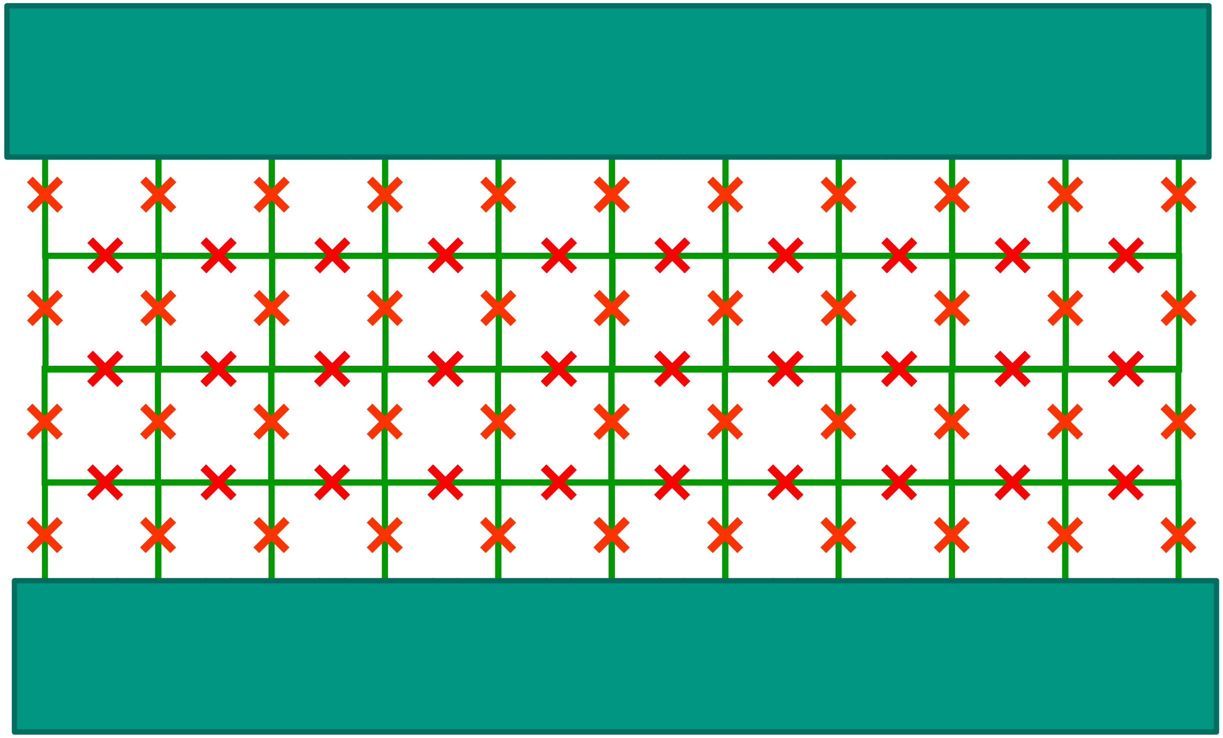
Field-induced S/I transition in 2D



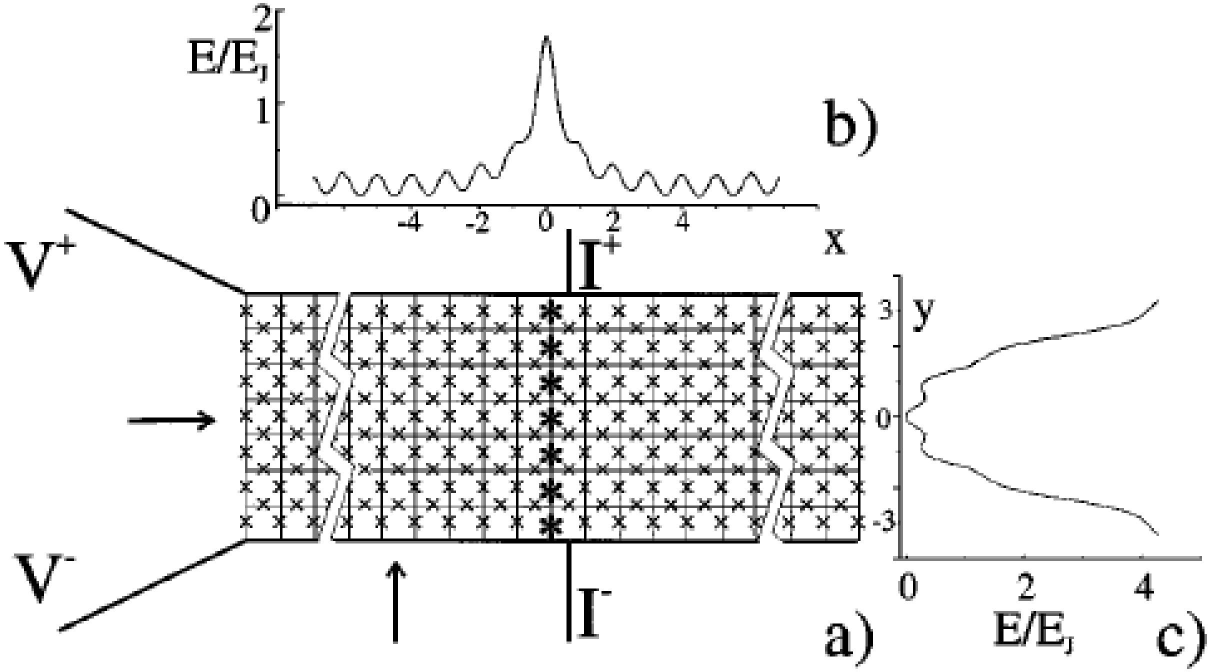


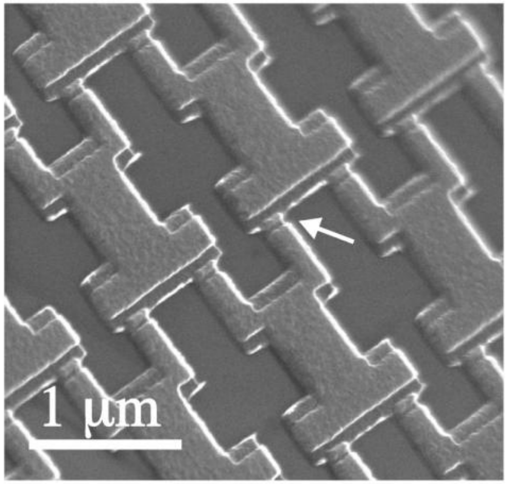
H.S.J. van der Zant, W.J. Elion, L.J. Geerligs, J.E. Mooij, Phys. Rev. B **54**, 10081 (1996)

Experiments with 1D/2D channels



Quantum vortices in 1D/2D channels



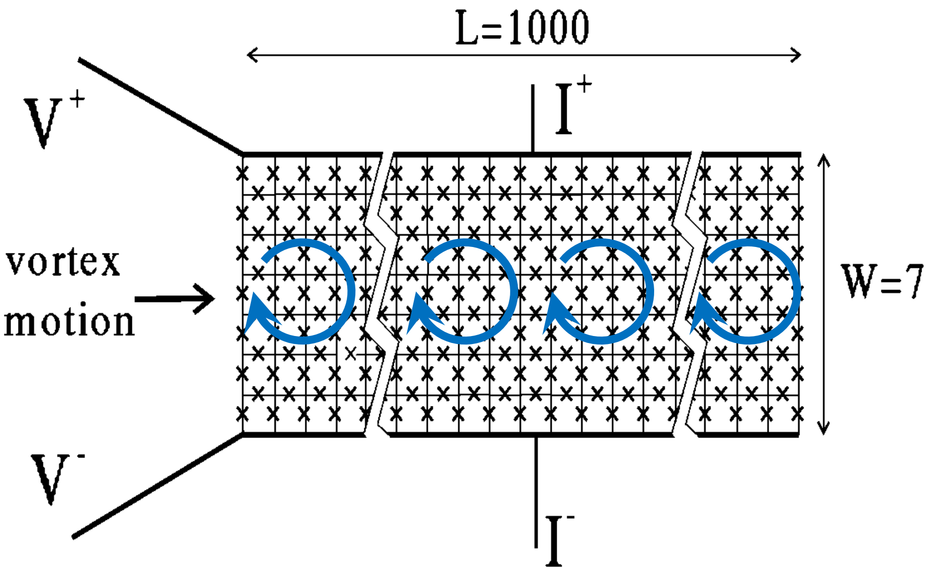


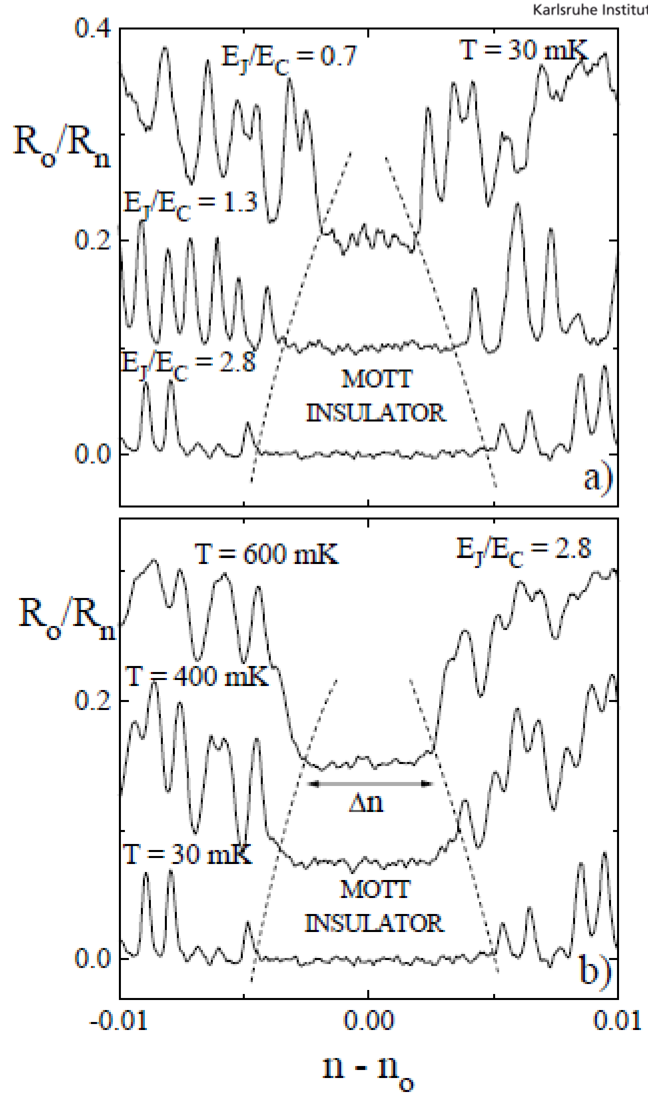
A. van Oudenaarden and J. E. Mooij, Phys. Rev. Lett. **76**, 4947 (1996)

A. van Oudenaarden, S. J. K. Várdy, and J. E. Mooij, Phys. Rev. Lett. **77**, 4257 (1996)

Quantum vortices in 1D/2D channels

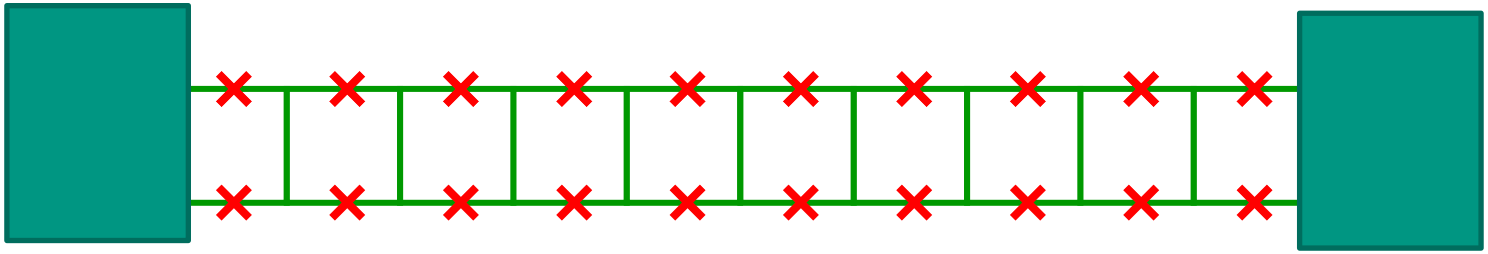
Mott insulator

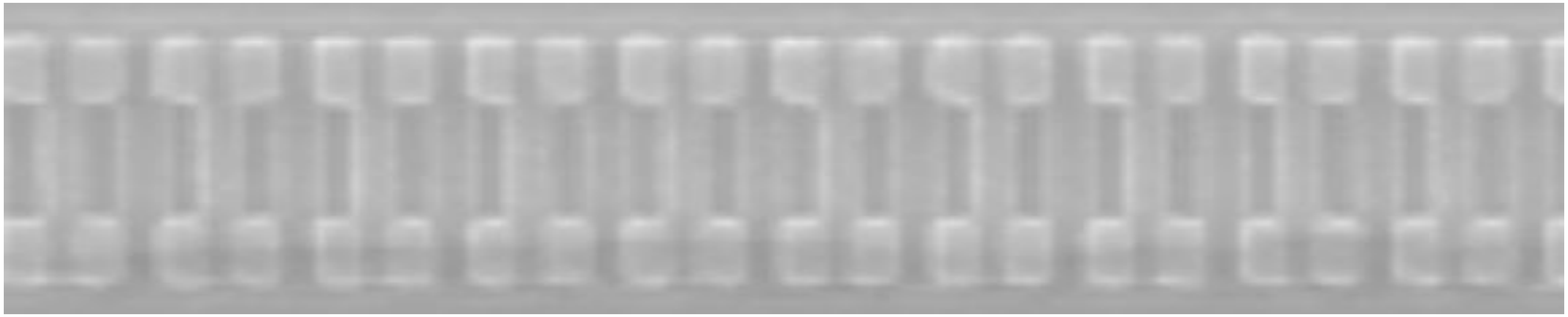




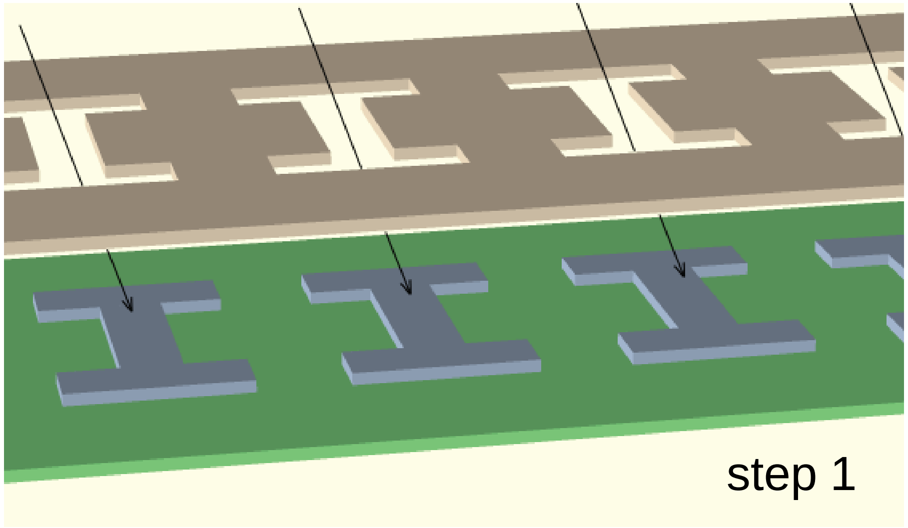
A. van Oudenaarden and J. E. Mooij, Phys. Rev. Lett. **76**, 4947 (1996)

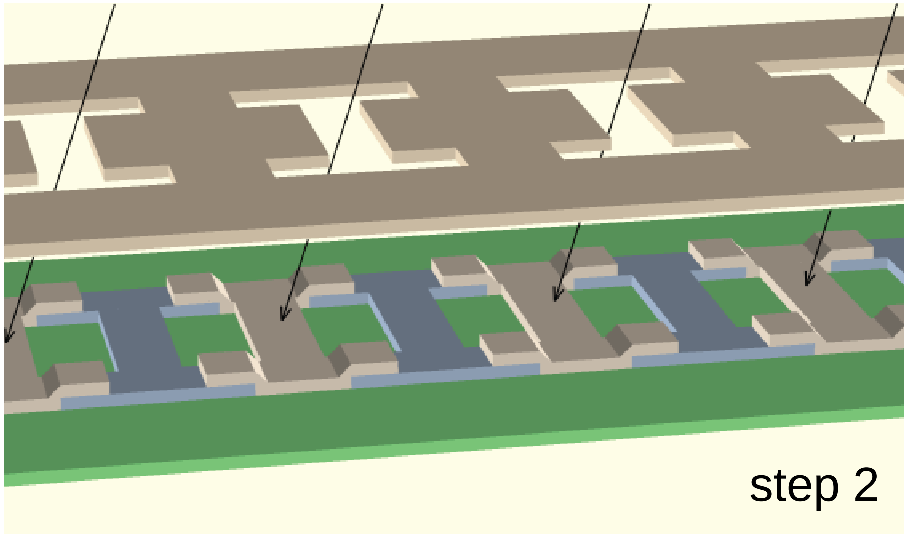
Experiments with 1D arrays



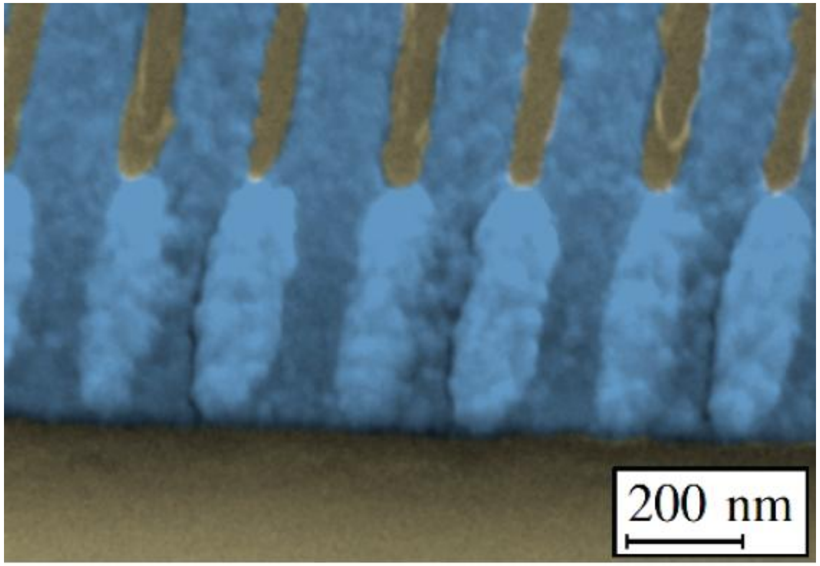


Shadow evaporation of SQUID arrays





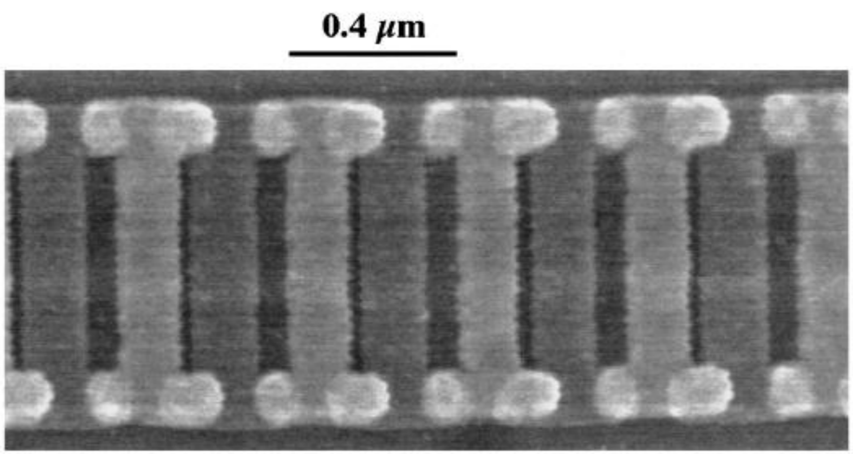
result

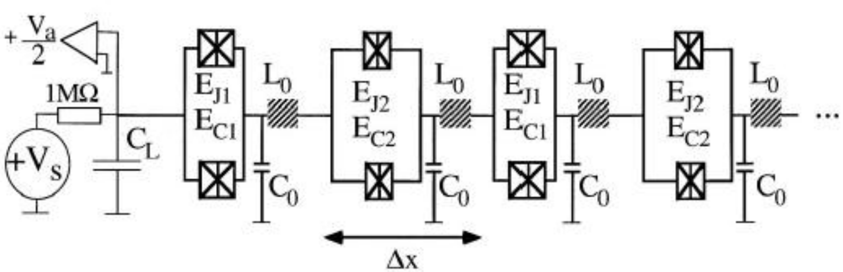


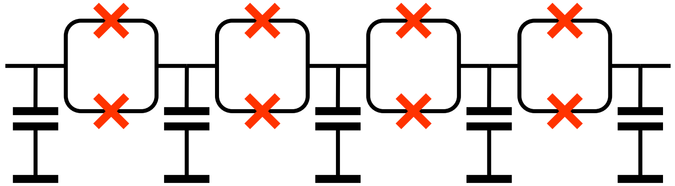
PHYSICAL REVIEW B VOLUME 54, NUMBER 10 1 SEPTEMBER 1996

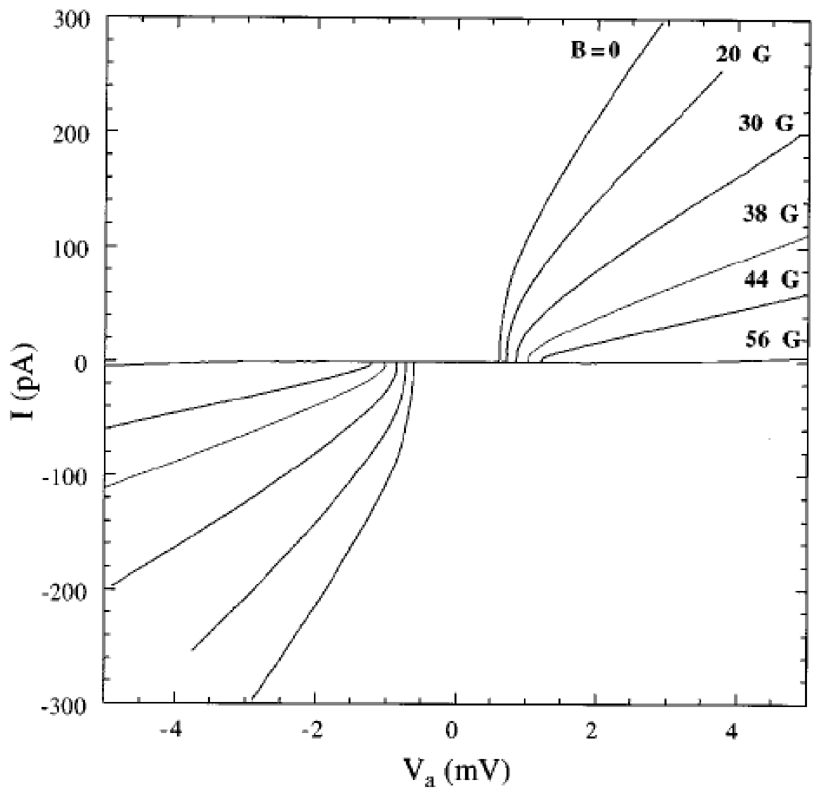
Cooper-pair charge solitons: The electrodynamics of localized charge in a superconductor

David B. Haviland and Per Delsing
Department of Physics, Chalmers University of Technology and Göteborg University, S-412 96 Göteborg, Sweden

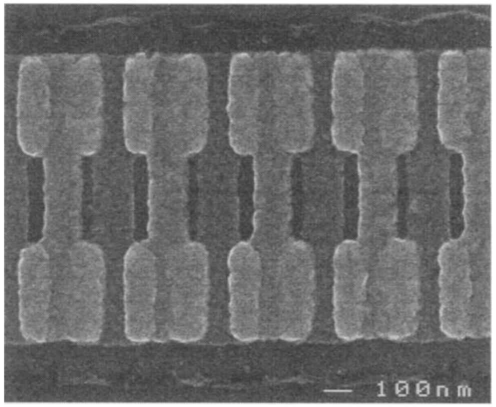




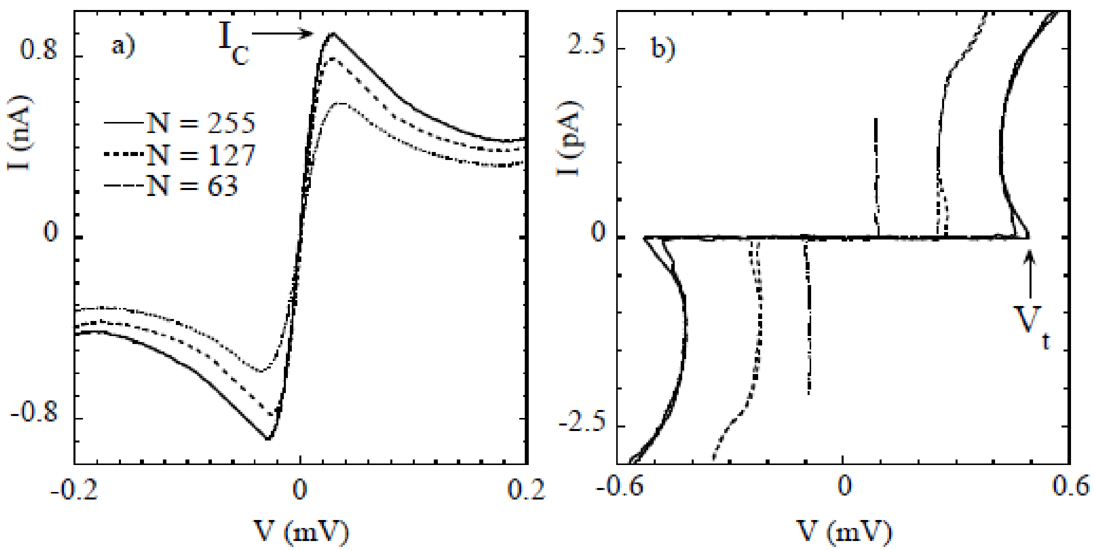


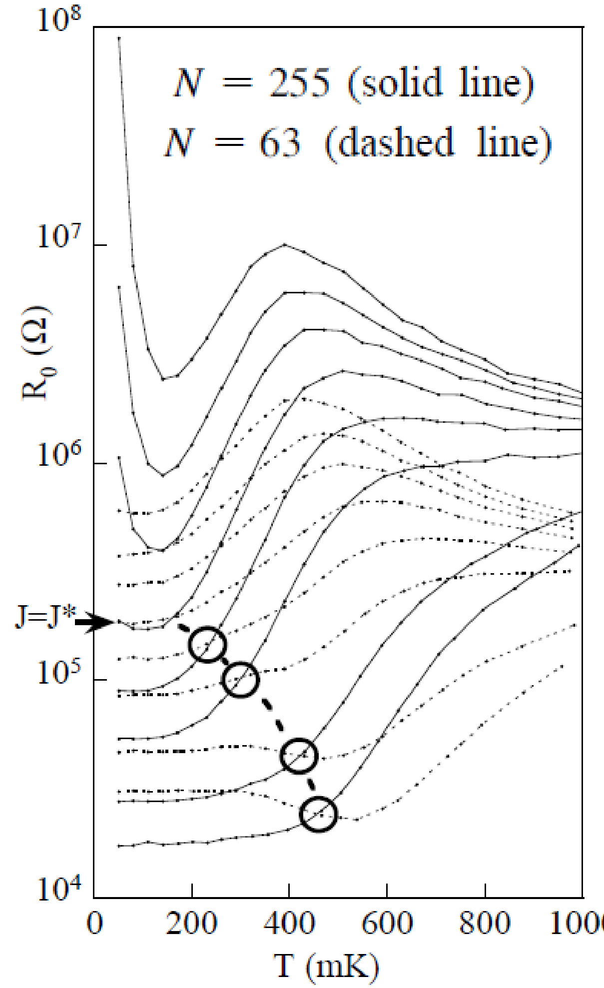


Observation of S/I transition in 1D



zero-bias resistance, extrapolated to *T = 0, is independent of length at a critical* magnetic field





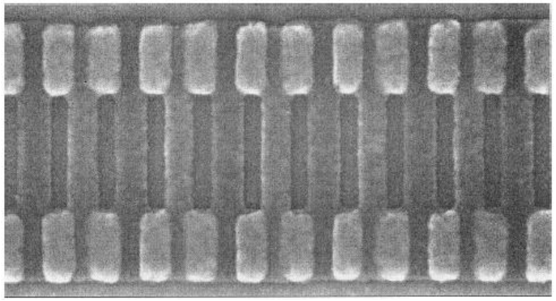
E. Chow, P. Delsing, and D. B. Haviland, Phys. Rev. Lett. **81**, 204 (1998)

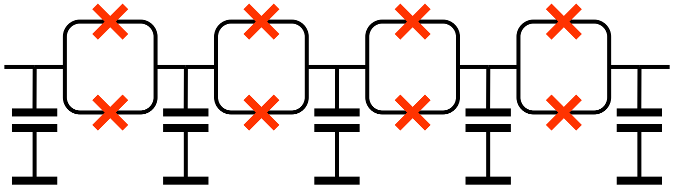
Journal of Low Temperature Physics, Vol. 124, Nos. 1/2, 2001

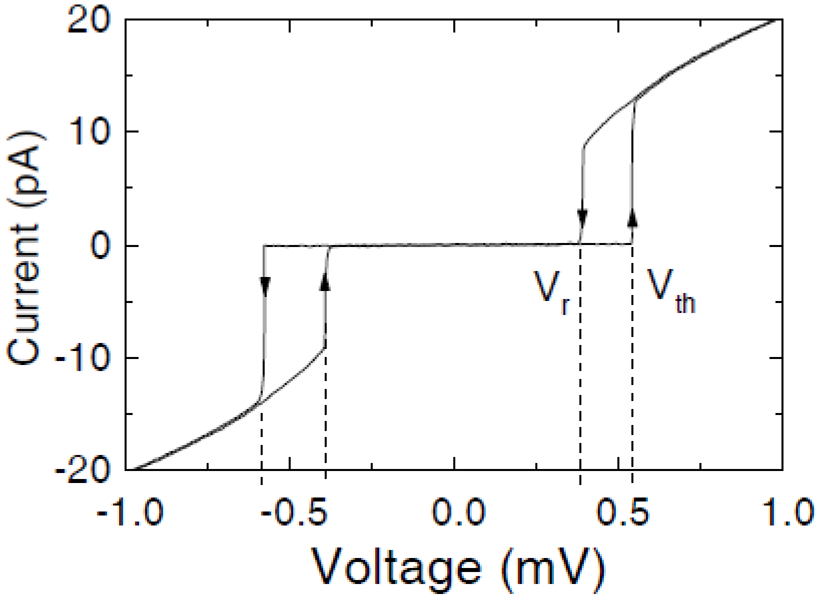
Kinetic Inductance and Coulomb Blockade in One Dimensional Josephson Junction Arrays

Peter Ågren, Karin Andersson and David B. Haviland

Department of Physics, Royal Institute of Technology, Lindstedtsvägen 24, SE-100 44 Stockholm, Sweden







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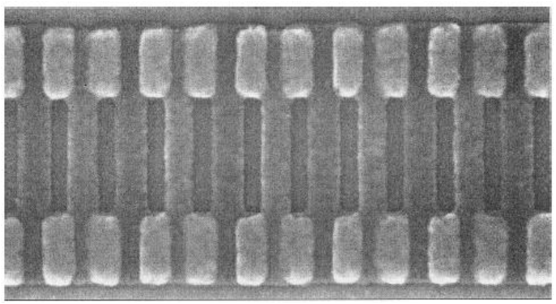

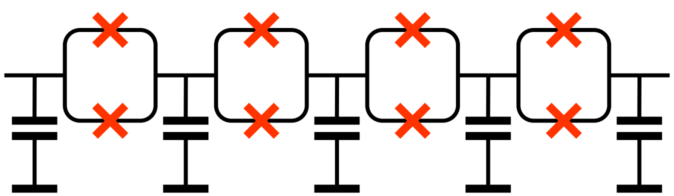

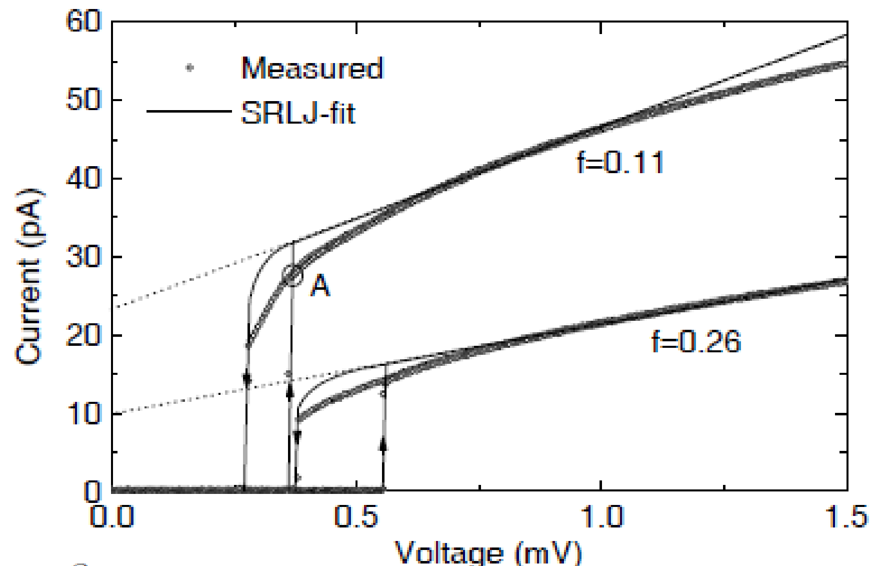

damping parameter β

The inductance per cell was then calculated from β, $L = \beta R^2 e/\pi V_C$.

PHYSICAL REVIEW B VOLUME 54, NUMBER 2 1 JULY 1996

Charge solitons in one-dimensional arrays of serially coupled Josephson junctions

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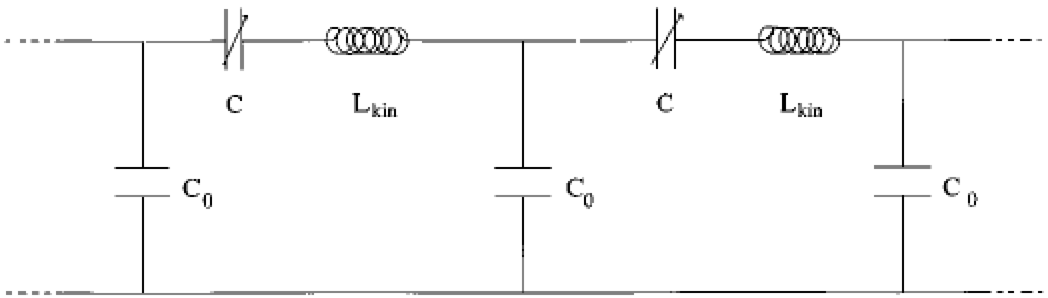


assumption taken:

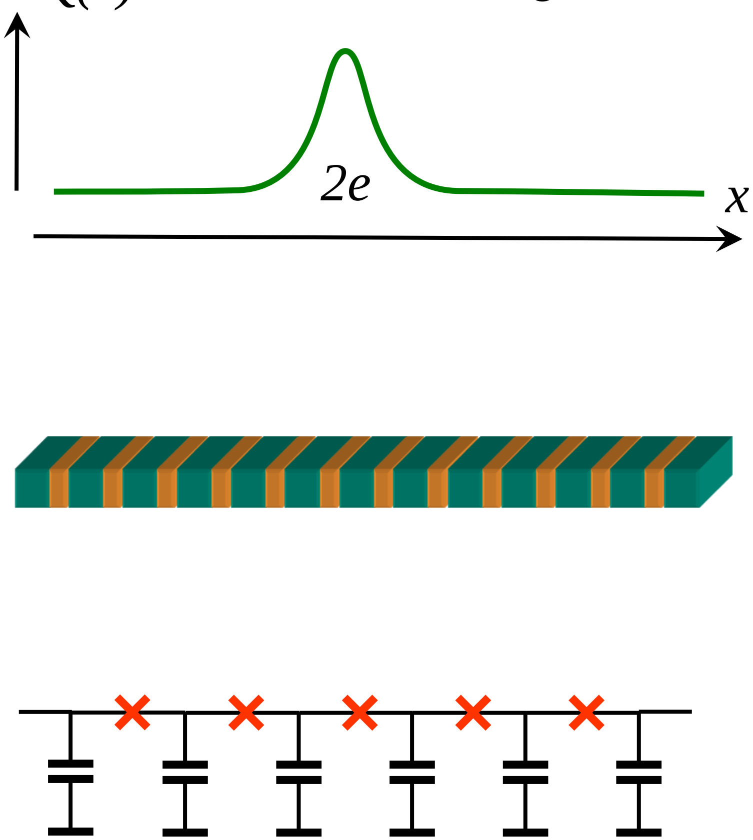
$$L_{\text{kin}}=\frac{m_e^* l_x}{e^{*2} n_s S} \gg L_J=\frac{1}{(2\pi)^2}\frac{\Phi_0^2}{E_J}$$

equation of motion for the charge: $$\frac{1}{2\pi}2eL_{\text{kin}}\ddot{q}-\frac{1}{2\pi}a^2\frac{2e}{C_0}q_{xx}+\frac{1}{2\pi}V_C\sin q=0$$

Duality between charge and flux solitons

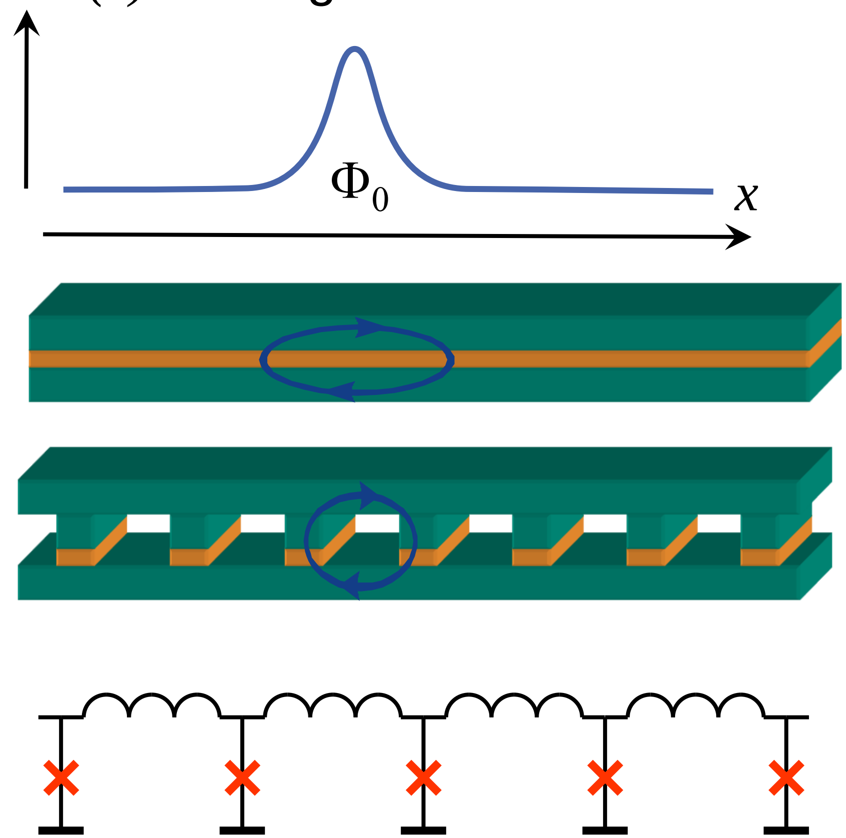
series array $E_J << E_C$

$Q(x)$ electric charge



parallel array $E_J >> E_C$

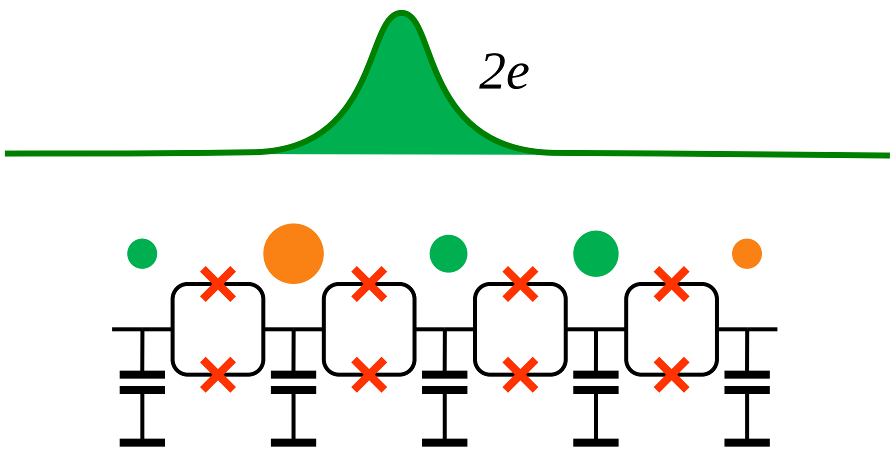
$\Phi(x)$ magnetic flux

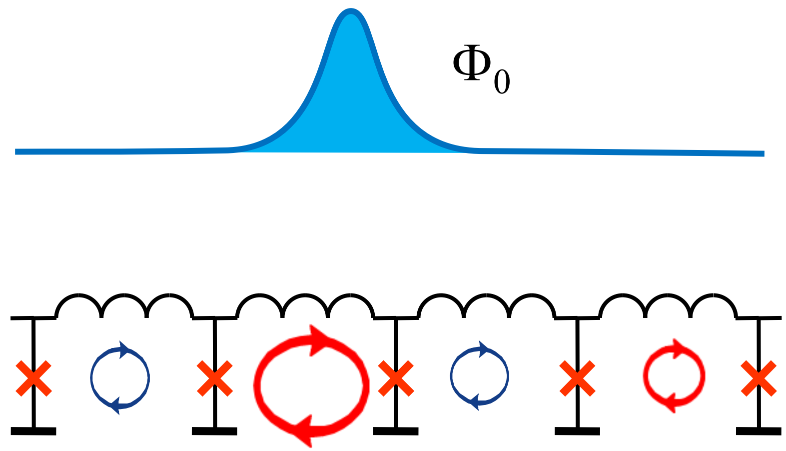


Soliton pinning problem

pinned random charges

pinned random fluxes





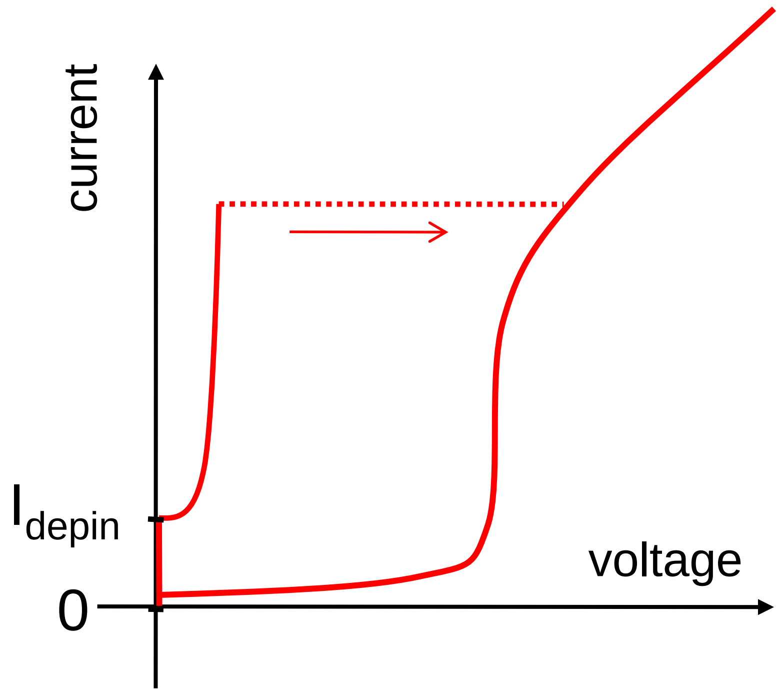
$-e/2 < Q_i < e/2$

$-\Phi_0/2 < \Phi_i < \Phi_0/2$

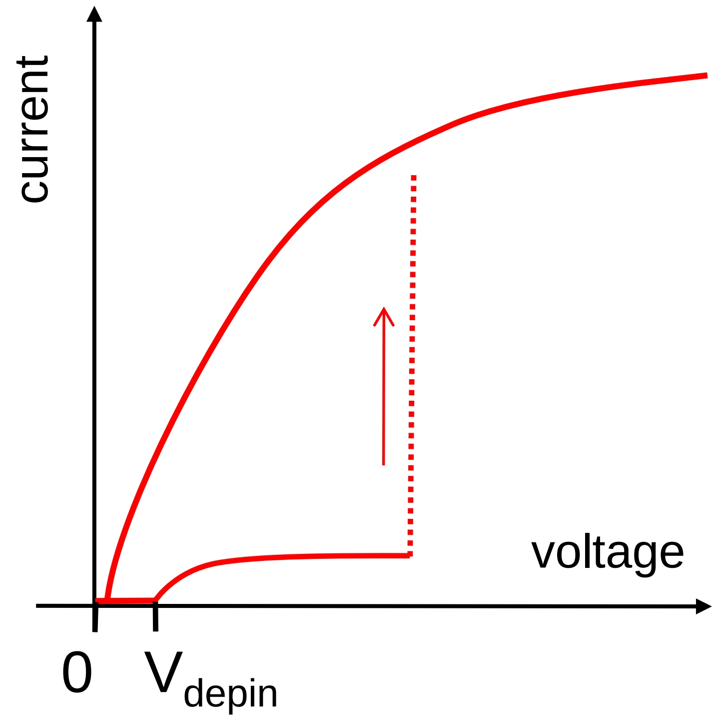
For flux regime: $$\frac{\partial^2 \varphi_i}{\partial t^2} + \alpha \frac{\partial \varphi_i}{\partial t} - \frac{\varphi_{i+1} - 2\varphi_i + \varphi_{i-1}}{a^2} = \sin \varphi_i - i + \Phi_i - \Phi_{i-1}$$

Φ_i – random fluxes

Depinning of solitons

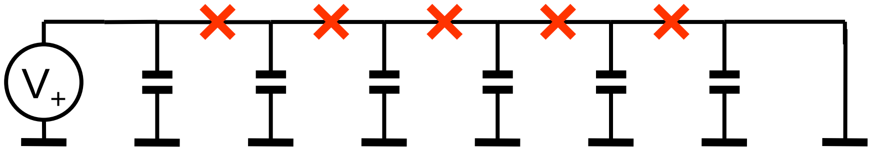


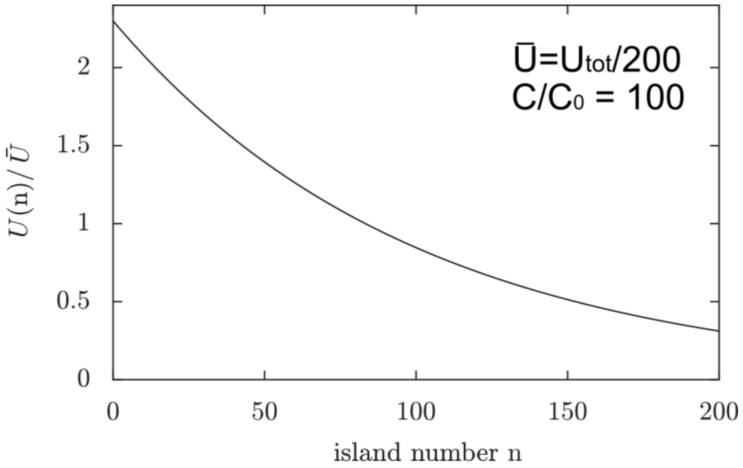
depinning of flux soliton



depinning of charge soliton

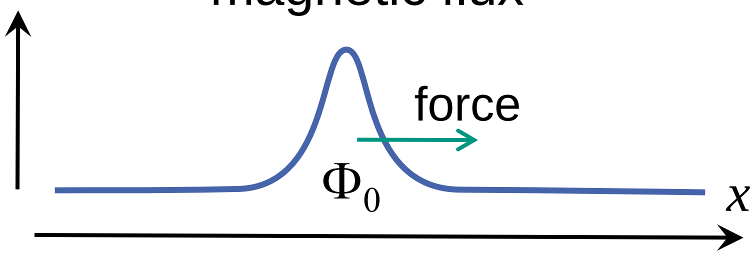
Problem of non-uniform voltage bias



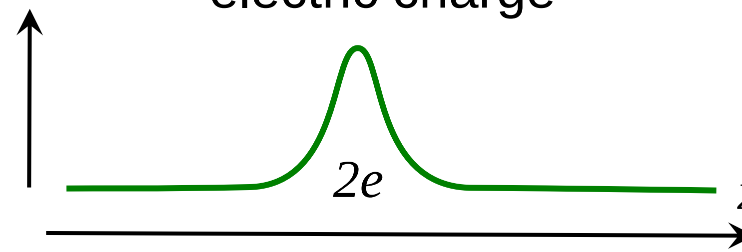


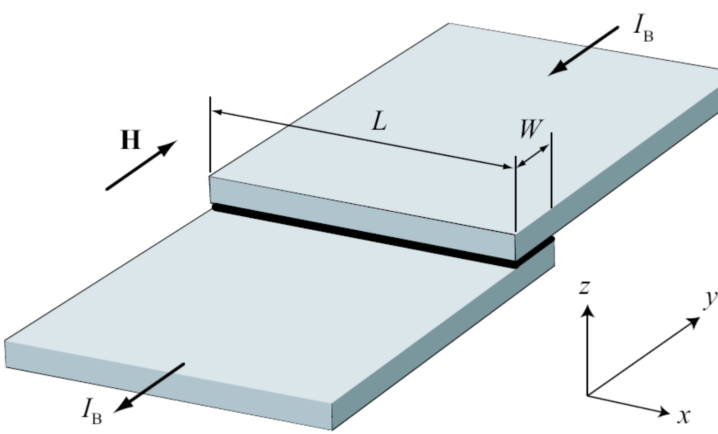
Uniform forcing of solitons

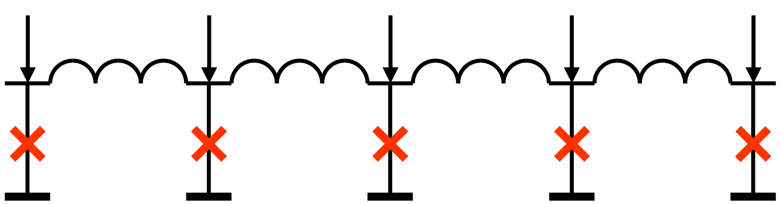
magnetic flux



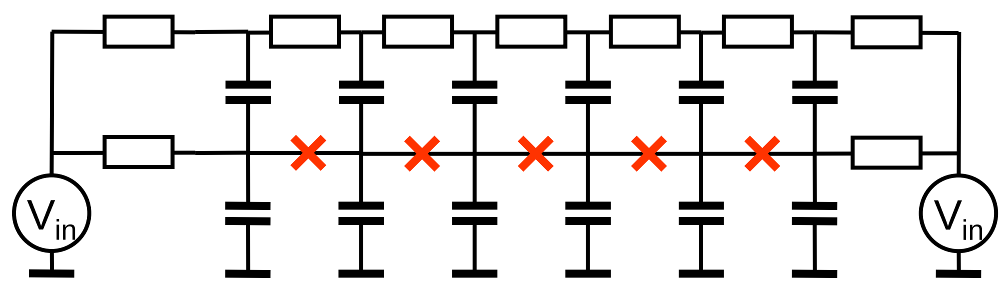
electric charge



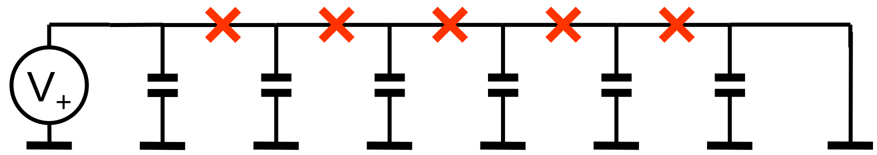


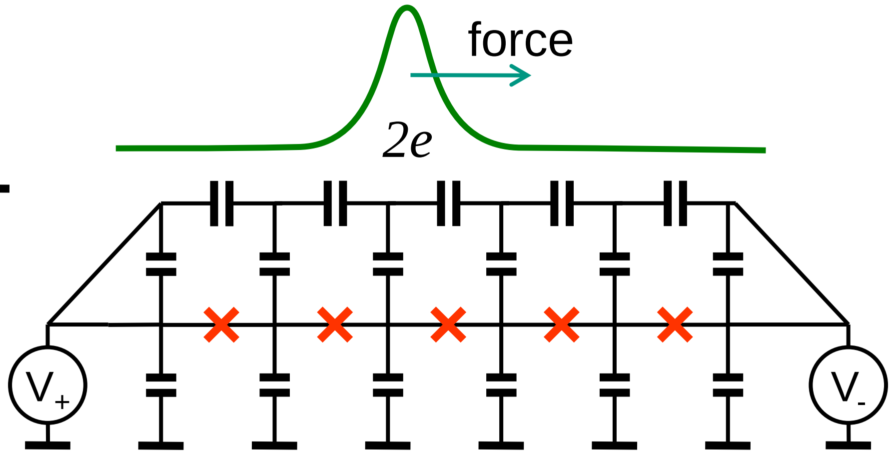


bias “comb” yielding uniform voltage bias

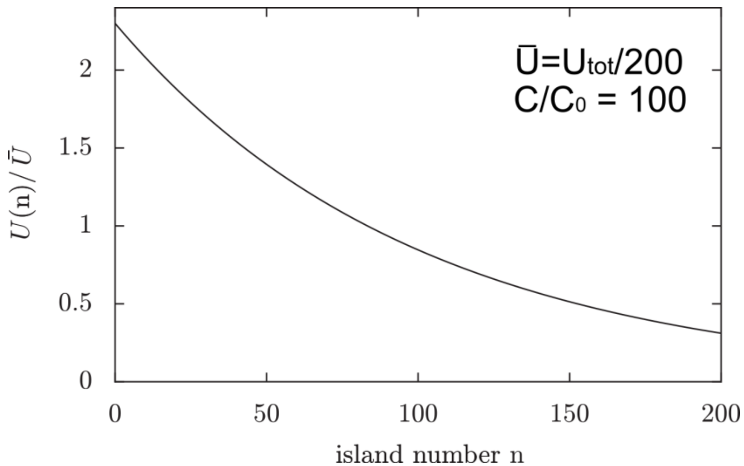


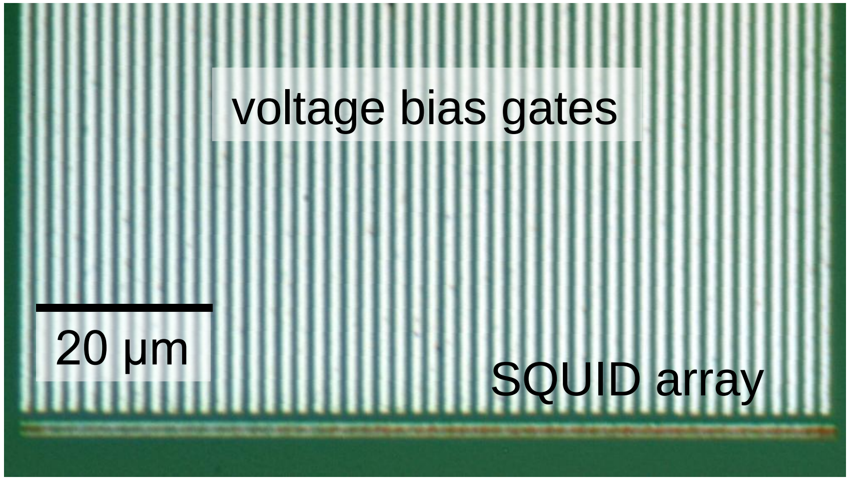
Implementation of the uniform biasing for charge solitons





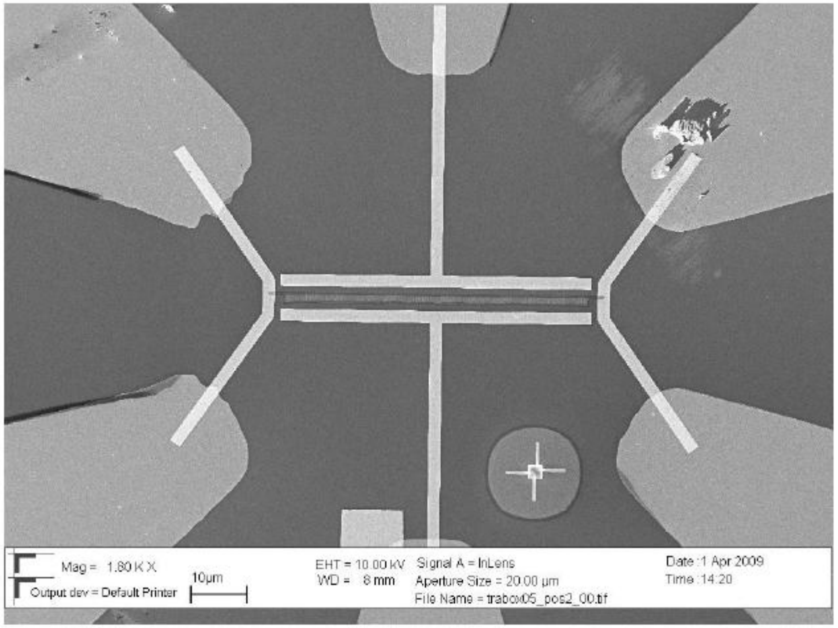
non-uniform voltage bias

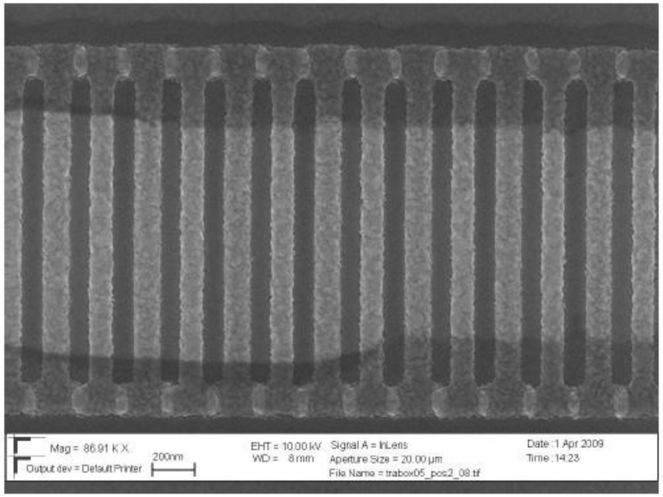




Experiments with JJ arrays in Karlsruhe

Josephson Energy: $E_j = \Delta g/8$ = 1140kB mK
Charging Energy: $E_c = e^2/2C$ = 930kB mK
Capacitance to ground: C_0 = 5 aF. . . 20 aF
Capacitance of single island: C = 1 fF
Size array length: L =51 µm
Array width: W =1.6 µm
Number of SQUID loops: 255



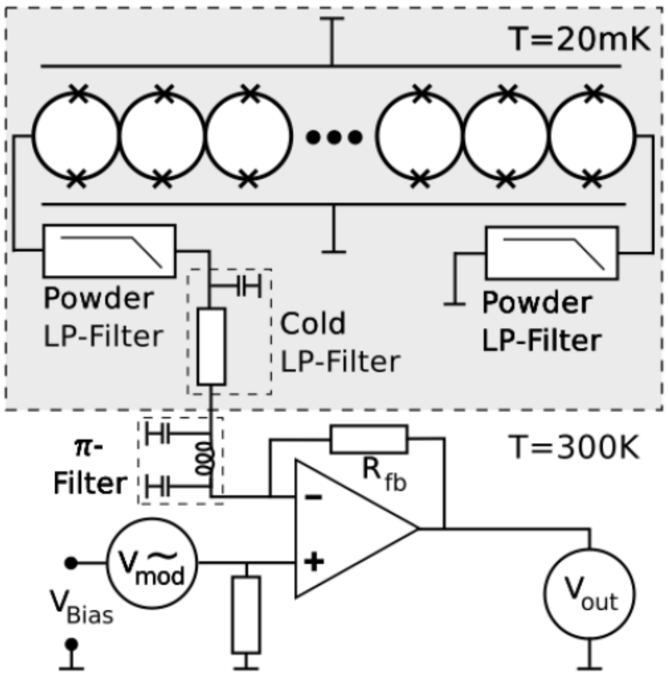


Loop size: 1.44 µm×100nm
→14.3mT per Φ_0

R. Schäfer, W. Cui, K. Grube, H. Rotzinger, and A. V. Ustinov, arXiv:1310.4295

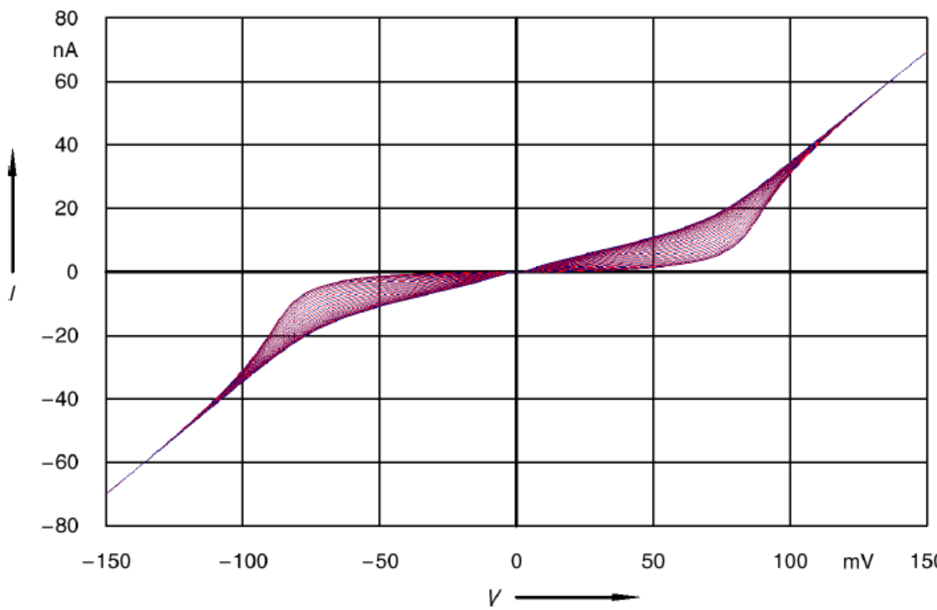
Tunable Josephson energy EJ

Measurement setup



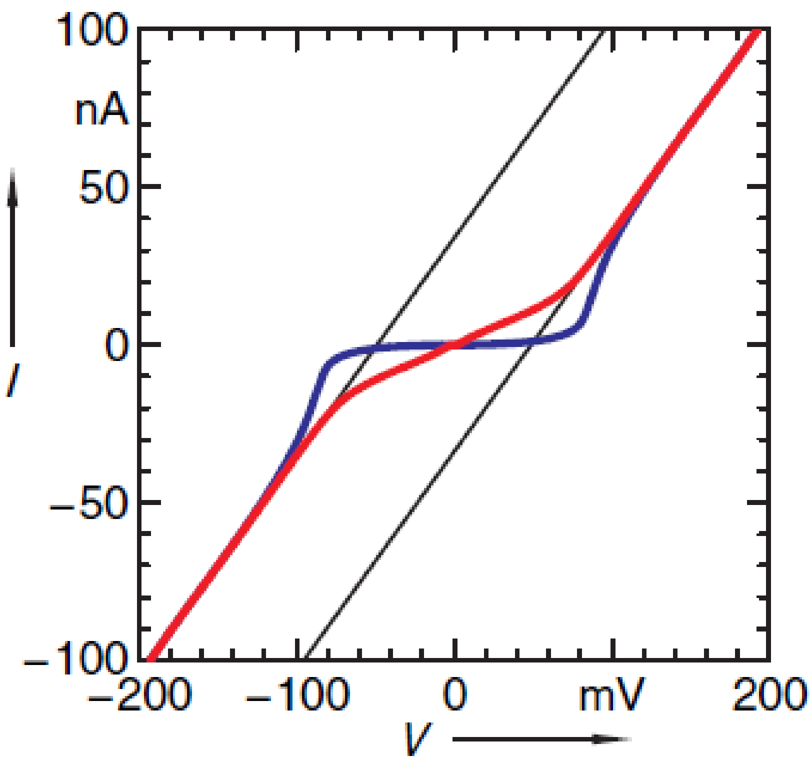
Measurements are done in voltage bias scheme.

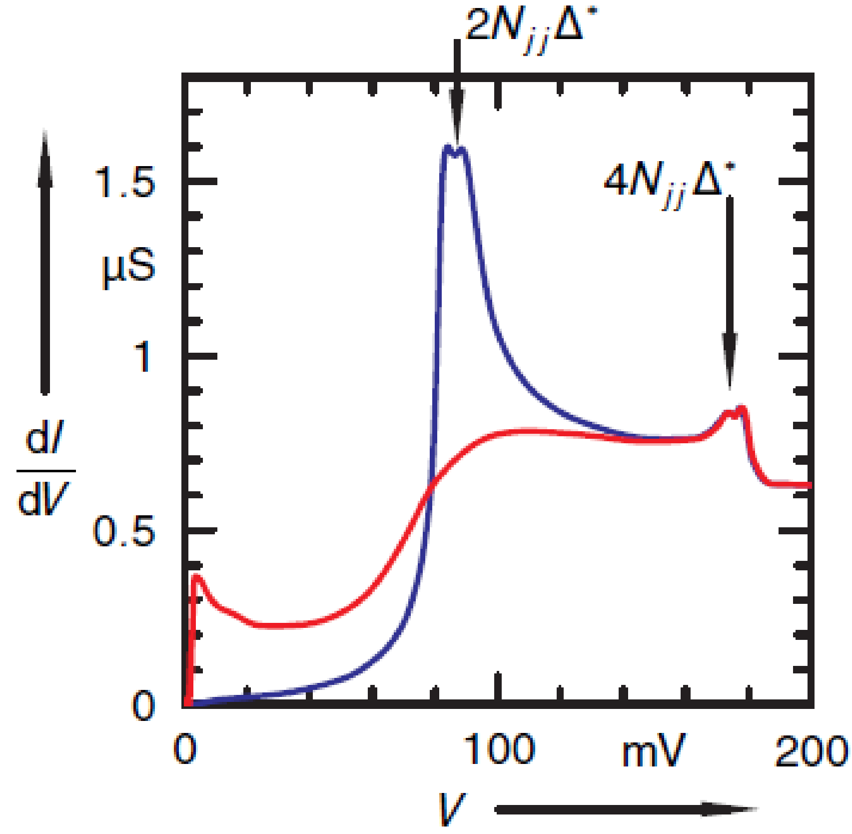
Magnetic field dependence: I-V at large bias voltages



R. Schäfer, W. Cui, K. Grube, H. Rotzinger, and A. V. Ustinov, arXiv:1310.4295

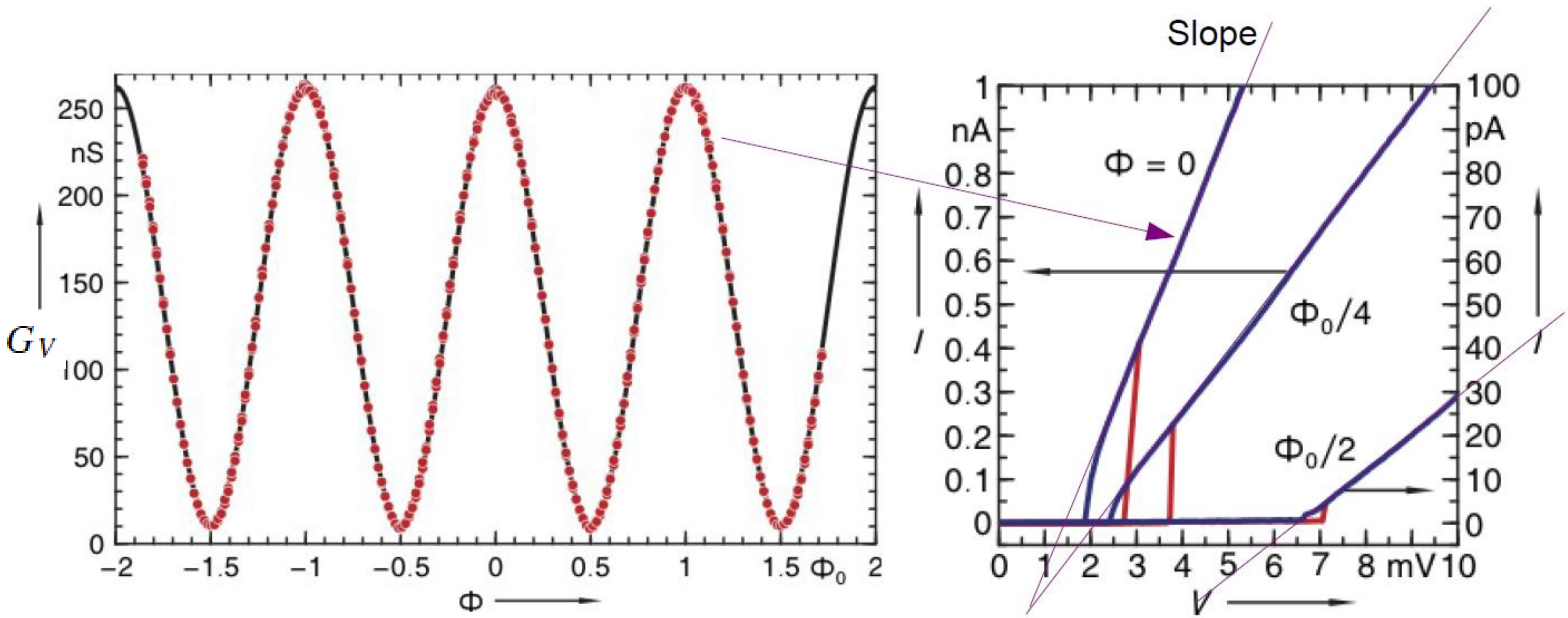
Large-scale I-V characteristics





R. Schäfer, W. Cui, K. Grube, H. Rotzinger, and A. V. Ustinov, arXiv:1310.4295

Conductance of dissipative branch



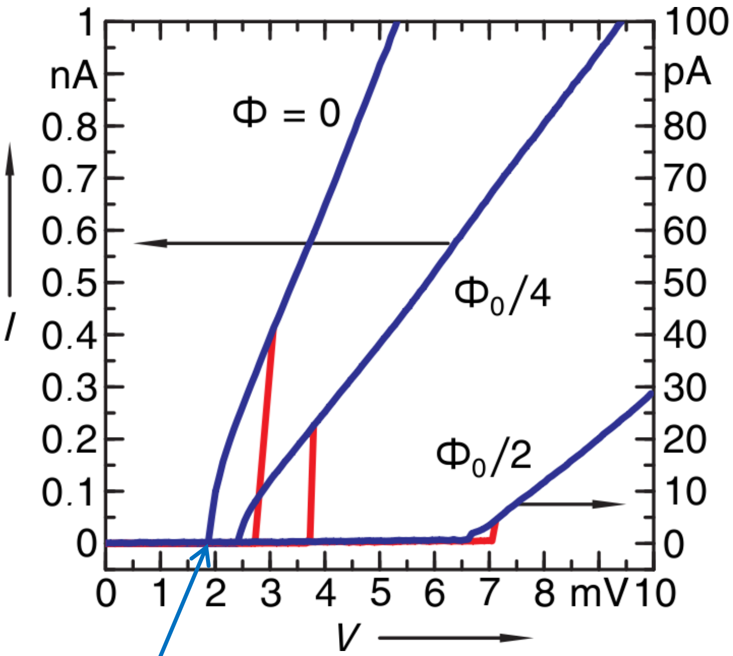
- $G_V \propto E_J^2$
- Conductance depends on the Josephson coupling of the islands

$$E_J(\Phi) = 2E_J \left| \cos\left(\frac{\pi \Phi}{\Phi_0}\right) \right|$$

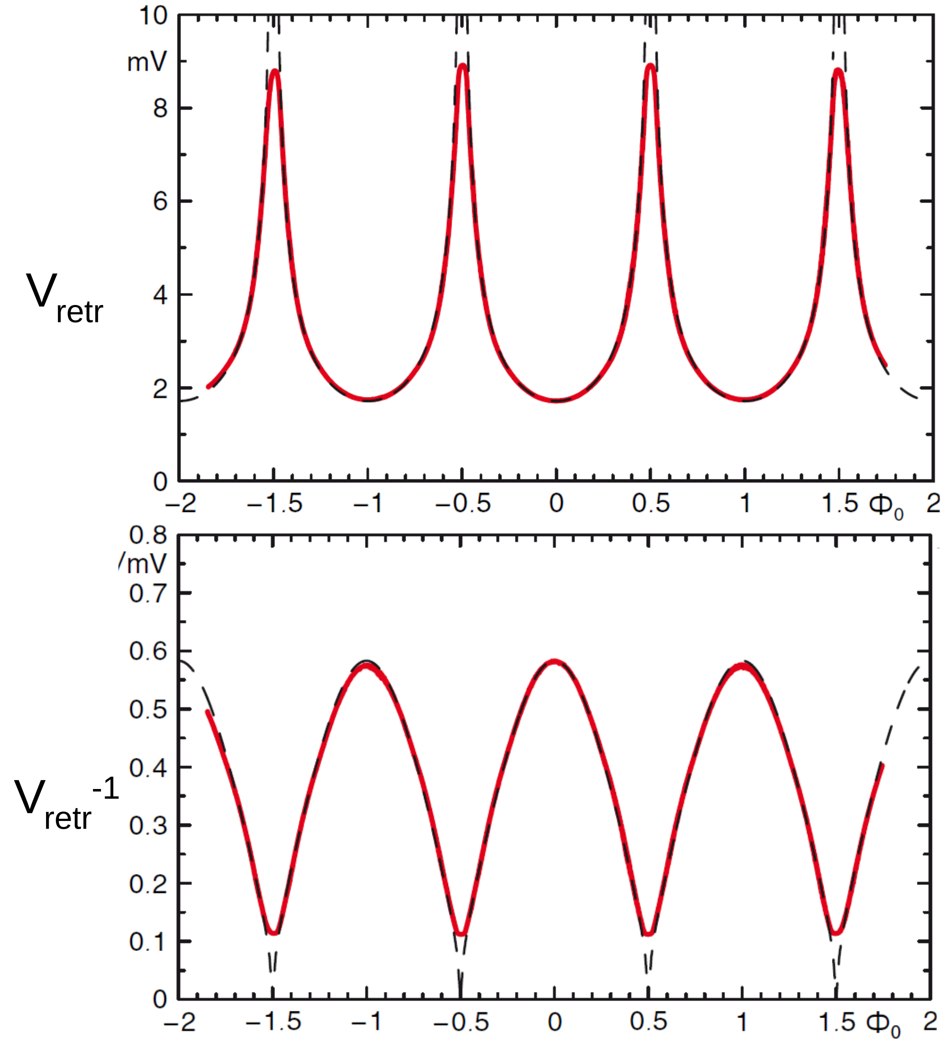
R. Schäfer, W. Cui, K. Grube, H. Rotzinger, and A. V. Ustinov, arXiv:1310.4295

Re-trapping voltage change with flux

Re-trapping voltage V_{retr}



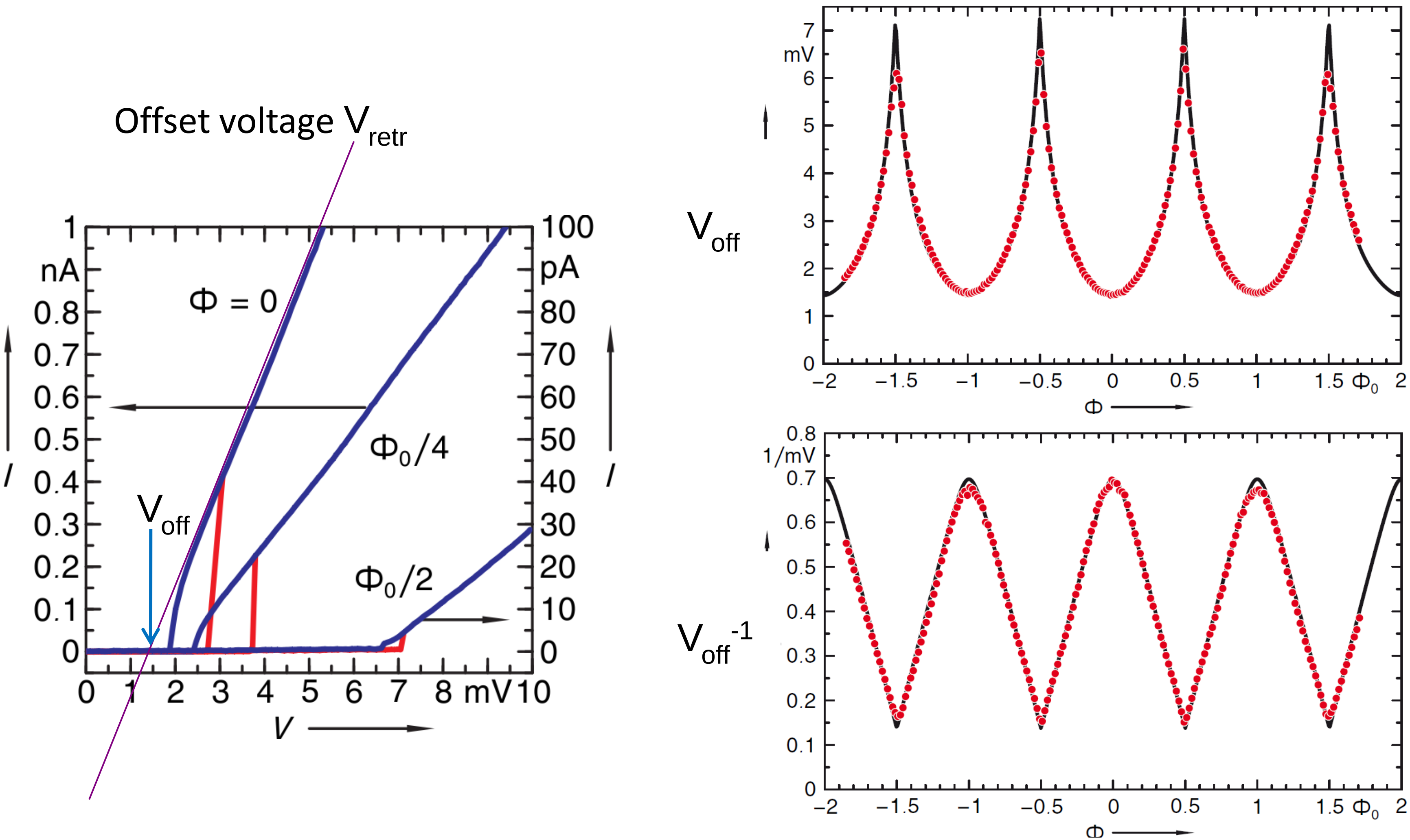
V_{retr}



R. Schäfer, W. Cui, K. Grube, H. Rotzinger, and A. V. Ustinov, arXiv:1310.4295

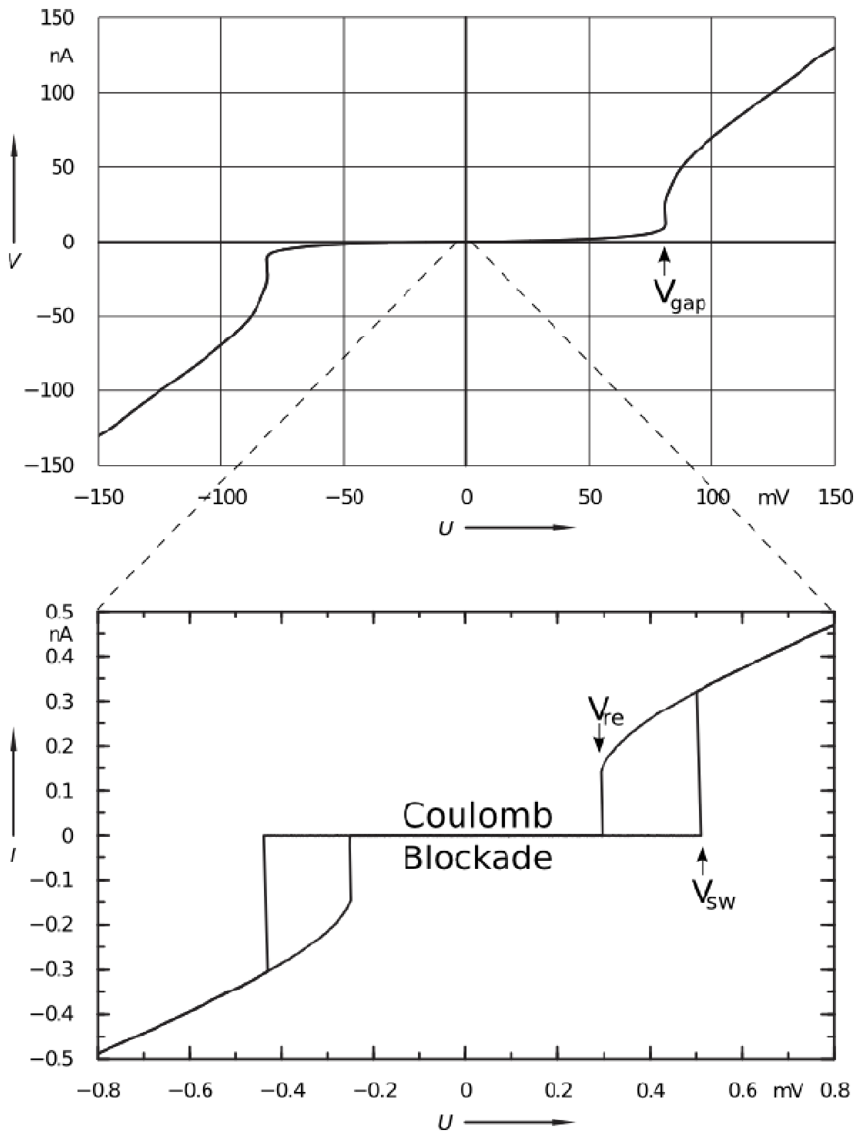
Φ ⟶

Offset voltage change with flux

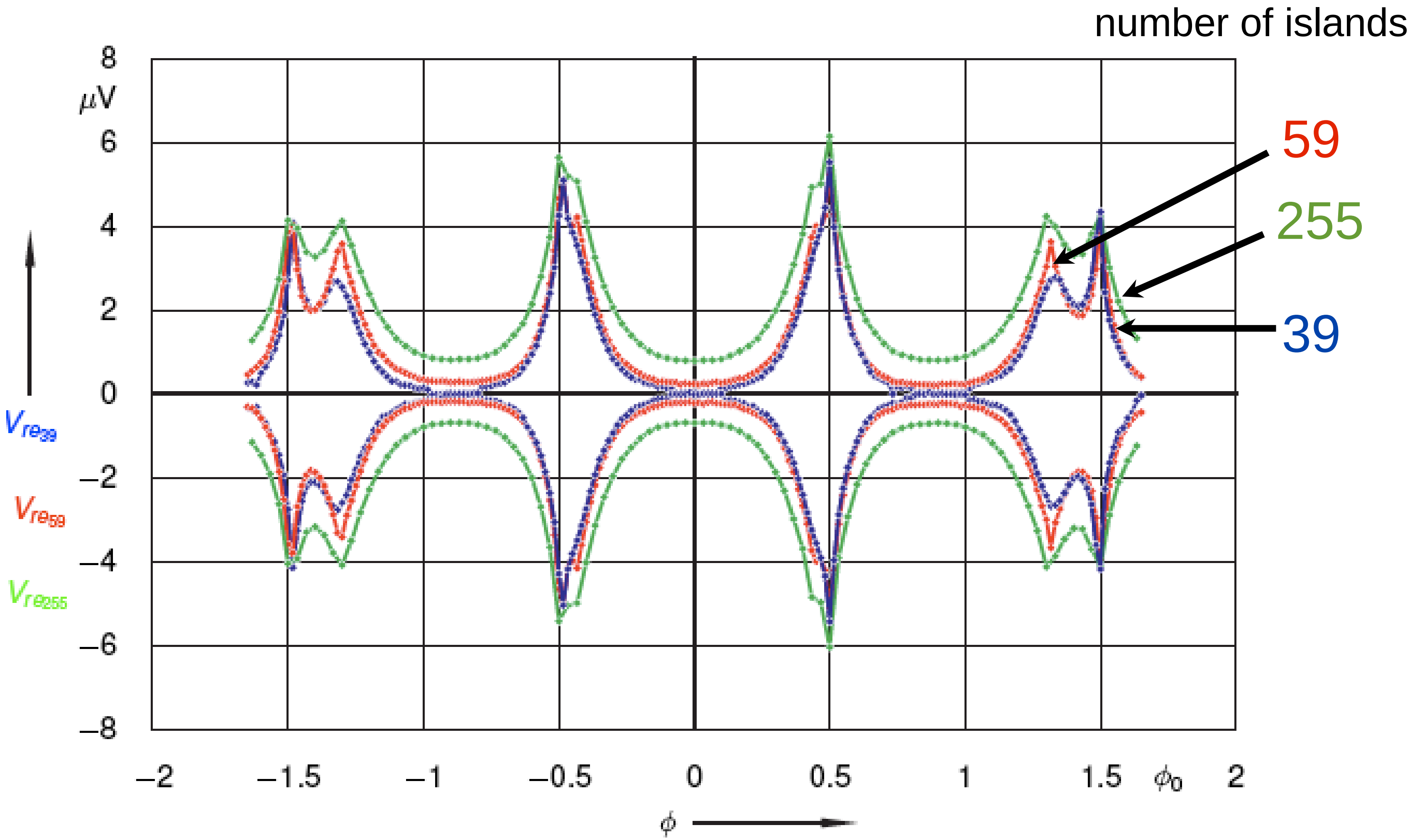


R. Schäfer, W. Cui, K. Grube, H. Rotzinger, and A. V. Ustinov, arXiv:1310.4295

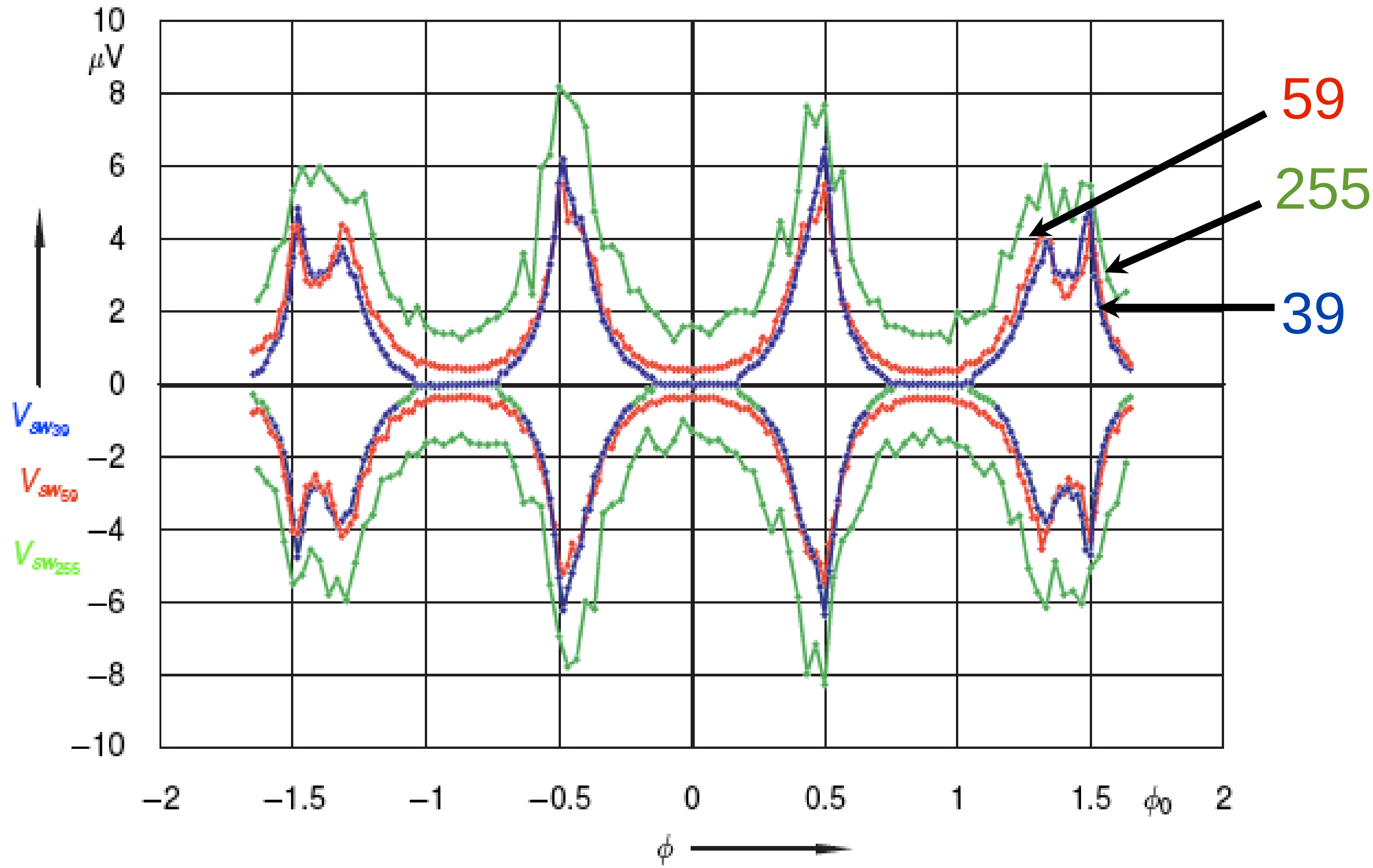
Switching and retrapping voltages



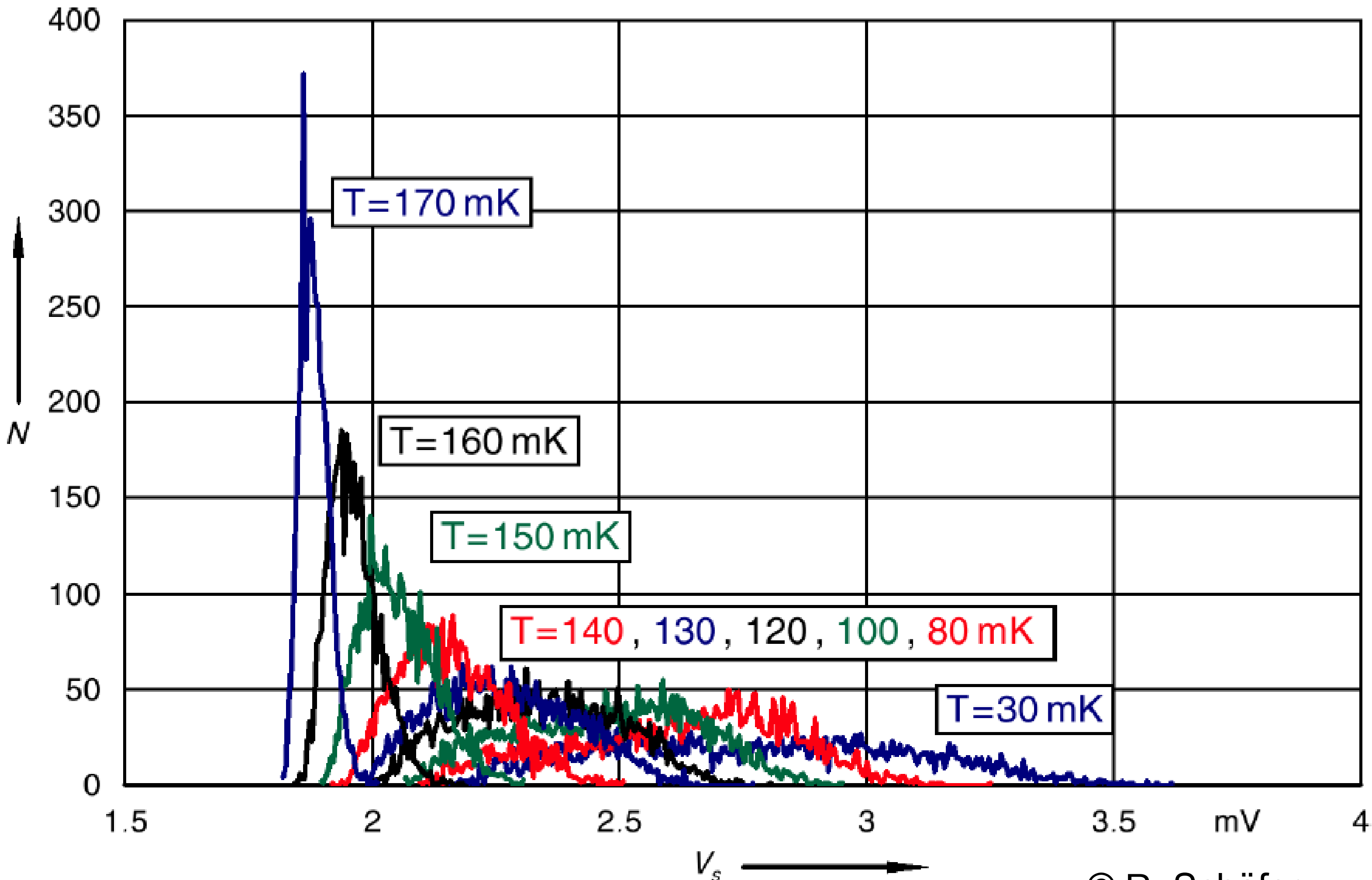
Retrapping voltage normalized to the number of islands



Switching voltage normalized to the number of islands



Switching voltage histograms



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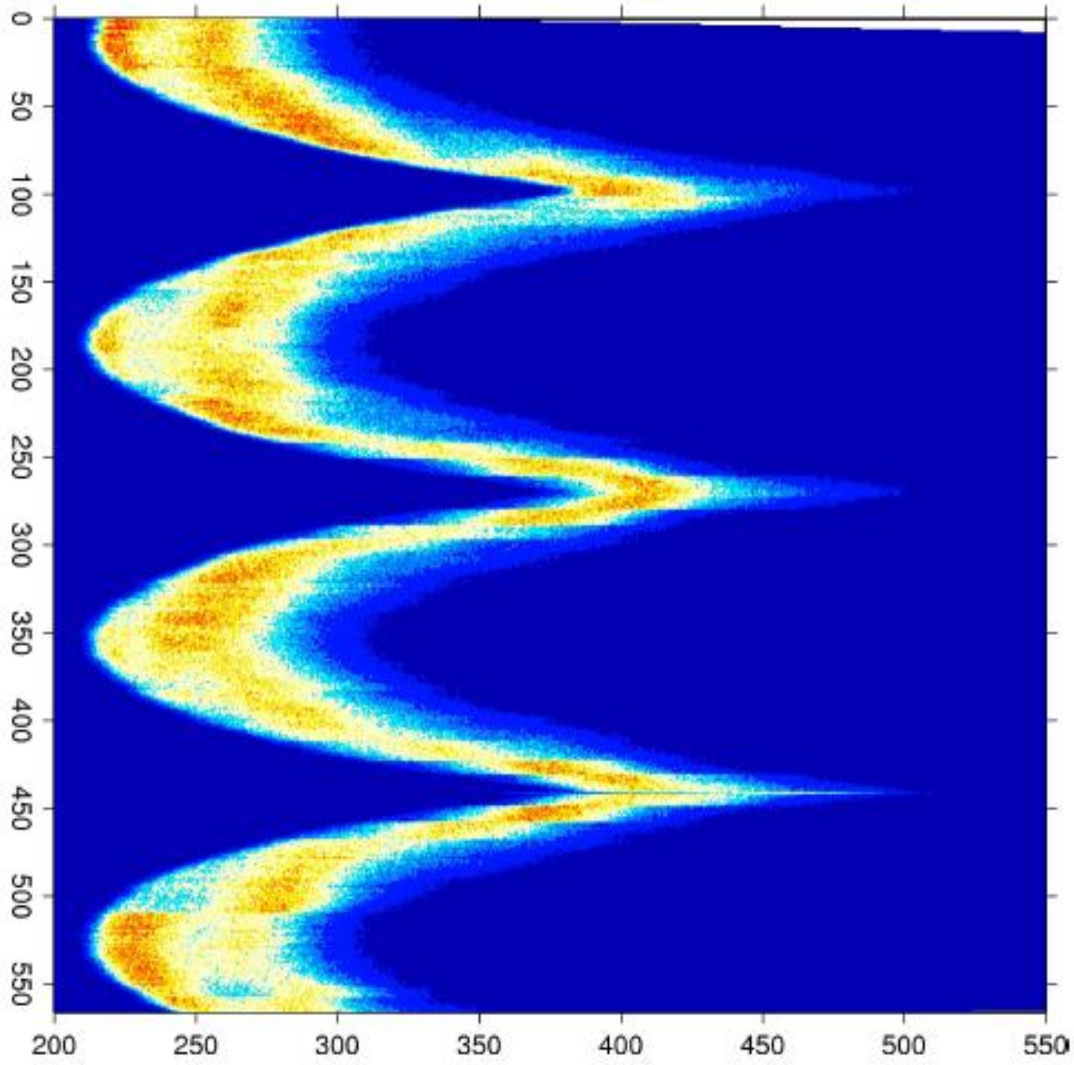
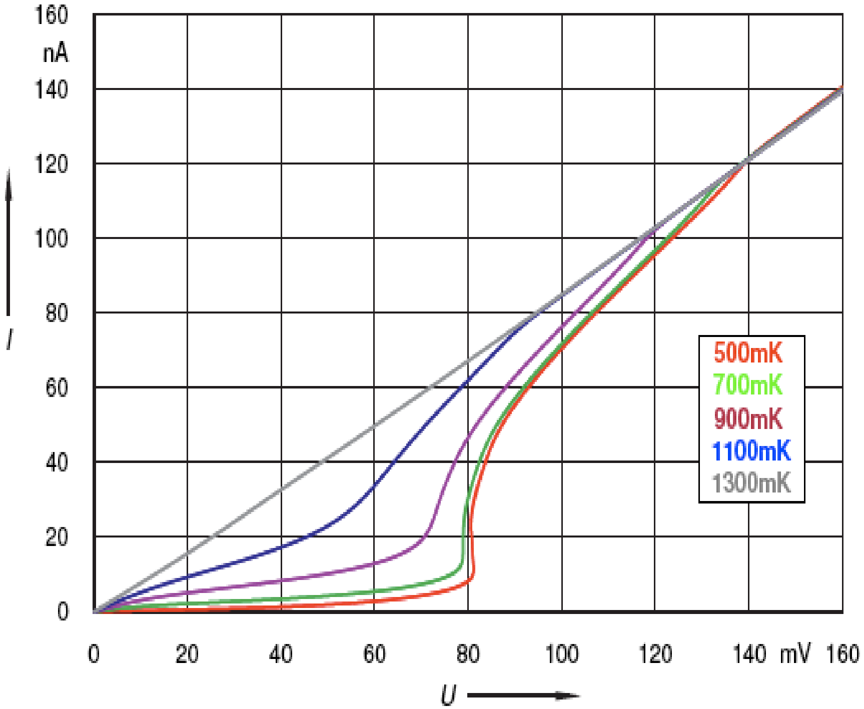
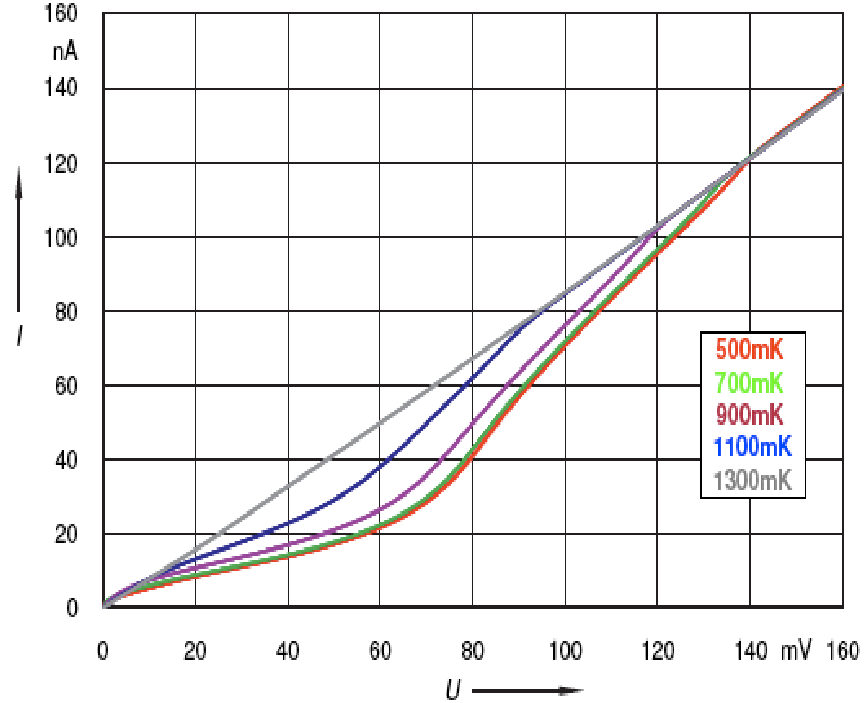
Switching voltage histograms



Thermally activated conductance



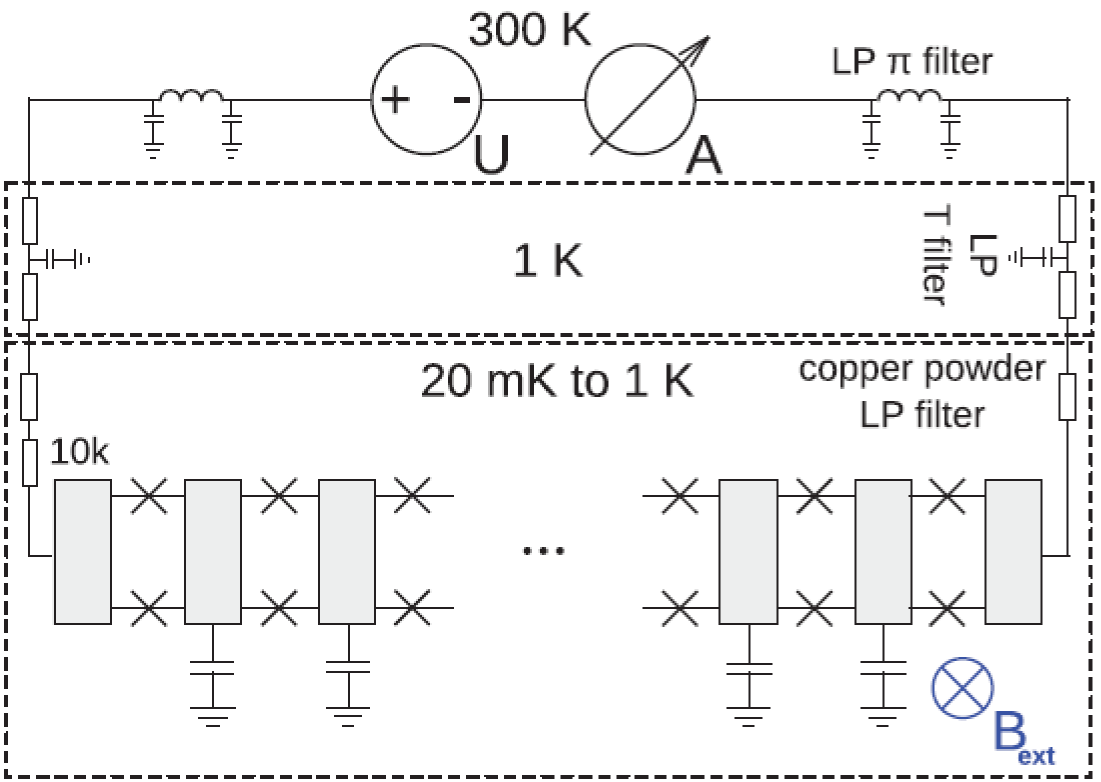
$\Phi/\Phi_0 = 0.5$



$\Phi/\Phi_0 = 0$

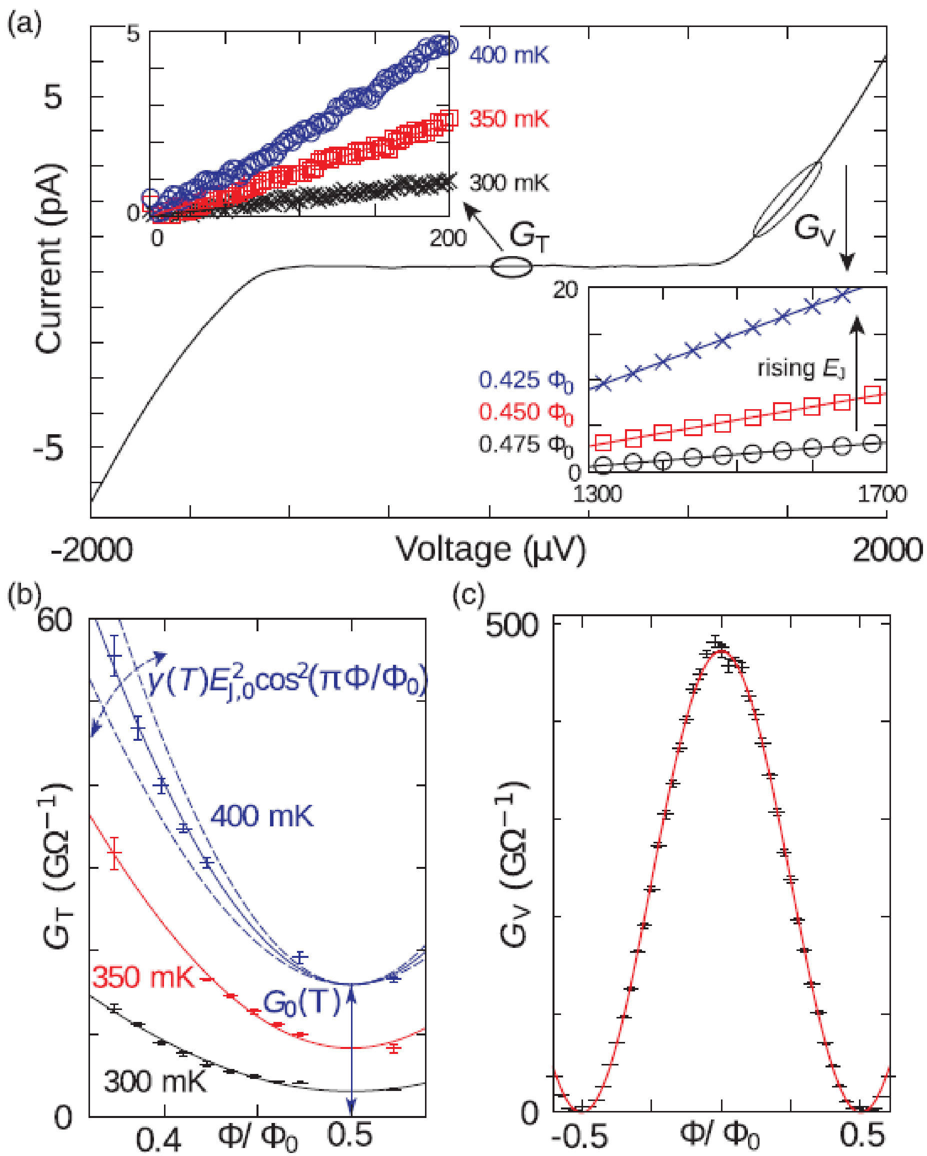
Thermally activated conductance in arrays of small Josephson junctions

experimental setup



J. Zimmer, N. Vogt, A. Fiebig, S. V. Syzranov, A. Lukashenko, R. Schäfer, H. Rotzinger, A. Shnirman, M. Marthaler, and A. V. Ustinov, Phys. Rev. B **88**, 144506 (2013)

I-V characteristic of the 255-JJ array



$$G(T) \propto T^{-\alpha} \exp(-T_0/T)$$

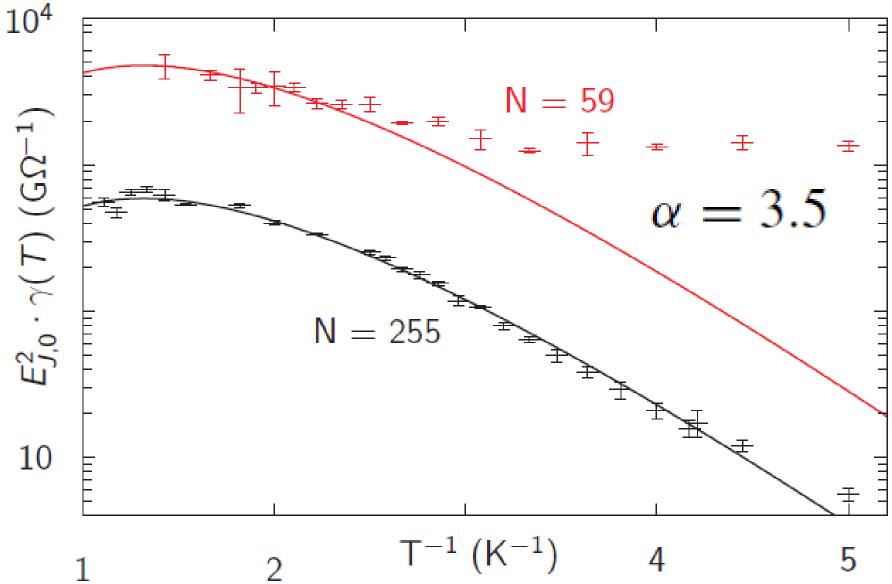
α depends on the nature of the bath

$$G_T(\Phi, T) = G_\Phi(T) + G_0(T)$$

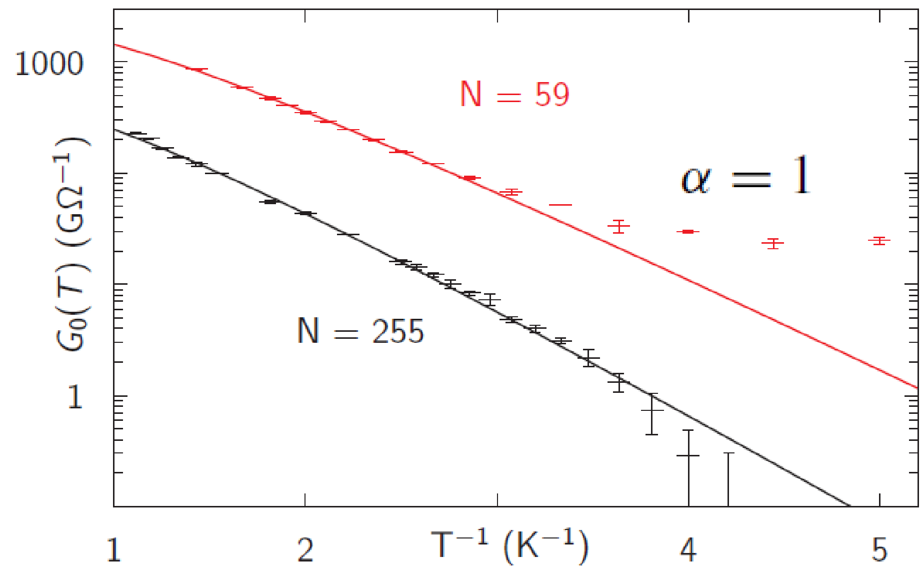
$$G_\Phi(T) = (2E_J)^2 \cos^2\left(\frac{\pi\Phi}{\Phi_0}\right)\gamma(T)$$

J. Zimmer, N. Vogt, A. Fiebig, S. V. Syzranov, A. Lukashenko, R. Schäfer, H. Rotzinger, A. Shnirman, M. Marthaler, and A. V. Ustinov, Phys. Rev. B **88**, 144506 (2013)

Thermally activated conductance in arrays of small Josephson junctions



(a) Flux-dependent part $\gamma(T)$ of G_T



(b) Flux-independent part $G_0(T)$ of G_T

$$G(T) \propto T^{-\alpha} \exp(-T_0/T)$$

inelastic hopping of Cooper pairs between neighboring islands

J. Zimmer, N. Vogt, A. Fiebig, et al., Phys. Rev. B **88**, 144506 (2013)

resulting from the fits

$$k_B T_0 = E_{\max} = 229\ \mu\text{eV}$$

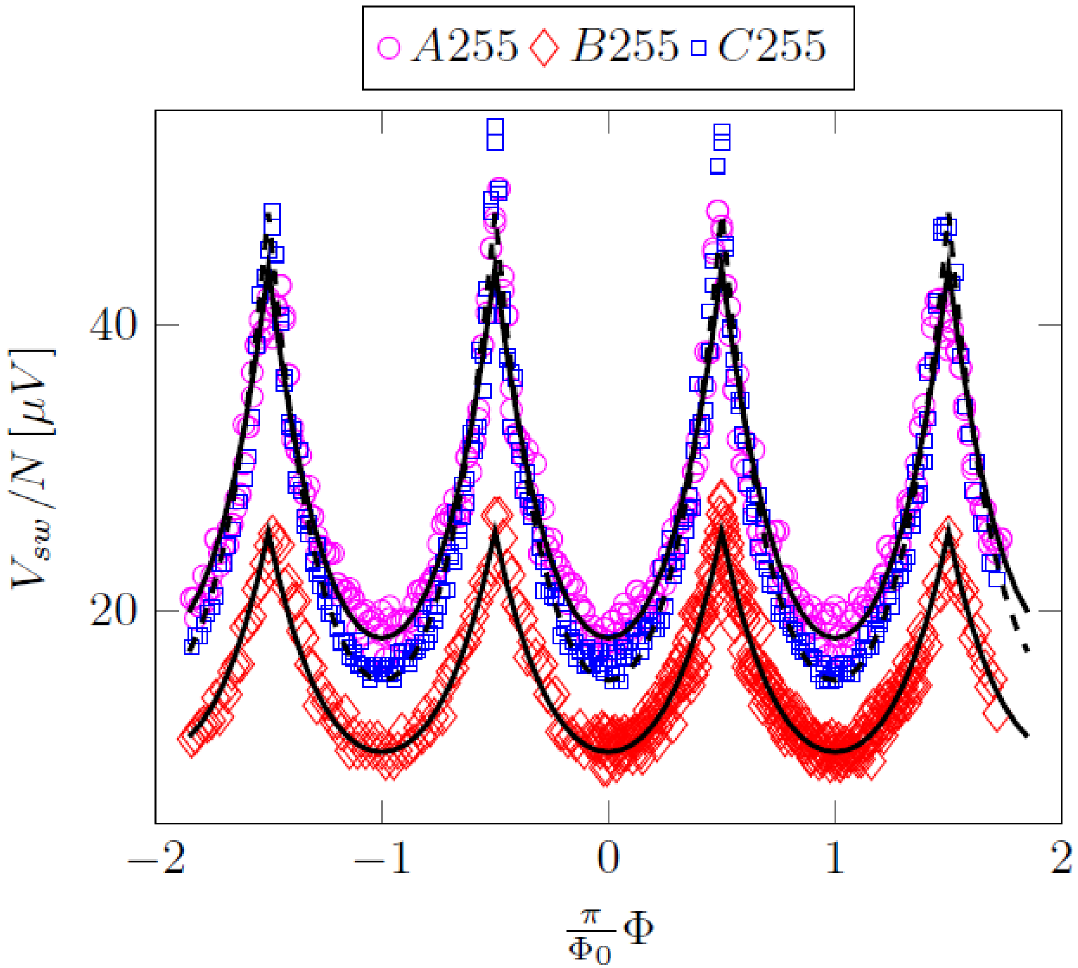
weak disorder estimate

$$\Lambda E_C/2 = 220\ \mu\text{eV}$$

! gap of Al $\Delta \approx 200\ \mu\text{eV}$

thermally generated quasiparticles?

Charge depinning in arrays of small JJs



The switching voltage normalized to the array length N as a function of the magnetic flux for 3 arrays of length 255

switching voltage

$$V_{sw} \approx \frac{NE_C}{2e}\Lambda^{-\frac{2}{3}}\tilde{R}^{2/3}$$

Larkin length

$$L_L \approx \Lambda^{4/3}\tilde{R}^{-1/3}$$

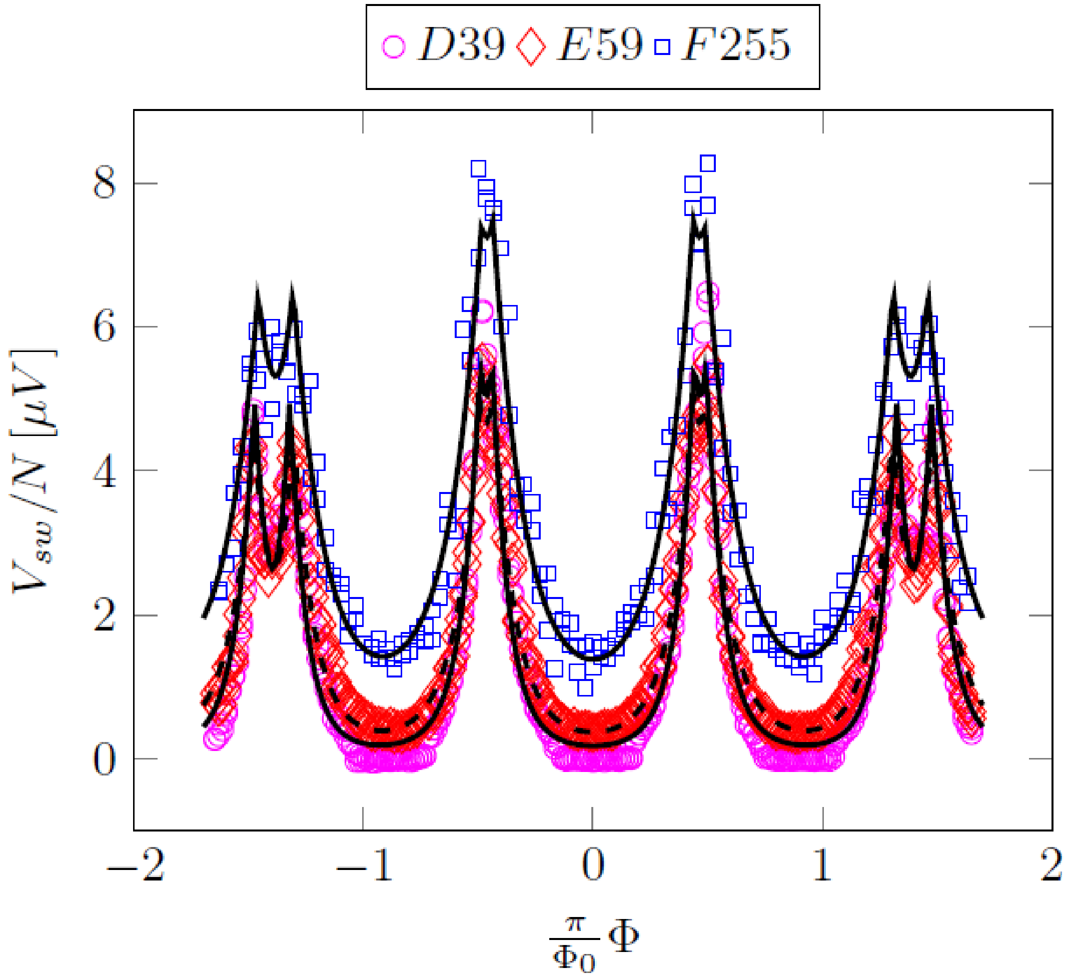
disorder correlation parameter

$$\tilde{R}\,[E_J(\Phi)/E_C]$$

N. Vogt, R. Schäfer, H. Rotzinger, W. Cui, A. Fiebig, A. Shnirman, and A. V. Ustinov, arXiv (2014)

=> talk of A. Shnirman today

Charge depinning in arrays of small JJs



The switching voltage normalized to array length N as a function of the magnetic flux for arrays of length 39, 59 and 255

switching voltage

$$V_{sw} \approx \frac{NE_C}{2e}\Lambda^{-\frac{2}{3}}\tilde{R}^{2/3}$$

Larkin length

$$L_L \approx \Lambda^{4/3}\tilde{R}^{-1/3}$$

disorder correlation parameter

$$\tilde{R}\,[E_J(\Phi)/E_C]$$

N. Vogt, R. Schäfer, H. Rotzinger, W. Cui, A. Fiebig, A. Shnirman, and A. V. Ustinov, arXiv (2014)

=> talk of A. Shnirman today

Summary

- Brief review of experiments with JJ arrays near S/I transition
  - 2D arrays
  - 1D/2D channels – shooting and localizing quantum vortices
  - 1D arrays – searching for ballistic Cooper pairs
- Our recent experiments with 1D arrays
  - tuning E_J/E_C
  - conductance ~ E_J^2, incoherent Cooper pair tunneling
  - thermal activation of charges
  - depinning of charges **=> talk of A. Shnirman today**