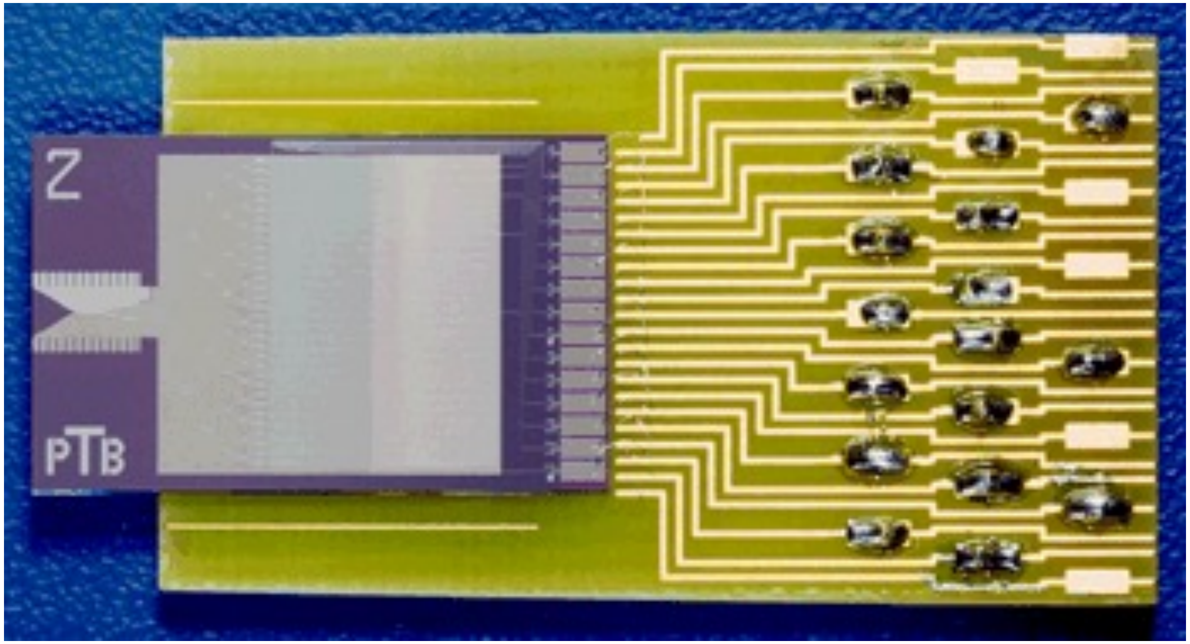
Superconductivity
Lecture 10

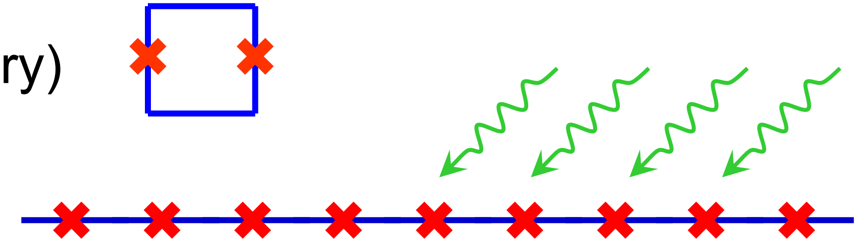


Superconducting electronics

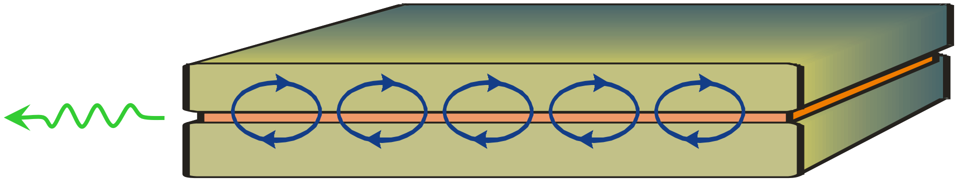
- Overview of superconducting devices
- Fabrication of superconducting circuits
- Voltage standards
- Digital electronics: RSFQ logic
- Josephson oscillators
- SIS mixers
- Integrated sub-mm wave receivers
- Qubits for quantum computing (next lecture)

Overview of superconducting devices

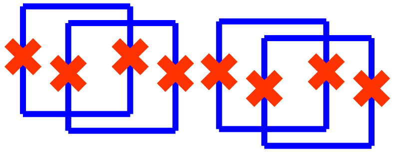
- SQUIDs (magnetometry)



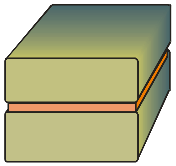
- Voltage standard
- Microwave generators
  (*1* GHz – *1* THz)



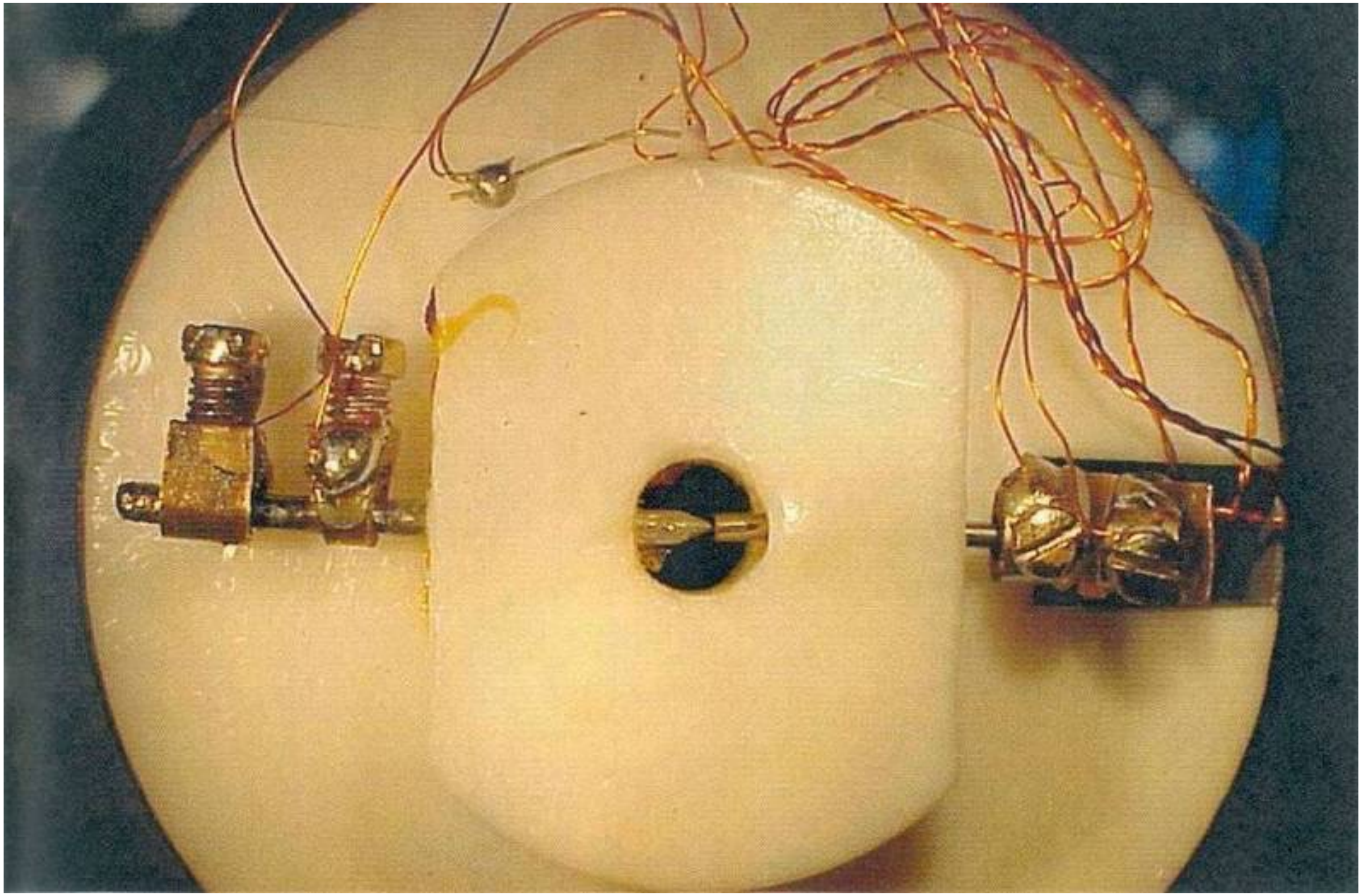
- RSFQ digital electronics



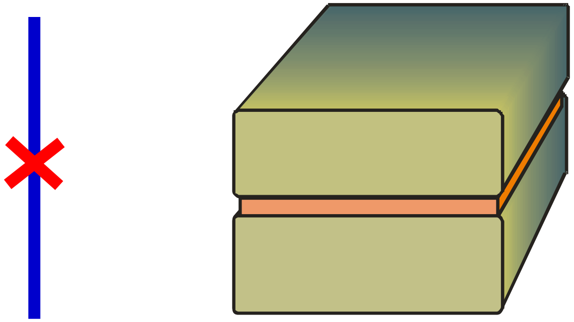
- Qubits



The simplest way of making a Josephson junction



Fabrication of Josephson devices

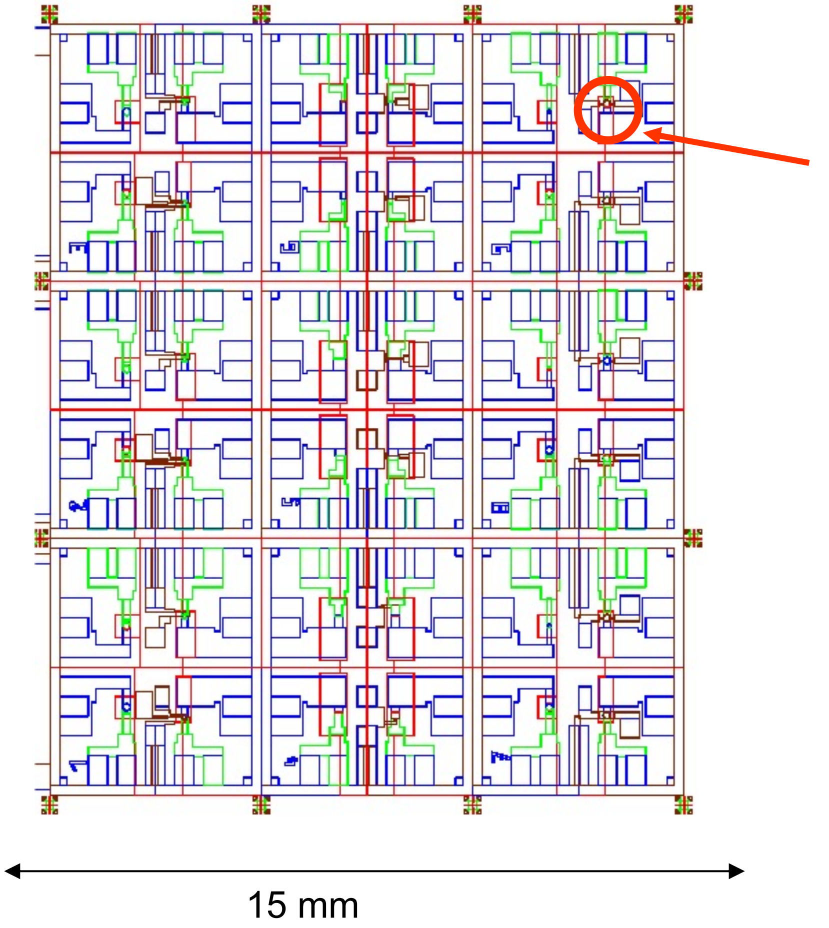


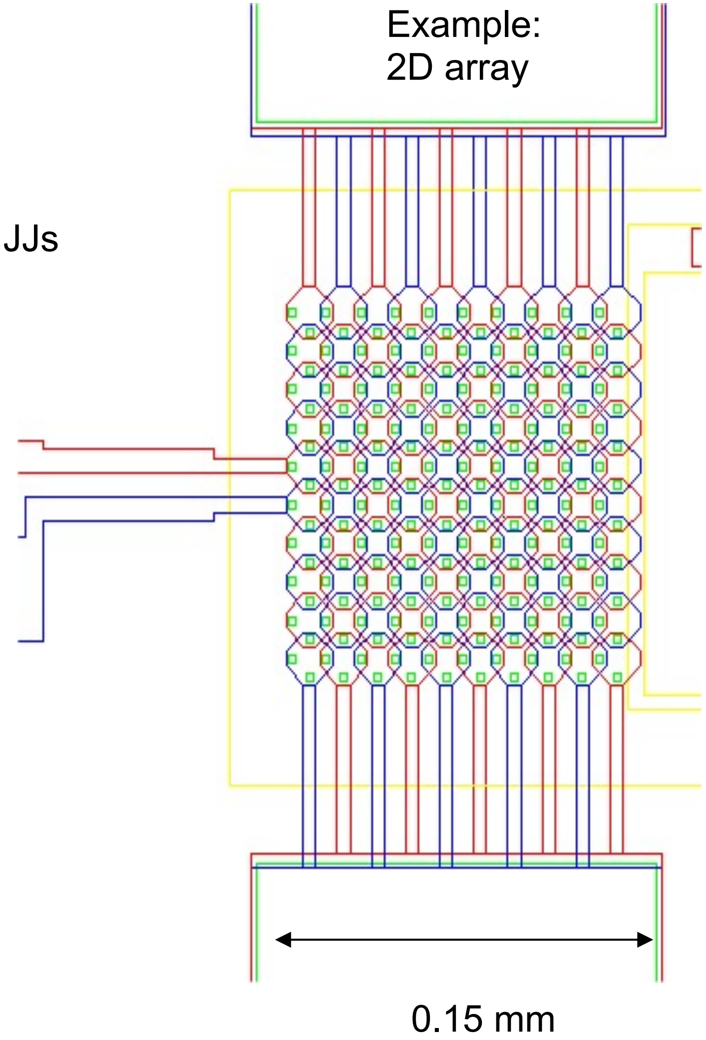
1. circuit layout (CAD)
2. fabrication of photomasks
3. deposition of superconducting and insulating layers on a wafer
4. photo (or e-beam) lithography
5. dicing the wafer into chips

- *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

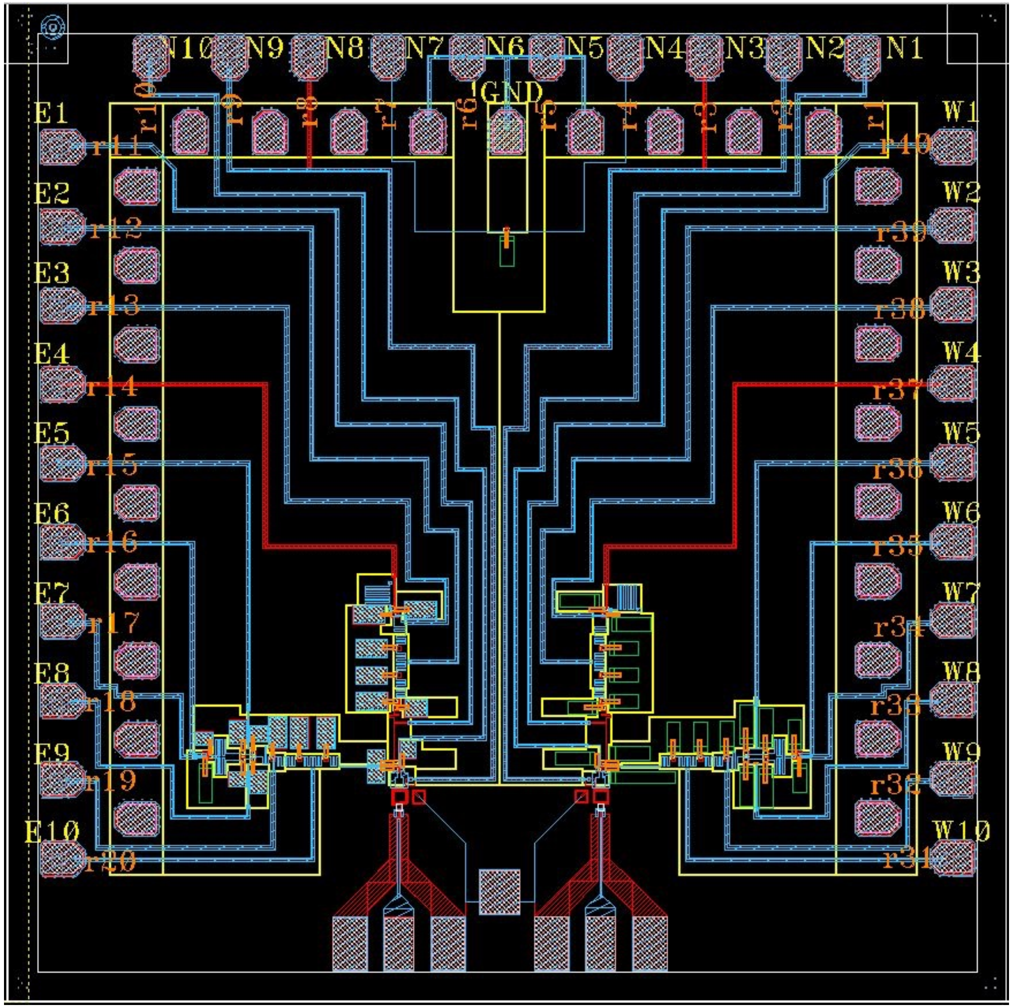
CAD = computer aided design




Example:
2D array

Example of circuit layout (RSFQ)

RSFQ = Rapid Single
Flux Quantum Logic

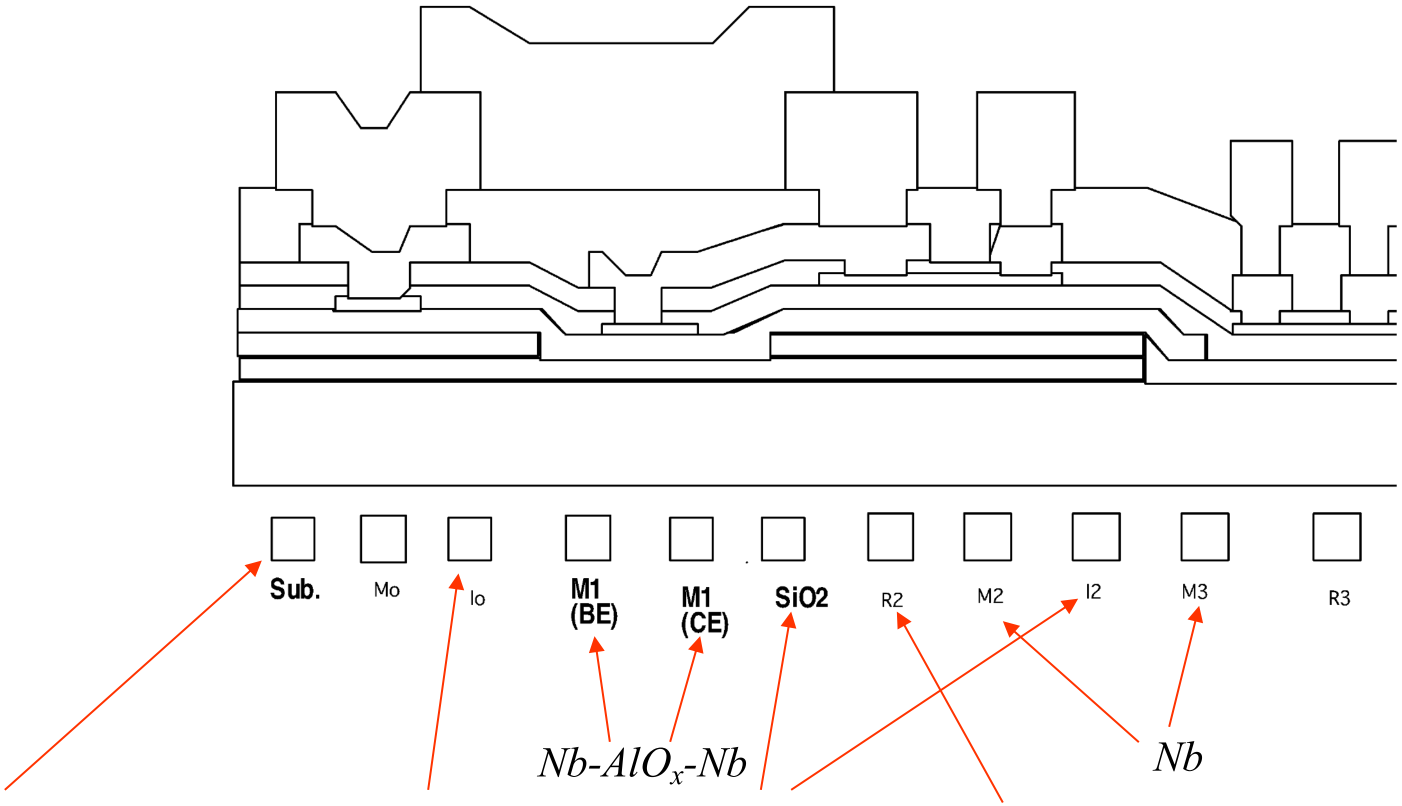


© T. Okhi (Chalmers, 2007)

Foundry rules: Example

design rules of Hypres Inc.

See: http://www.hypres.com



Nb-AlO$_x$-Nb

Nb

Si substrate

Insulator (SiO_2)

insulator

resistive layer (*Mo* or *AuPd*)

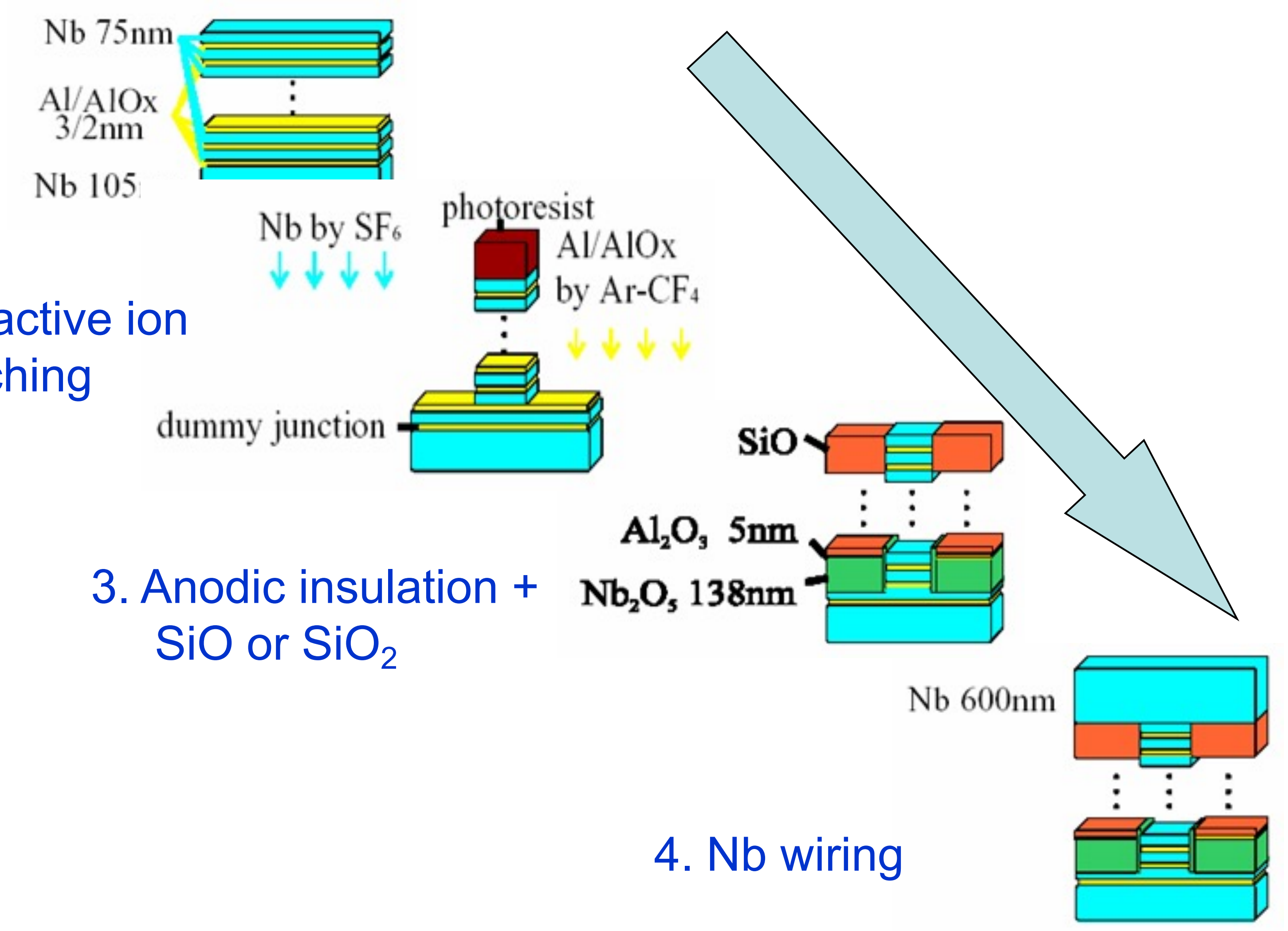
Wafer processing

Photolithography can be used for JJ size down to 1 μm

Clean room

mask alignment

Fabrication of Nb-AlO$_x$-Nb junctions



1. Deposition of a multilayer

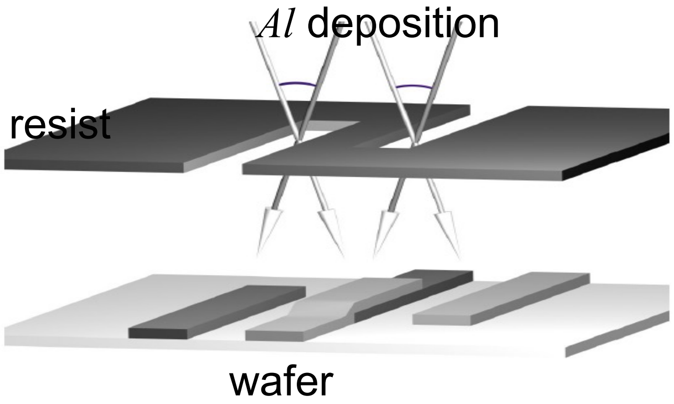
2. Reactive ion etching

3. Anodic insulation + SiO or SiO$_2$

4. Nb wiring

Shadow evaporation technique

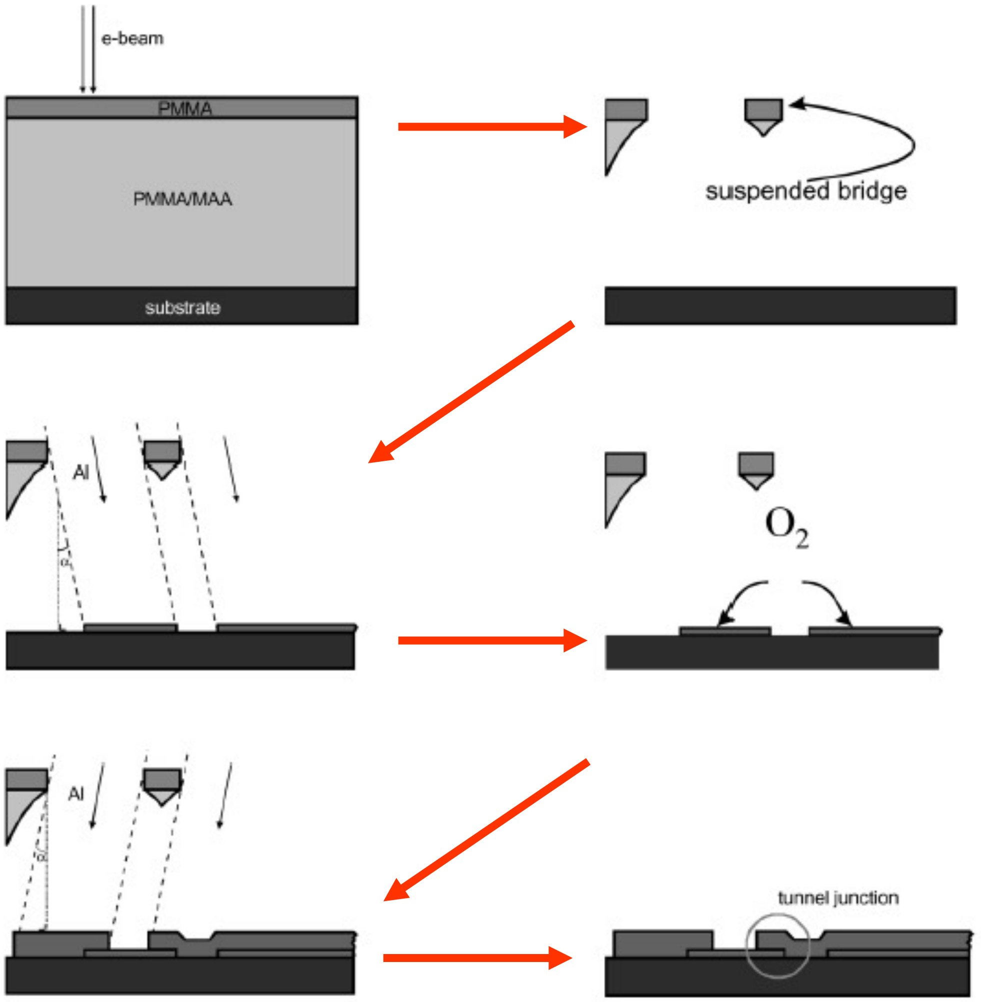
Electron beam lithography can produce JJ size < 0.1 μm



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

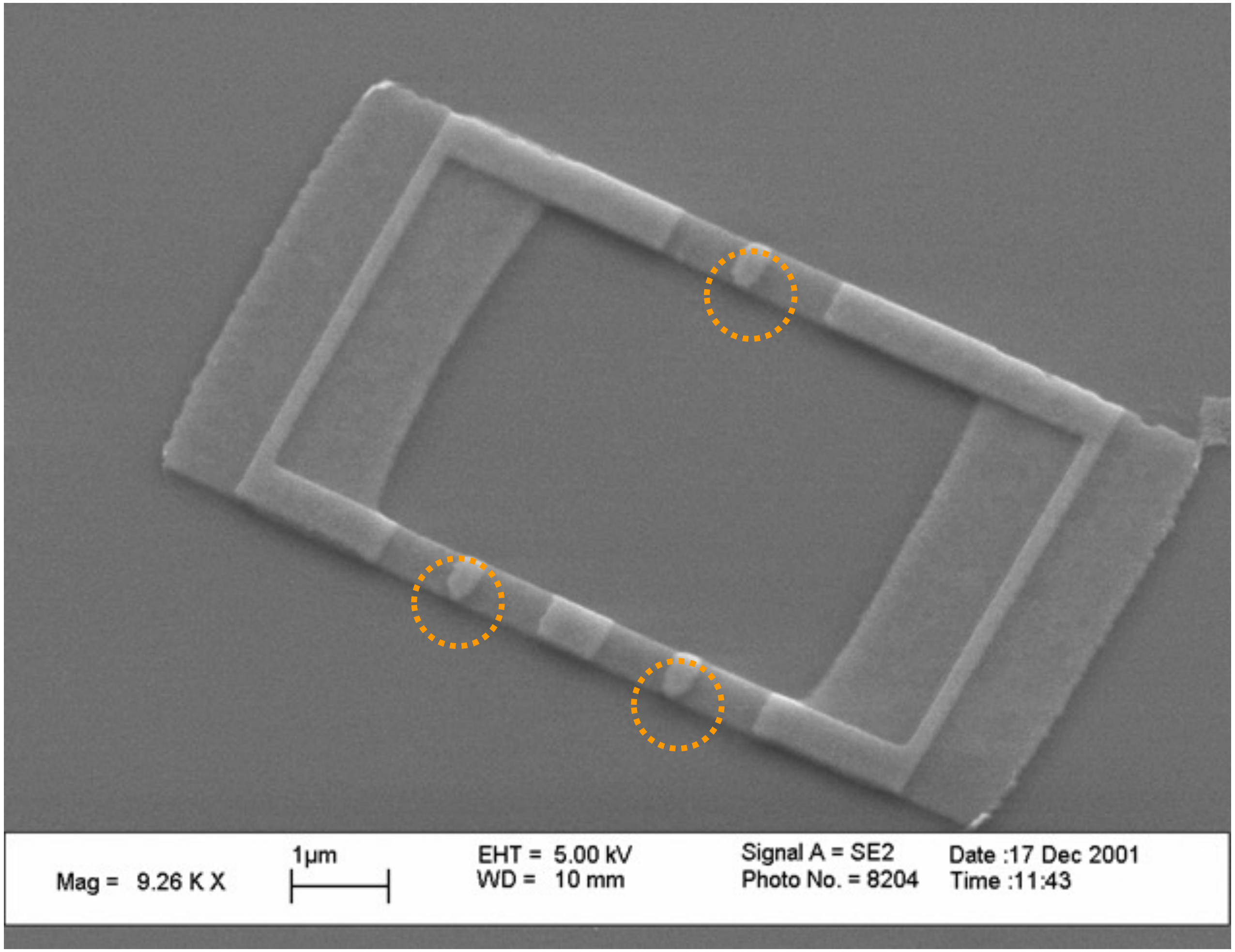
The bottom layer of aluminum is deposited under an angle +α

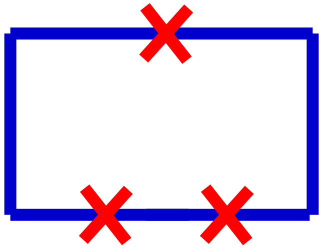
The sample is exposed to O$_2$ to form the oxide layer

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

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

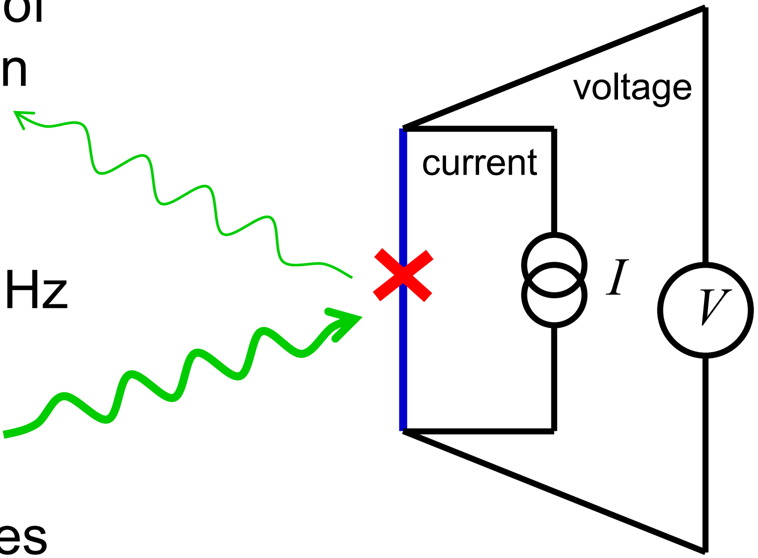
Sub-micron Al-AlO$_x$-Al JJs produced by electron beam lithography





3-JJ flux qubit

Making your choice: Microwave in or microwave out?



detection of
Josephson
radiation

10 - 600 GHz

applying
microwaves

AC techniques

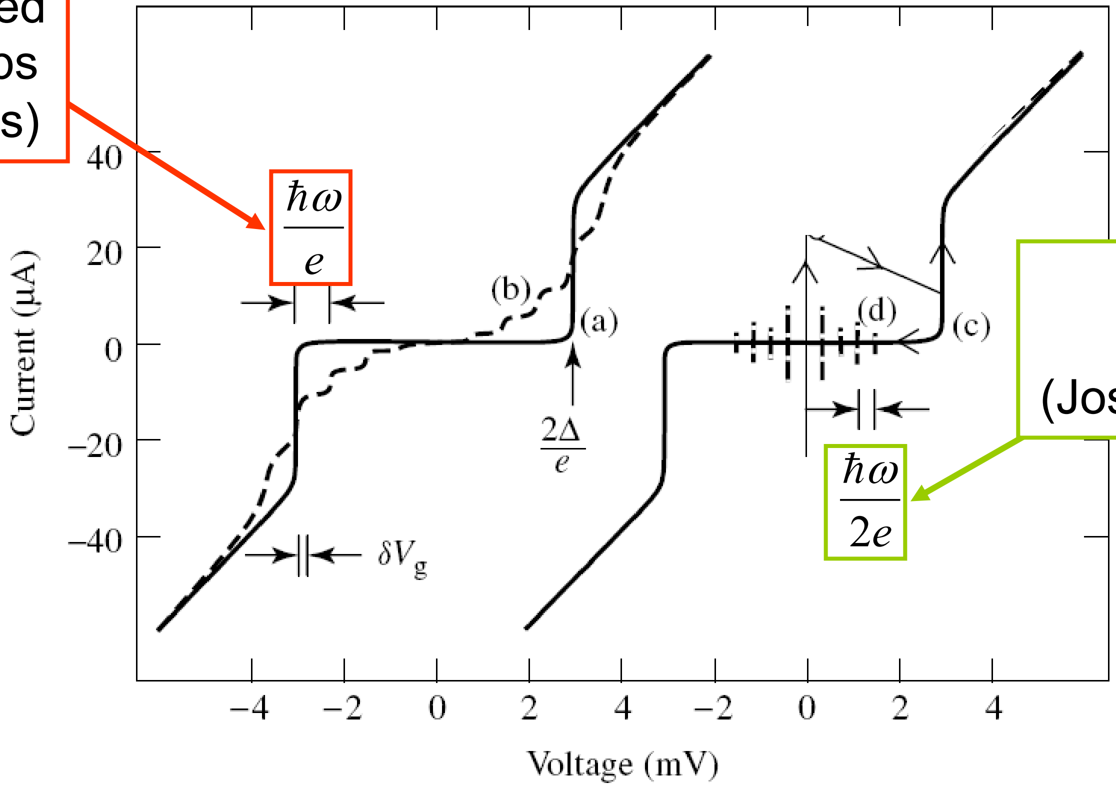
DC techniques

expensive and difficult

cheap and easy

Josephson tunnel junctions under microwaves

photon-assisted tunneling steps (quasiparticles)

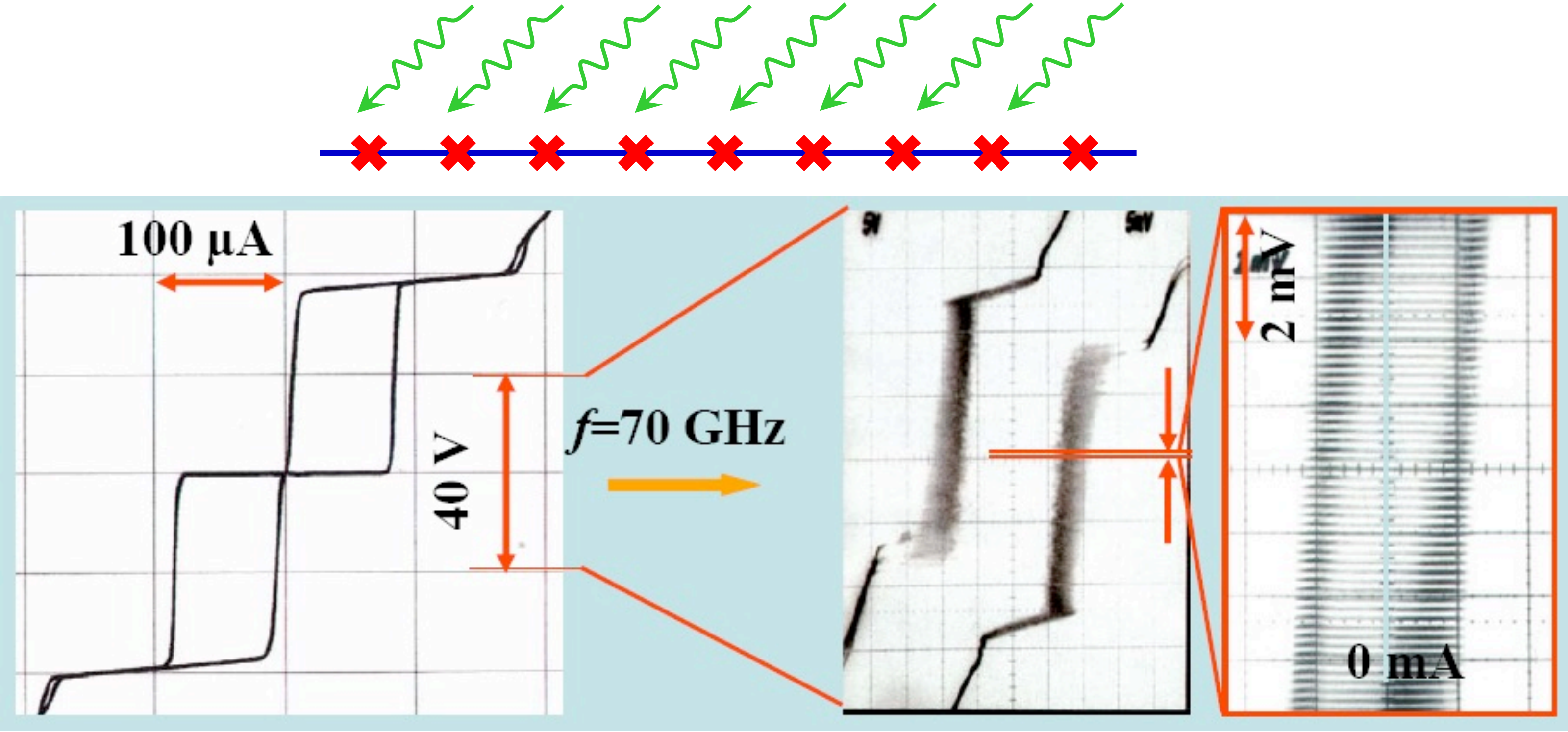


Shapiro steps (Josephson effect)

© K.Fossheim and A.Sudbø, “Superconductivity”

Conventional 10 V voltage standard

13 984 SIS junctions



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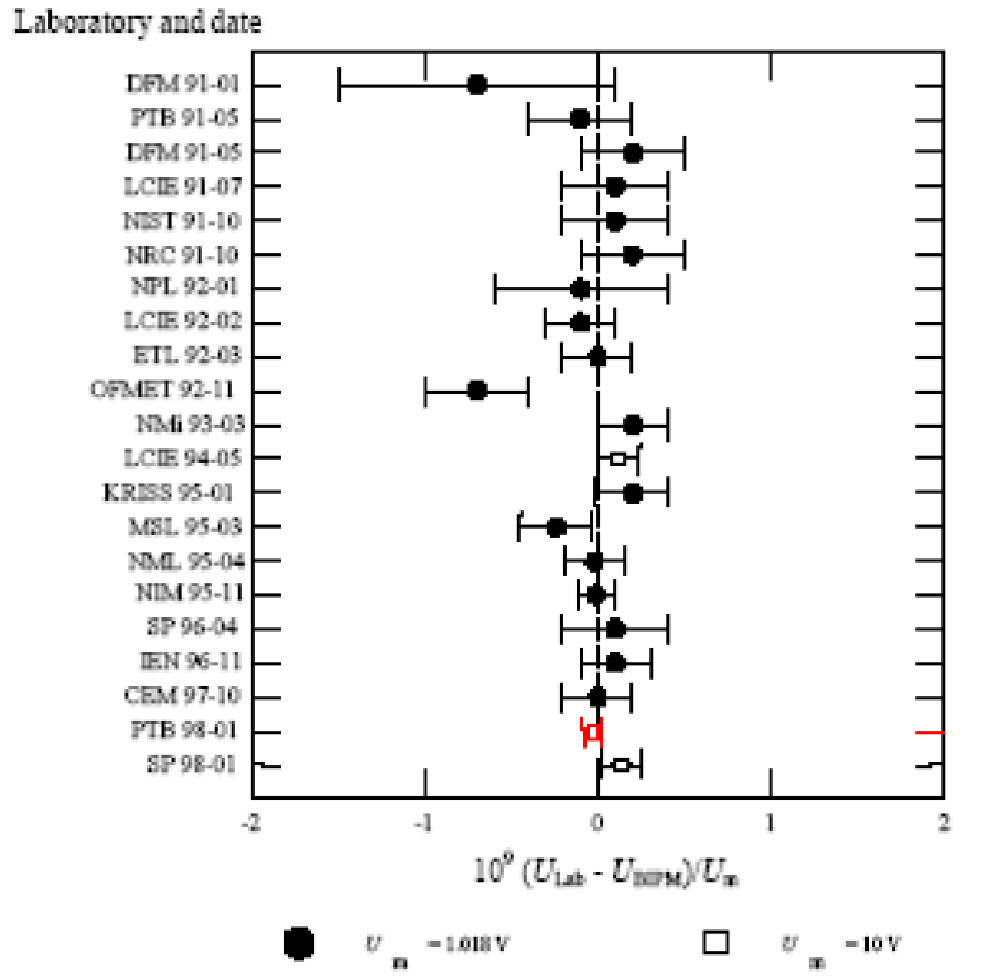
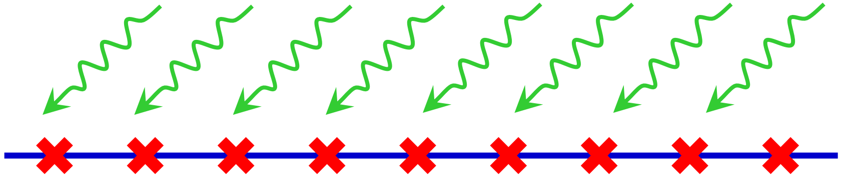
- Rapid adjustment of a certain voltage is difficult
- AC-voltage generation requires rapid and programmable switching between the reference voltage steps
- To achieve a defined number of steps per junction one has to use highly damped Josephson junctions in series arrays: SINIS- or SNS-junctions

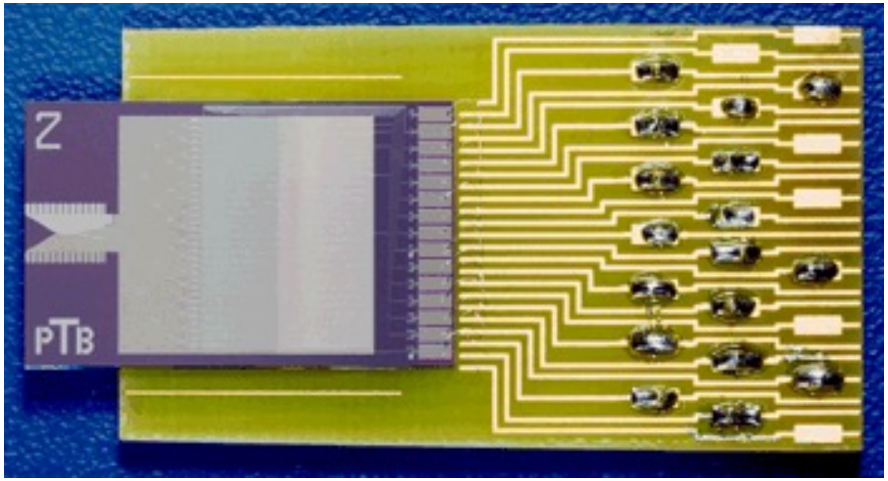
Comparison of Josephson voltage standards

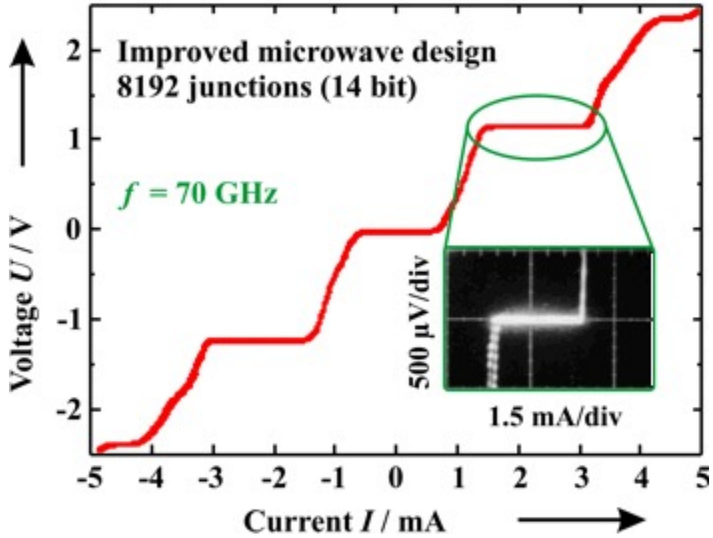


$U_{PTB} - U_{BIPM} = -3 \cdot 10^{-11}$ V with a relative uncertainty of $5 \cdot 10^{-11}$ V

Circuits for Josephson Voltage Standards



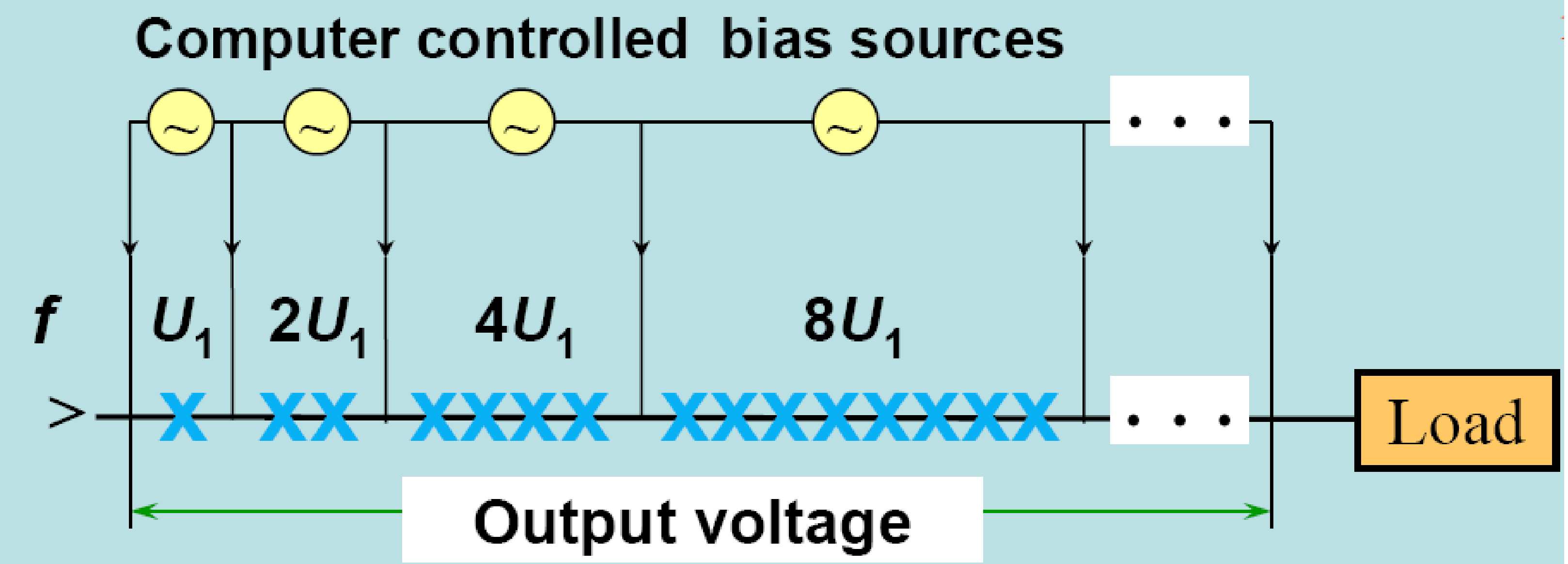




Picture of a 1-V series array consisting of 8192 SINIS junctions divided into a binary sequence

© PTB Brauschweig

Programmable Voltage Standard



Hamilton et al., IEEE Trans. Instrum. Meas. **44**, 223 (1995)

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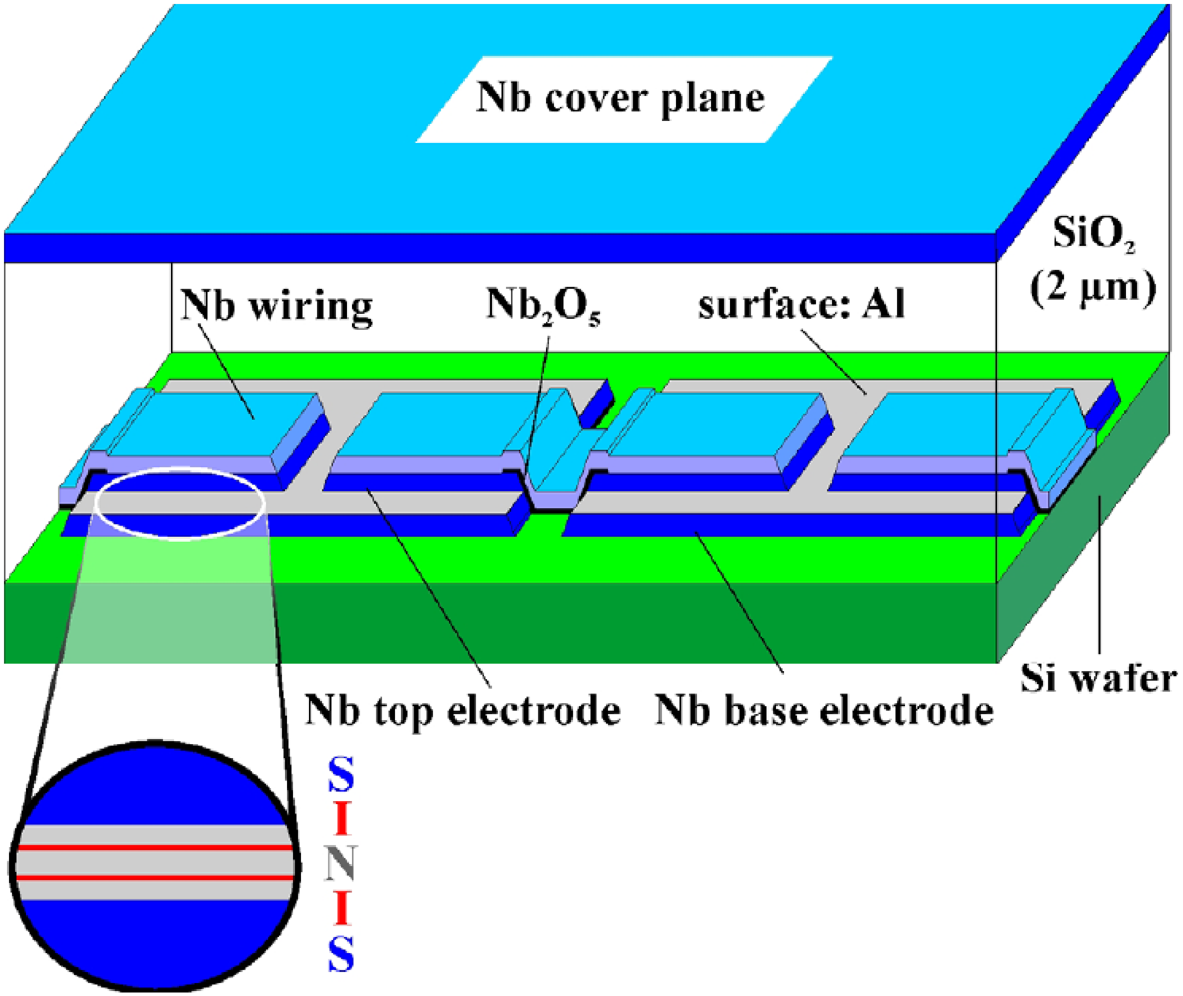
SINIS junctions integrated into a stripline



Impedance: 5 Ω

Area of a single junction:

12 µm x 30µm

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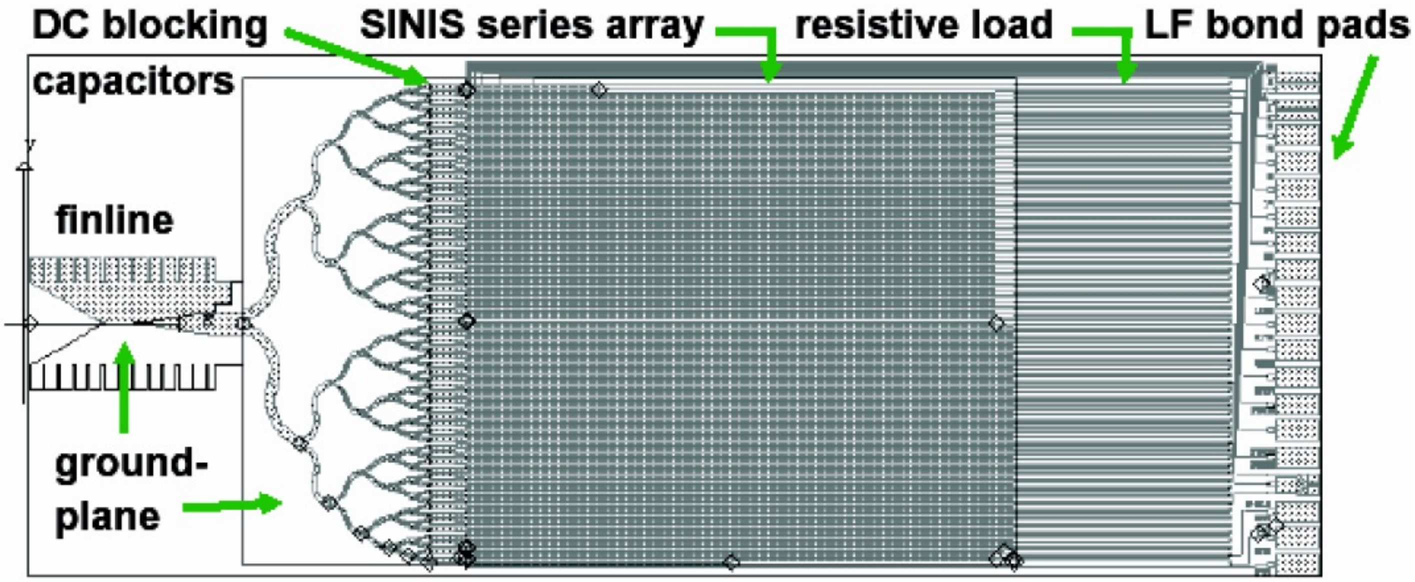
PTB SINIS voltage standard

- **69,632 SINIS junctions divided into binary segments**
- **128 microwave branches** (containing up to 562 junctions)



junction areas: 12 µm x 30 µm

chip size: 10 mm x 24 mm

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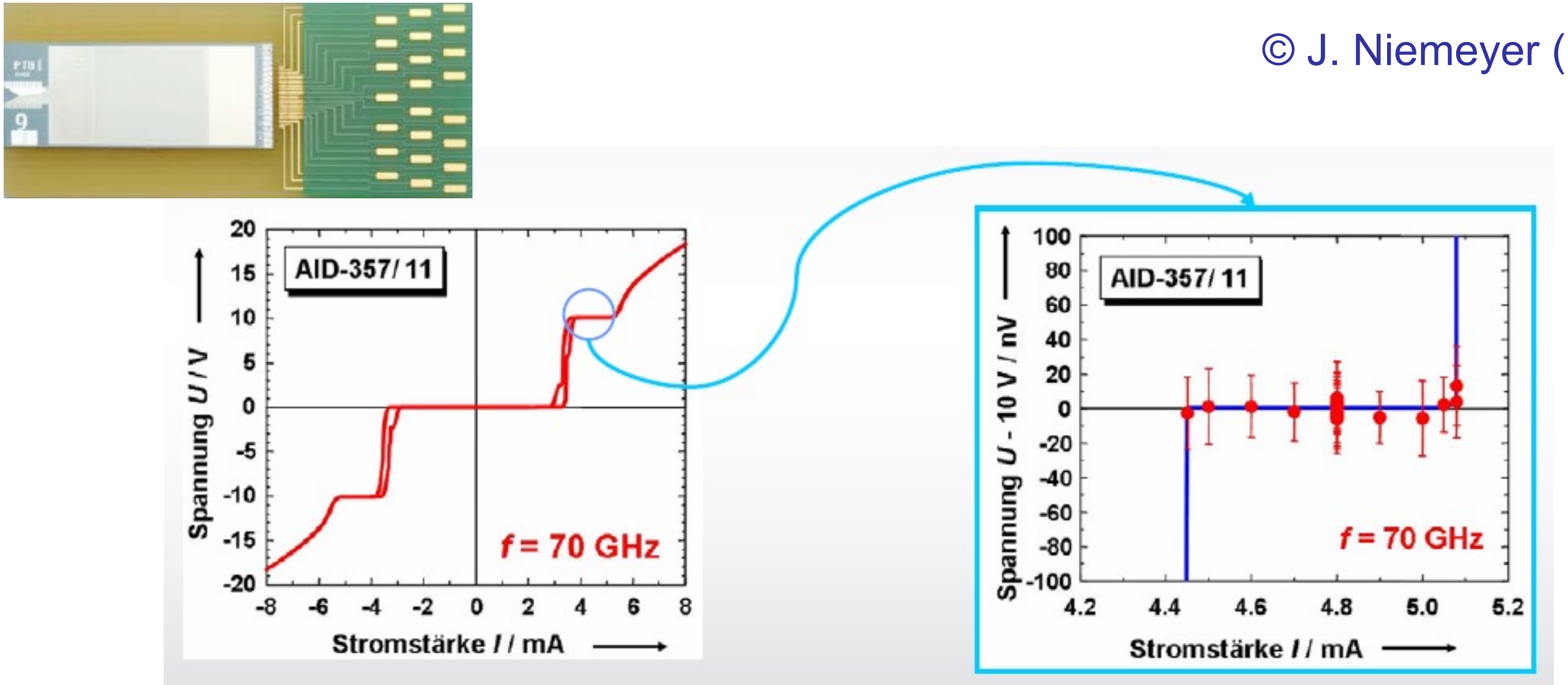
Programmable 10-V-Josephson-Standard



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- Current step 600 μA
- 70000 SINIS Josephson contacts
- Operation with rapidly switchable computer controlled current source

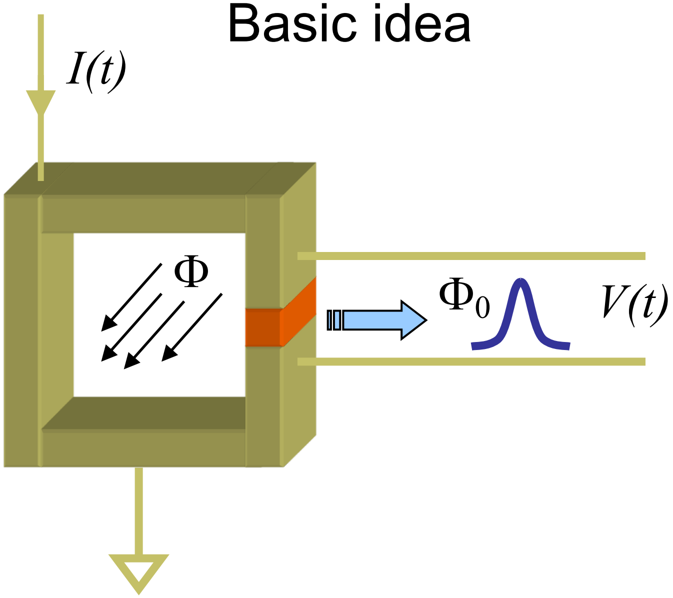
Applications:

- Quantum voltmeter for AC and DC voltages
- Primary standard for the electrical power
- Linearity measurements (DC)

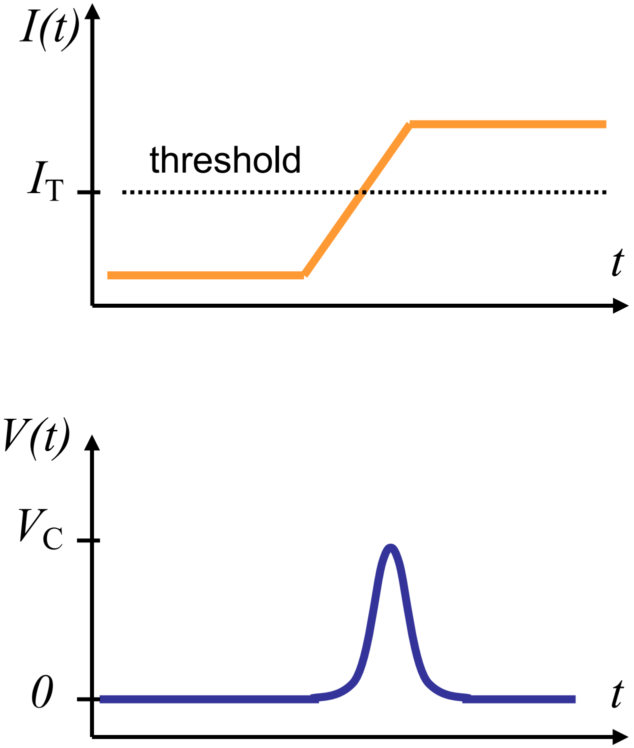
RSFQ logic

RSFQ = Rapid Single-Flux-Quantum logic is an ultrafast digital technology based on coding digital bits by single quanta of magnetic flux in superconductors.

Basic idea



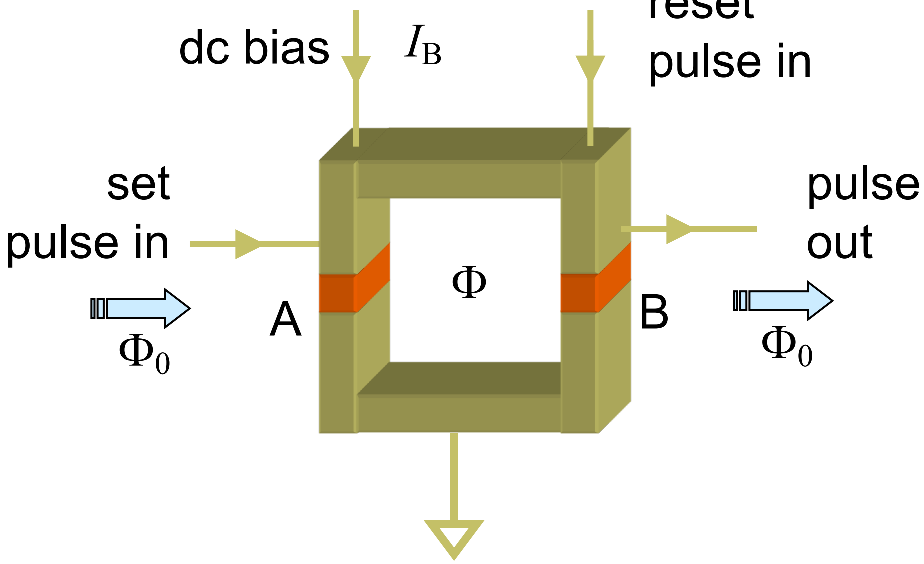
$$\int V(t)dt = \Phi_0 = 2.07 \times 10^{-15}\ \mathrm{V\ s}$$



- K. Likharev and V. Semenov, IEEE Trans. Appl. Supercon. **1**, 3 (1991)

RSFQ flip-flop

RS-flip-flop: a comparator with reset



loop inductance L ⇒ $\beta_L = \dfrac{2\pi I_C L}{\Phi_0} \approx 1$

junction resistance R_N ⇒ $\beta_C = \dfrac{2\pi I_C R_N^2 C}{\Phi_0} \approx 1$

Energy dissipation

$E \approx I_C \Phi_0$ ~ 5 × 10^{-19} J

(per junction per pulse)

Dissipated power

$W \approx I_C \Phi_0 f_{\mathrm{CLOCK}}$ ~ 50 nW

(per junction with 100 GHz clock)

Time delay $\tau \approx \dfrac{\Phi_0}{I_C R_N}$ ~ 7 ps

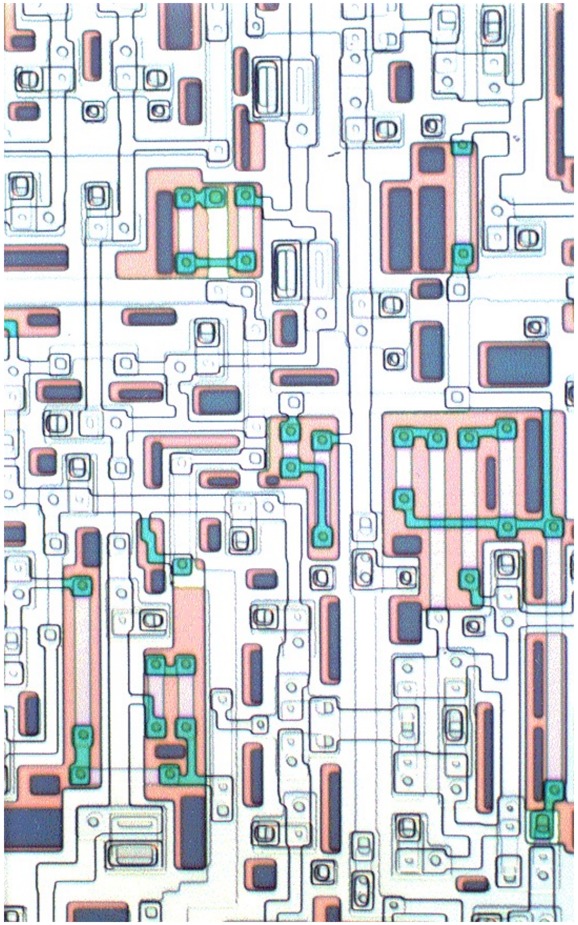
⇑

for typical parameters

! no dissipated power in the waiting state

RSFQ features

- Data and clock signals are generated in the moments of flux quanta switching
- Data and clock signals are transferred as picosecond pulses along superconductor microstrip lines
- Clock frequency of RSFQ devices may approach 1000 GHz, i.e. at least 10 times higher than that in the fastest semiconductor circuits. (A 770 GHz device have been already demonstrated experimentally.)
- Power consumption of RSFQ devices is extremely low, below 10^{-18} Joule per bit, i.e. at least 5 orders of magnitude lower than that of the fastest semiconductor circuits, thus allowing compact packaging of integrated circuits.



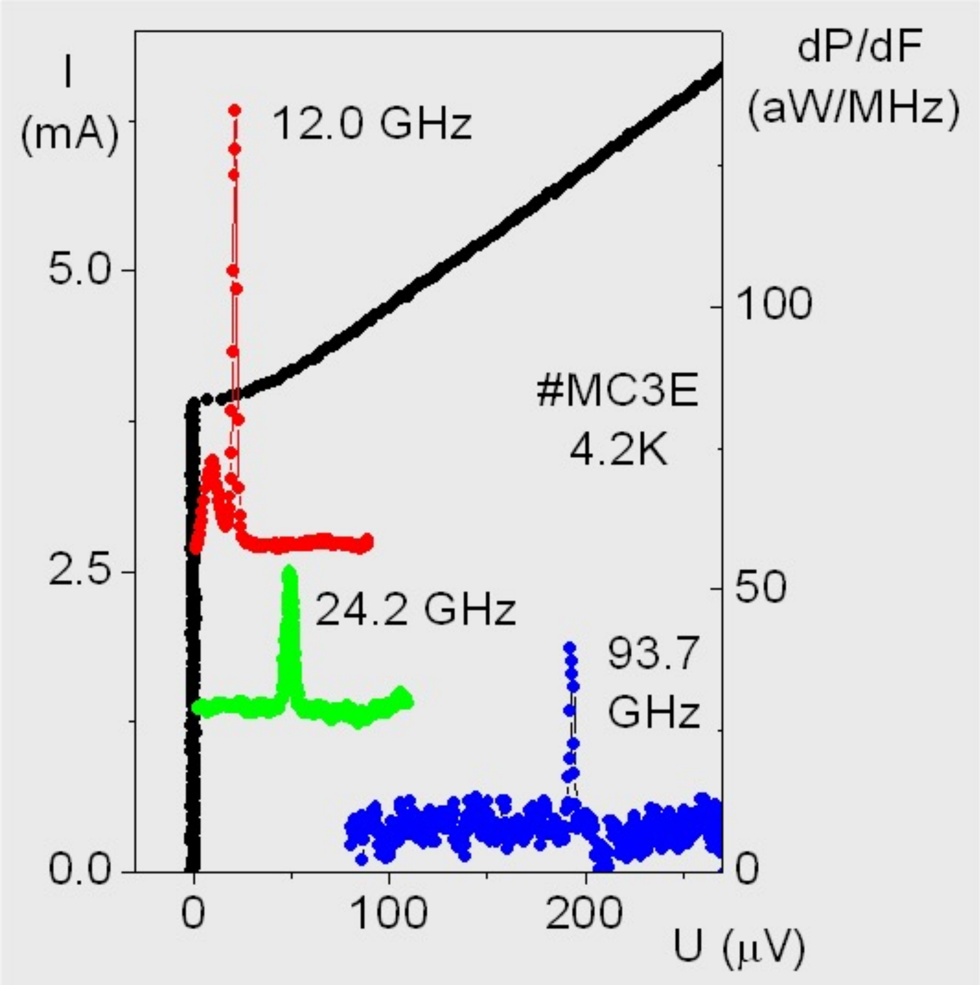
- For further reference see: http://rsfq1.physics.sunysb.edu/~likharev/personal/

Microwave emission from YBCO junction

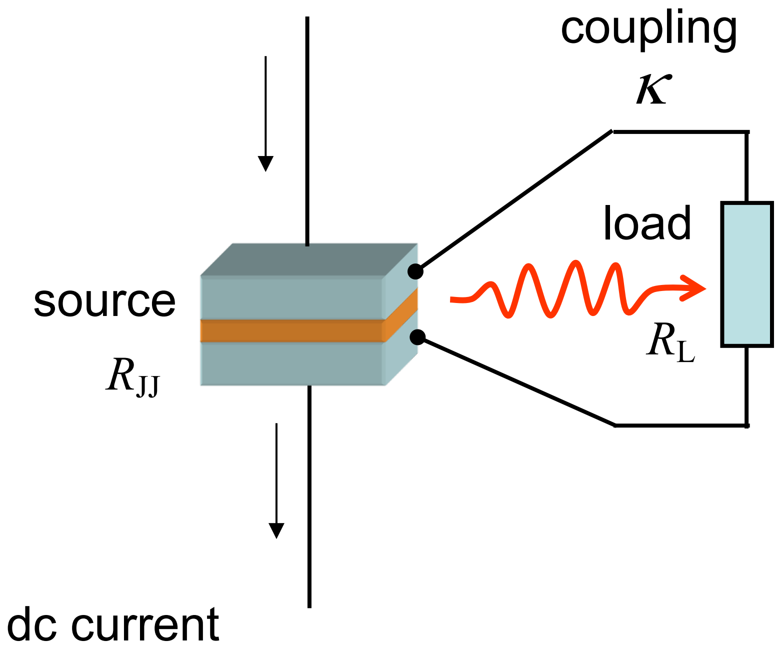
Electromagnetic radiation at the frequency f

$$\boxed{f = \frac{V}{\Phi_0}}$$

$$\Phi_0 = \frac{h}{2e} \approx 2.07 \times 10^{-15} \mathrm{V \cdot s}$$



Josephson radiation power



Maximum ac power of an oscillator:

$$P_{\mathrm{ac}} < P_{\mathrm{dc}} = I \cdot V$$

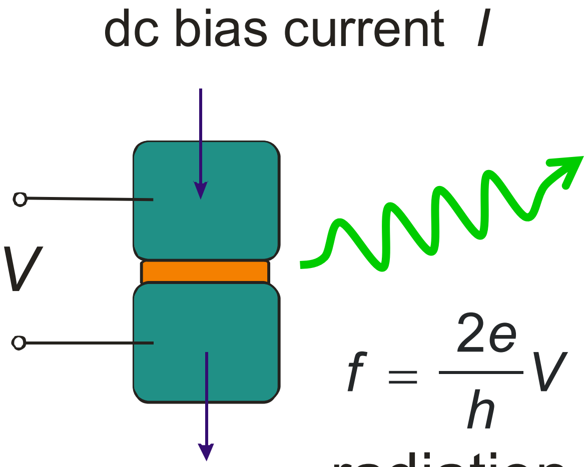
with typical $I \sim 1$ mA and $V \sim 1$ mV
we get $P_{\mathrm{dc}} \sim 1$ μW .

ac power delivered to the load $P_L = \kappa \cdot I \cdot V \dfrac{R_{JJ} R_L}{2(R_{JJ} + R_L)^2}$

the maximum ac power is hence delivered at $R_{JJ} \approx R_L$

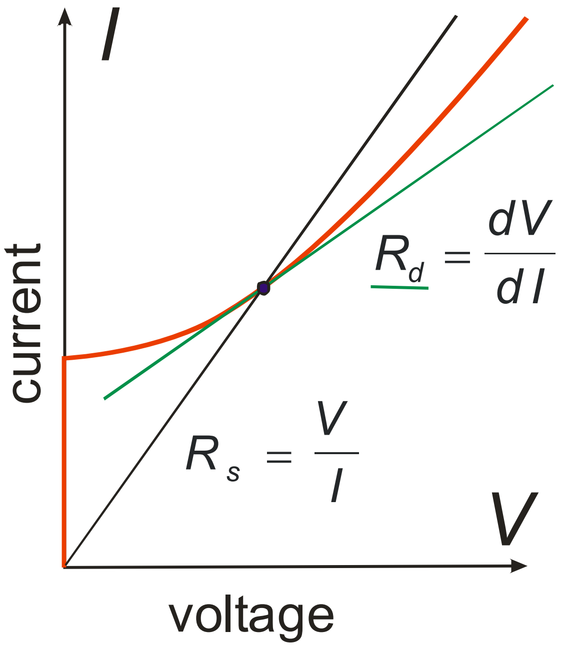
! <u>Impedance matching is required</u>

Josephson radiation linewidth



$$f = \frac{2e}{h}V$$

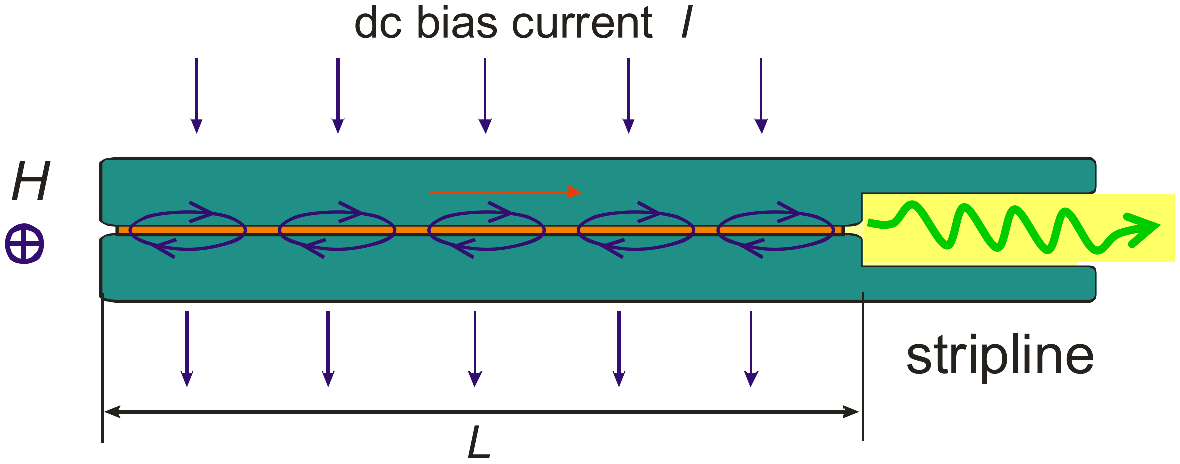
radiation frequency



Radiation linewidth

$$\boxed{\Delta f = \frac{4\pi k_B T}{\Phi_0^2}\frac{R_D^2}{R_s}}$$

Josephson flux-flow oscillator

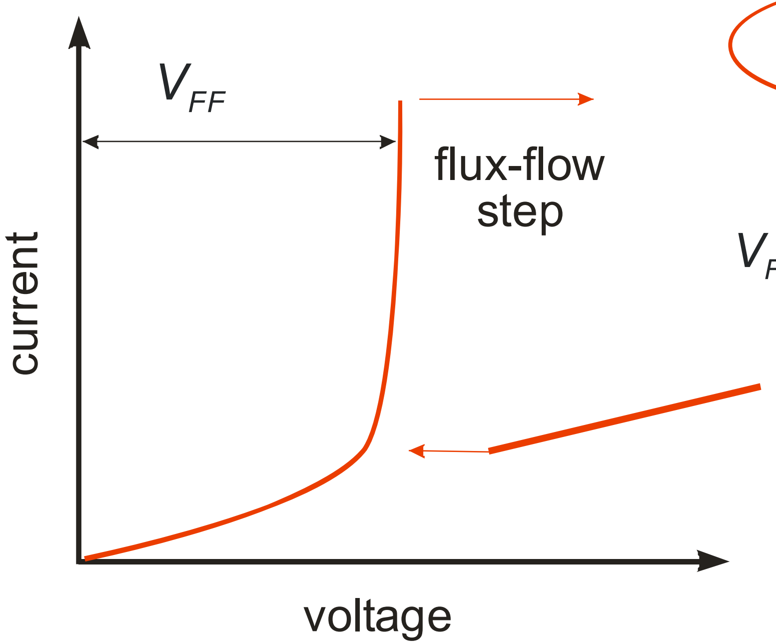


$B \sim 10$ G

$f \sim 200\text{-}700$ GHz

Josephson vortices

$$\boxed{\Delta f_{FF} < 10^{-6} f_{FF}}$$



$$V_{FF} = \frac{\bar{c} n_F \Phi_0}{L} = \bar{c} H \Lambda$$

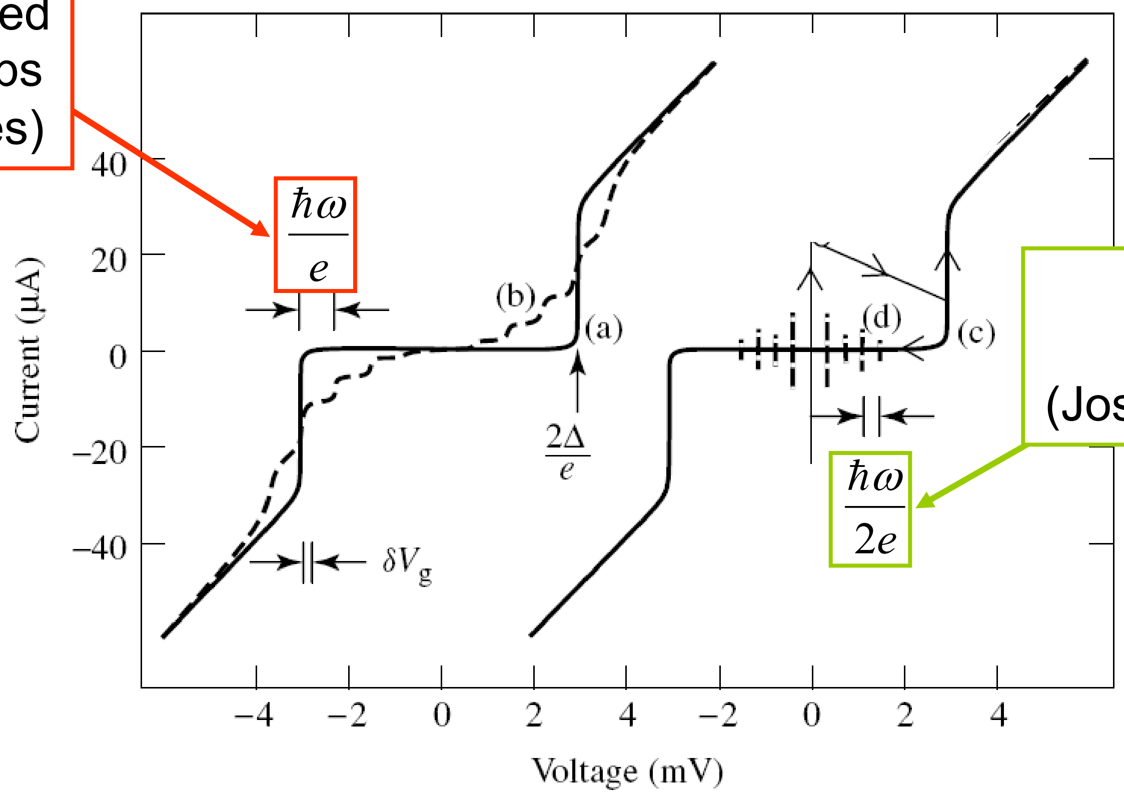
$$f_{FF} = \frac{V_{FF}}{\Phi_0}$$

- high frequencies
- narrow linewidth
- stability is controlled by magnetic field
- good tunability
- low harmonics

Practical issues about using Josephson radiation sources

- Frequency range
  - Niobium junctions: 100-700 GHz
  - Niobium-nitride junctions: up to 1.4 THz
  - High-temperature superconductors: up to 3-5 THz
- Impedance of the source
  - few Ω (typical)
- Maximum output power
  - up to few μW (single junction)
  - up to 1 mW (mutually locked junction arrays)
- Radiation linewidth
  - down to 10^{-7} (free running) and 10^{-12} (phase locked)
- Frequency tunability, spectral purity, presence of high harmonics

Josephson tunnel junctions under microwaves



photon-assisted tunneling steps (quasiparticles)

Shapiro steps (Josephson effect)

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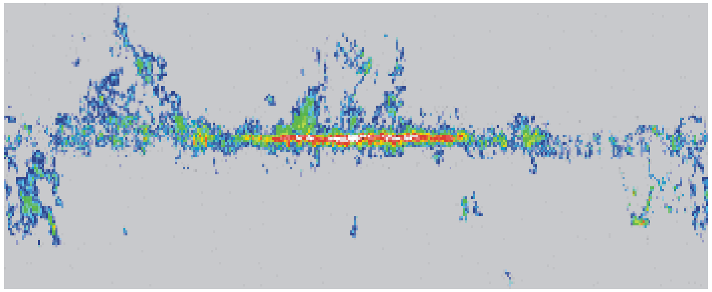
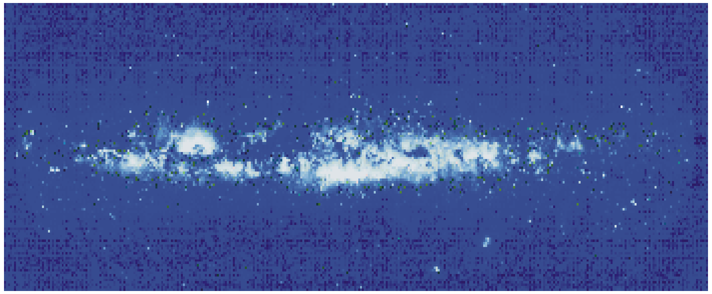
Applications of Josephson oscillators

The Milky Way



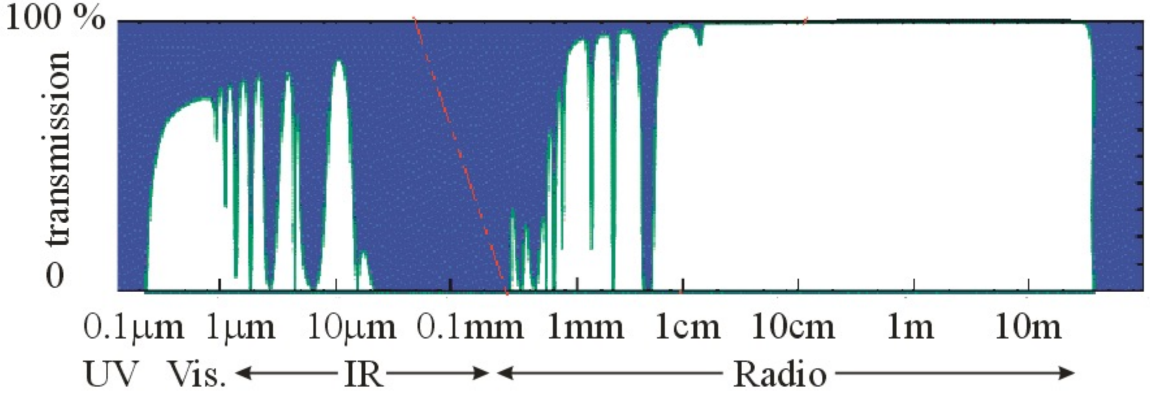
at millimeter wavelengths



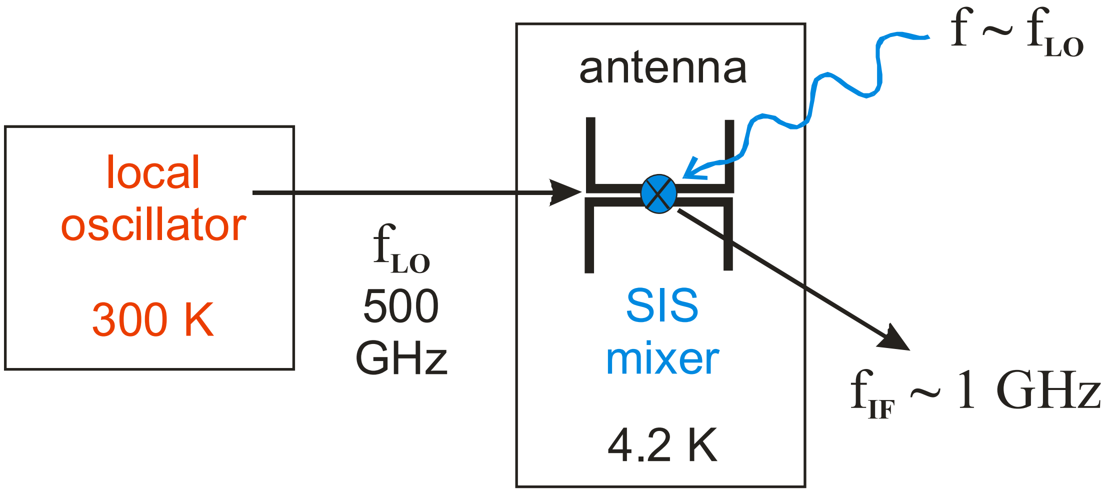
at optical wavelengths

Sub-millimeter and millimeter wave radio astronomy

Atmospheric transmission



Most of radio-astronomical heterodyne receivers for 0.3-3 mm radio waves use superconducting SIS mixers but with bulky room temperature local oscillators



local oscillator

300 K

f_{LO}
500 GHz

antenna

SIS mixer

4.2 K

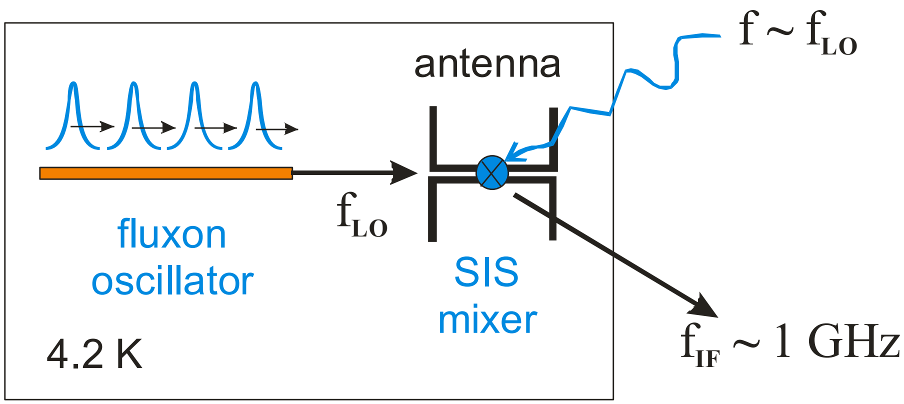
$f \sim f_{LO}$

$f_{IF} \sim 1$ GHz

Integrated superconducting sub-millimeter band receiver

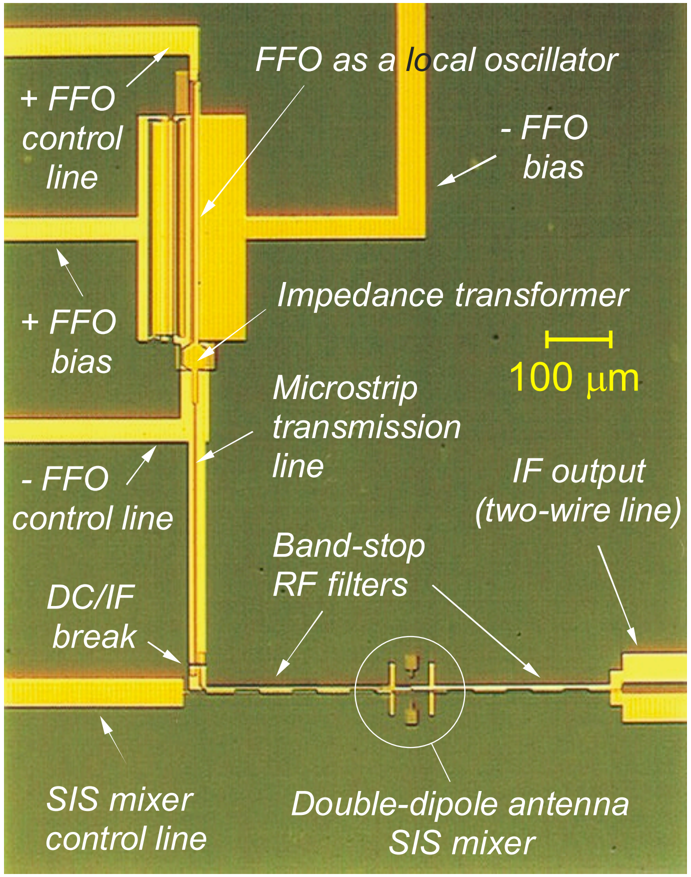
Layout

Single-chip heterodyne receiver for 300-600 GHz
using superconducting SIS mixers with
local fluxon oscillator



Noise temperature at 500 GHz:
~100 K

Phase-locked operation, frequency tuneable

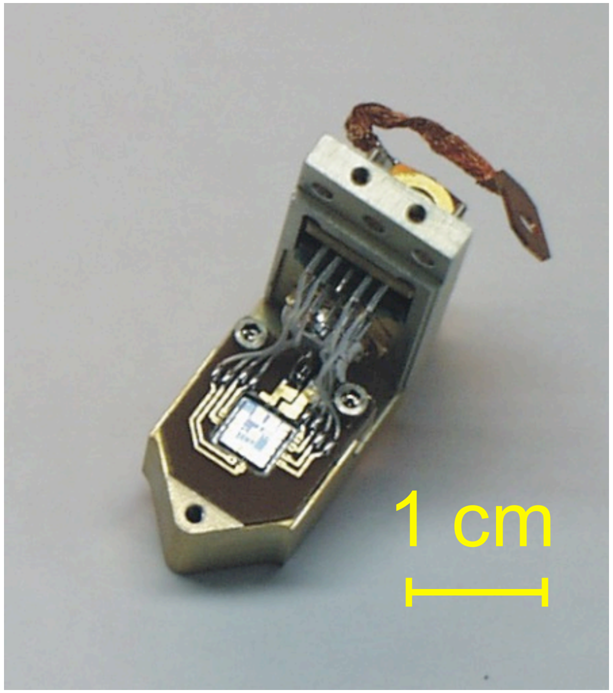


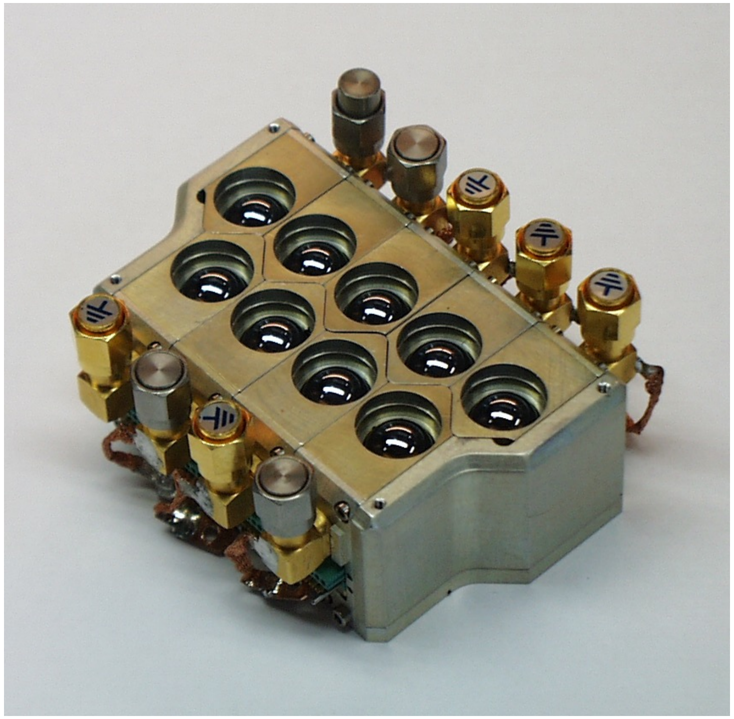
FFO = flux-flow (fluxon) oscillator
SIS = superconductor-insulator-superconductor

© SRON + IREE Moscow

V. P. Koshelets and S. V. Shitov @ ESA, SRON (1998)

Integrated superconducting sub-millimeter band receiver





A single pixel receiver
using an integrated
Josephson oscillator

9-pixel array receiver
for 500 GHz

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(V.Koshelets & S.Shitov)