6.1 Fabrication of JJ for quantum circuits

Repetition

Current-phase and **voltage-phase** relation are classical, but have quantum origin (macroscopic quantum model)

→ Primary quantum macroscopic effects

Quantization of conjugate variable pairs such as (I, V) or (Q, φ)

→ Secondary quantum macroscopic effects

Canonical quantization, operator replacement $$\frac{\hbar}{2e}Q \rightarrow -\imath\hbar\frac{\partial}{\partial\varphi}$$ $$p \rightarrow -\imath\hbar\frac{\partial}{\partial x}$$

$$\boxed{\mathcal{H} = -4E_C\frac{\partial^2}{\partial\varphi^2} + E_{J0}(1-\cos\varphi)}$$

→ Hamiltonian for single JJ

Commutation rules → $[\varphi, Q] = \imath 2e$; $[\varphi, N] = \imath$ or $[\varphi, \frac{\hbar}{2e}Q] = \imath\hbar$

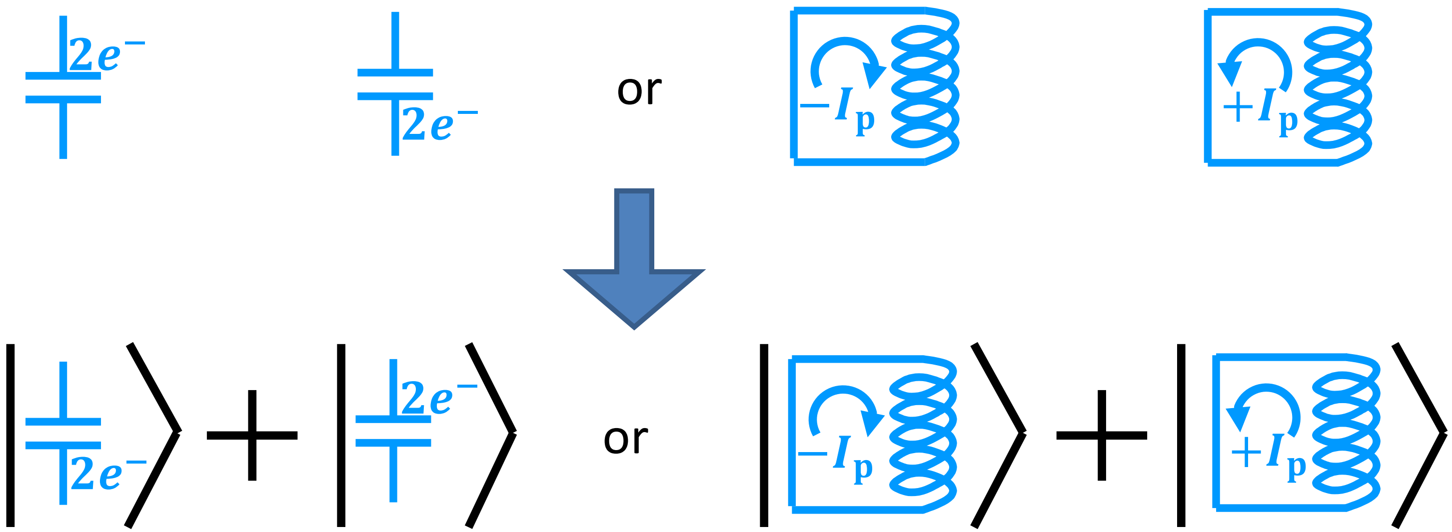
$N \equiv Q/2e$: deviation of the CP number in the electrodes from equilibrium

Heisenberg uncertainty relation $$\Delta N \cdot \Delta\varphi \geq 1$$

Coherent charge and flux states

Classical circuit

Quantum circuit

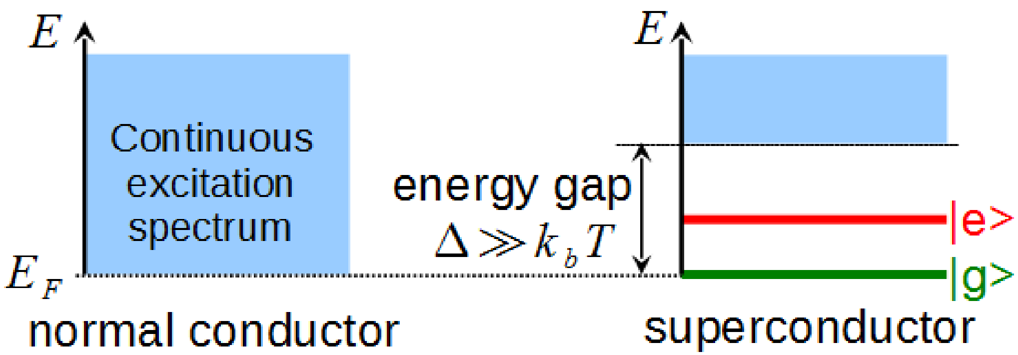


More than quantization effects → Coherence, superposition, entanglement

→ Superconducting circuits offer quantum resources!

→ Applications in Quantum information processing, simulation & communication
Tests of fundamental quantum mechanics

Practical considerations



Al: $\Delta \approx$ 50 GHz

Typical transition frequencies: few GHz

Millikelvin temperatures (dilution fridge)
$1\text{GHz} \Leftrightarrow 50\text{ mK}$

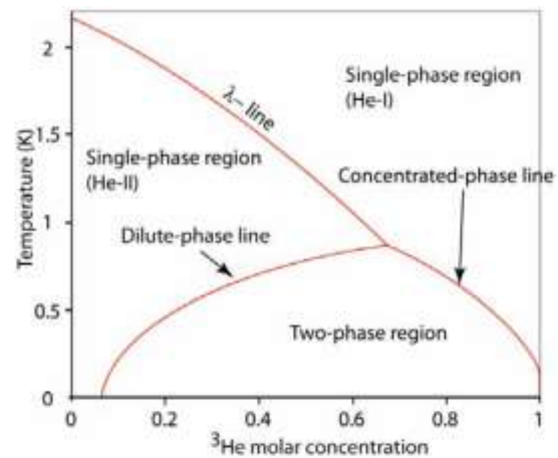
→ Experimental challenges:
Ultralow-power measurements & millikelvin cryotechnology

Dilution refrigerator

Continuous cooling method using a liquid mixture of ^{3}He and ^{4}He

→ Phase separation below $\simeq 900\ \mathrm{mK}$
(Concentrated & dilute phase)

→ In dilute phase $\simeq 6\%$ ^{3}He even for $T \to 0$

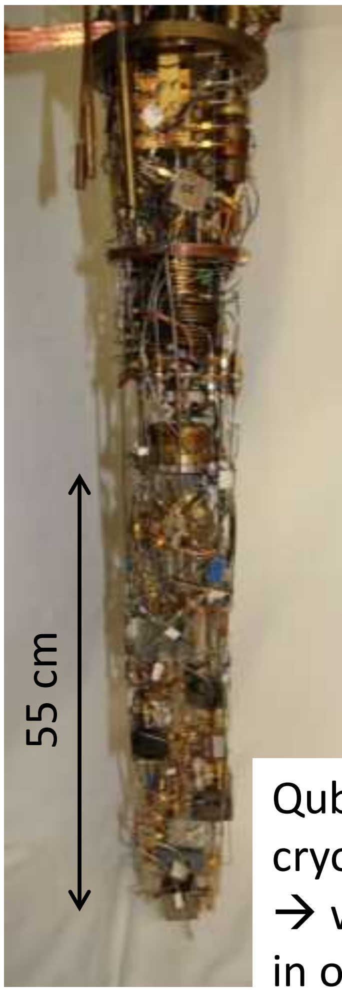


→ Pump on dilute (heavy) phase
→ Remove mainly ^{3}He
→ 3He has to diffues from concentrated phase over the phase boundary
→ Cooling power (heat taken from environment)

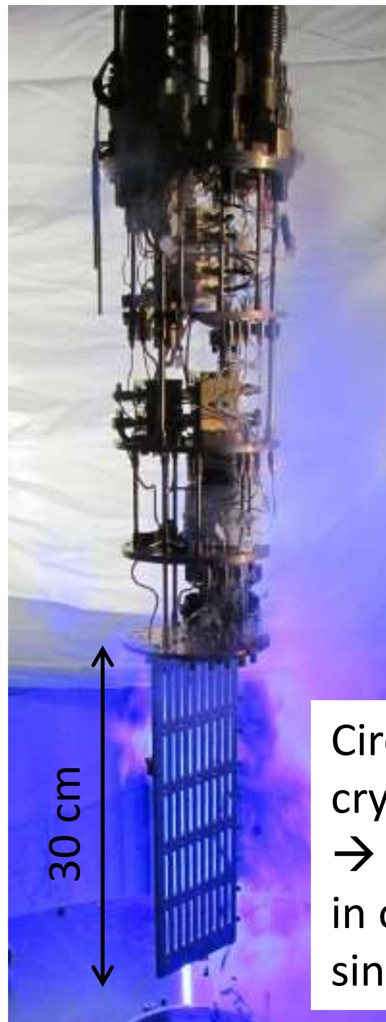
→ Can easily reach $20 - 50\ \mathrm{mK}$ → Suitable for investigating quantum junctions

Dilution refrigerator

WMI-made microwave-ready dilution refrigerators



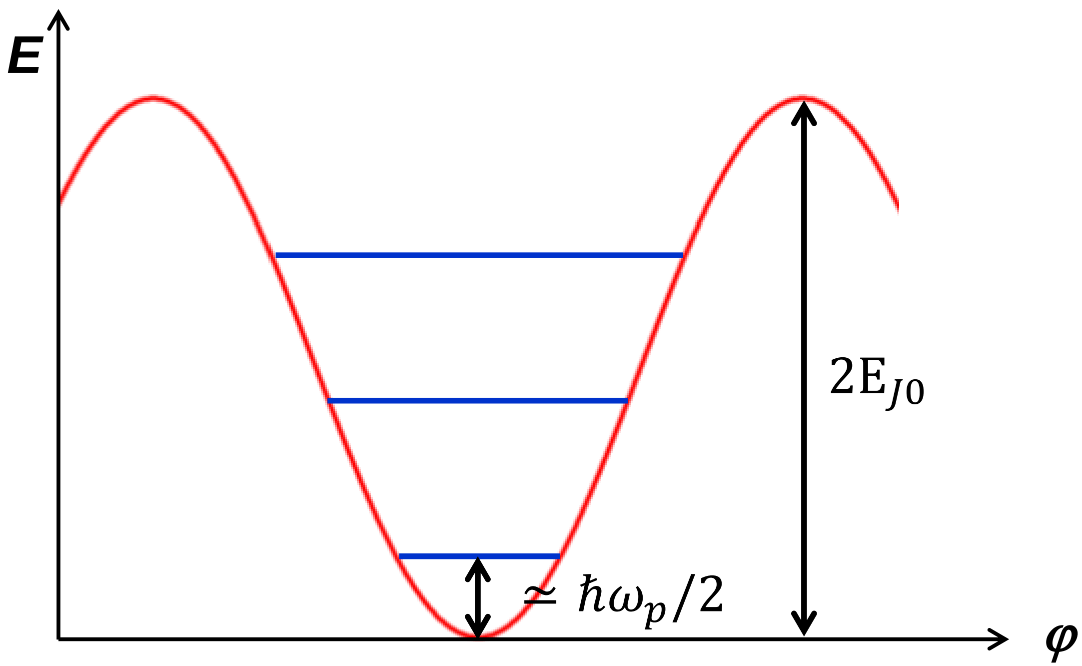
Qubit lab wet cryostat → wired and in operation



Cirqus lab wet cryostat → wired and in operation since 2013

K21 lab dry cryostat (very large) → in operation since 2014

Repetition – When is a junction "quantum"?



Classical junction

→ $\frac{E_{J0}}{\hbar\omega_p} \approx \sqrt{\frac{E_{J0}}{E_C}} \gg 1$

→ Dense level spacing (quasi-continuum)

Quantum junction

→ $\sqrt{\frac{E_{J0}}{E_C}} \propto A$

→ Small junction (typically submicron dimensions)

→ Making quantum junctions is demanding from a technological point of view

→ Advanced nanofabrication techniques required!

Materials for superconducting circuits

Typical superconductors

→ Nb
- → Type-II superconductor, $T_c \approx 9\mathrm{K}$
- → Fast measurements at 4K possible
- → Shadow evaporation for nanoscale junction not possible

→ Al
- → Type-I superconductor, $T_c \approx 1.5\mathrm{K}$
- → Measurements require millikelvin temperatures
- → Shadow evaporation possible (stable oxide)

Normal metals

→ Mainly Au (no natural oxide layer)

→ For on-chip resistors and passivation layers

Dielectric substrates

→ Silicon, sapphire

→ Contribute to dielectric losses (T_1)

6.1 Fabrication of JJ for quantum circuits

Micro- and nanopatterning of superconducting circuits

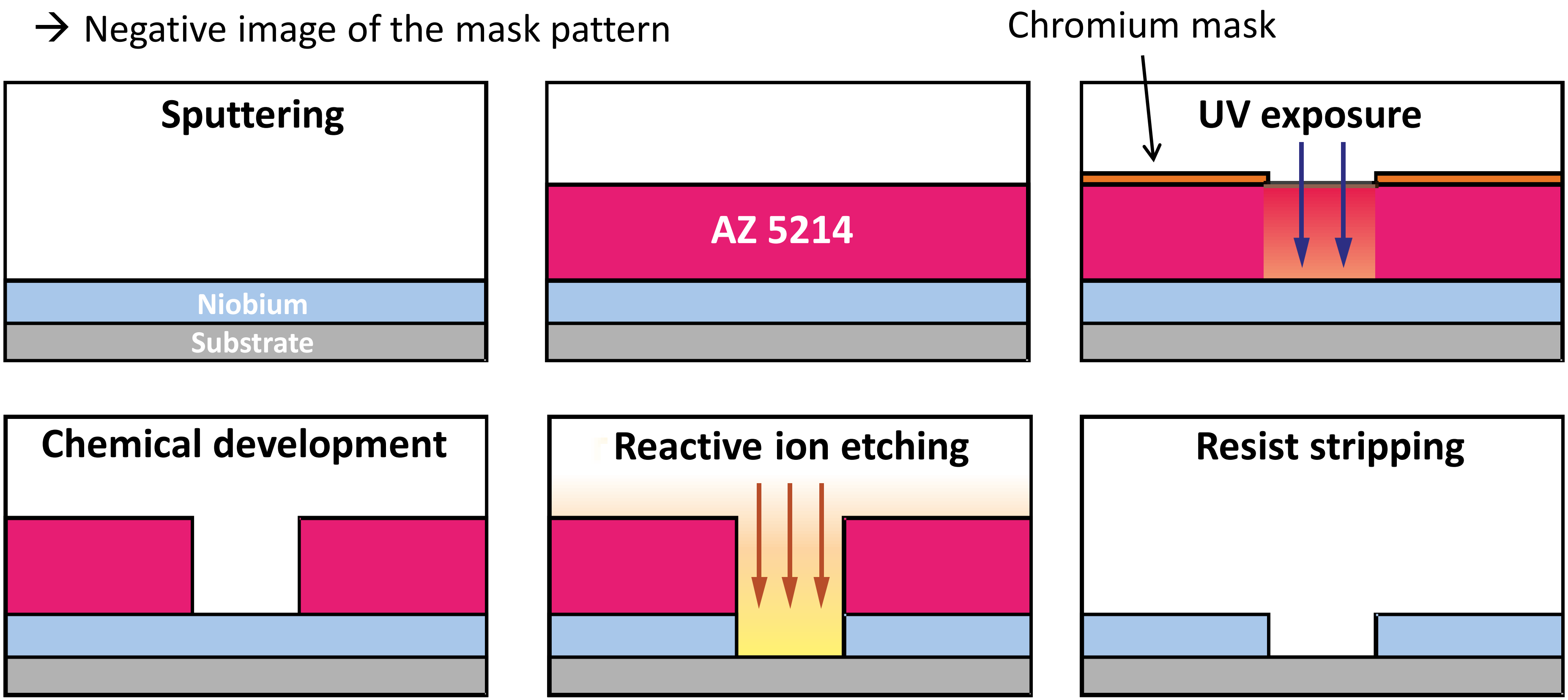
Lithography
→ Define pattern
→ Optical lithography (UV)
→ Electron beam lithography (EBL)

Thin-film deposition
→ Deposit materials
→ DC sputtering (metals)
→ RF sputtering (insulators)
→ Electron beam evaporation (metals)
→ Epitaxial growth (Molecular beam epitaxy)

Processing
→ Positive pattern → Lift-off
  → Deposit material only where you want it
→ Negative pattern → Etching
  → Deposit material everywhere
  → Remove what you don‘t want

Etching process

→ Negative image of the mask pattern



Submicron dimensions

→ EBL instead of optical lithography

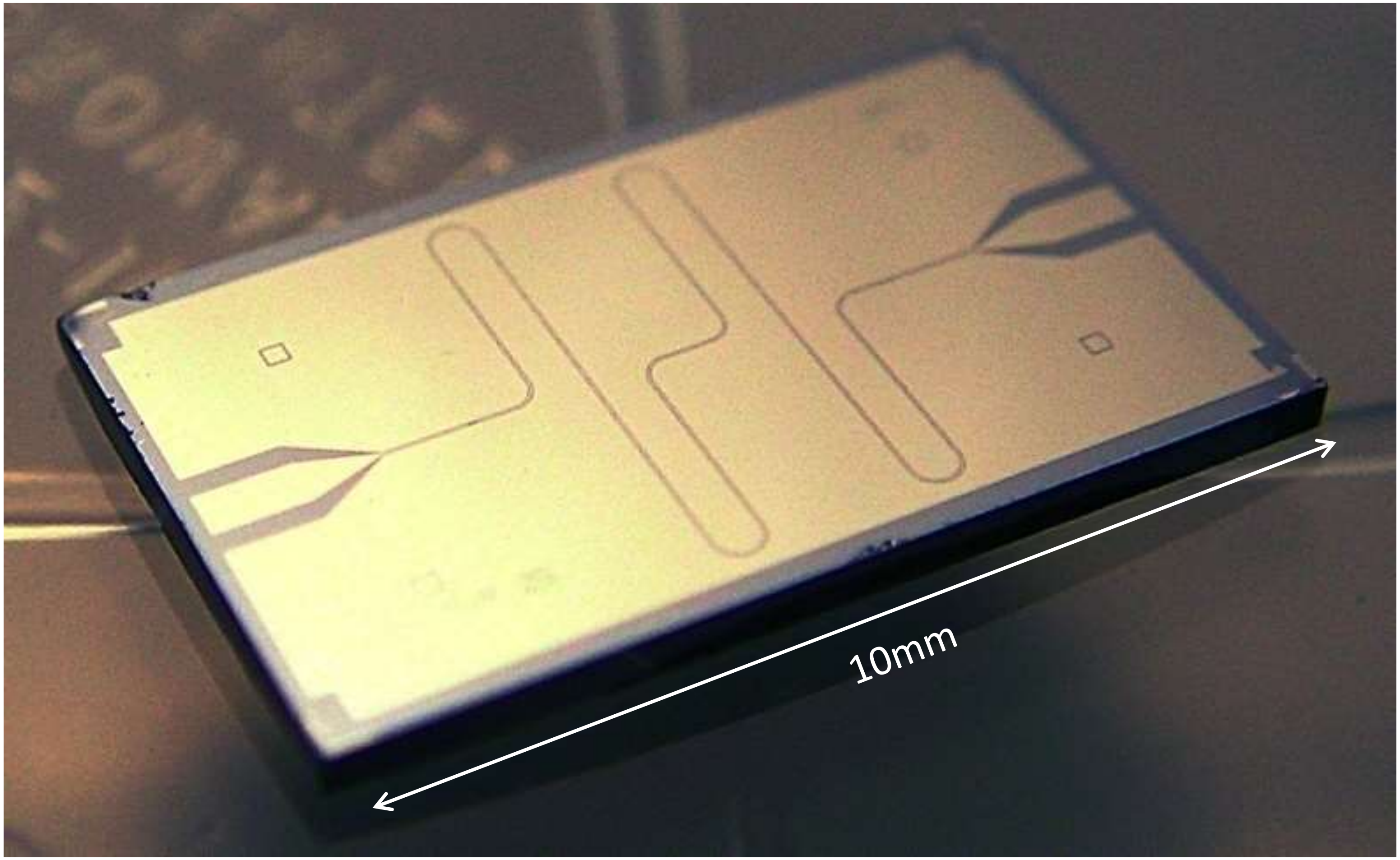
→ Same principle, but resist and exposure different

T. Niemczyk, *PhD Thesis* (2011)

Etching process

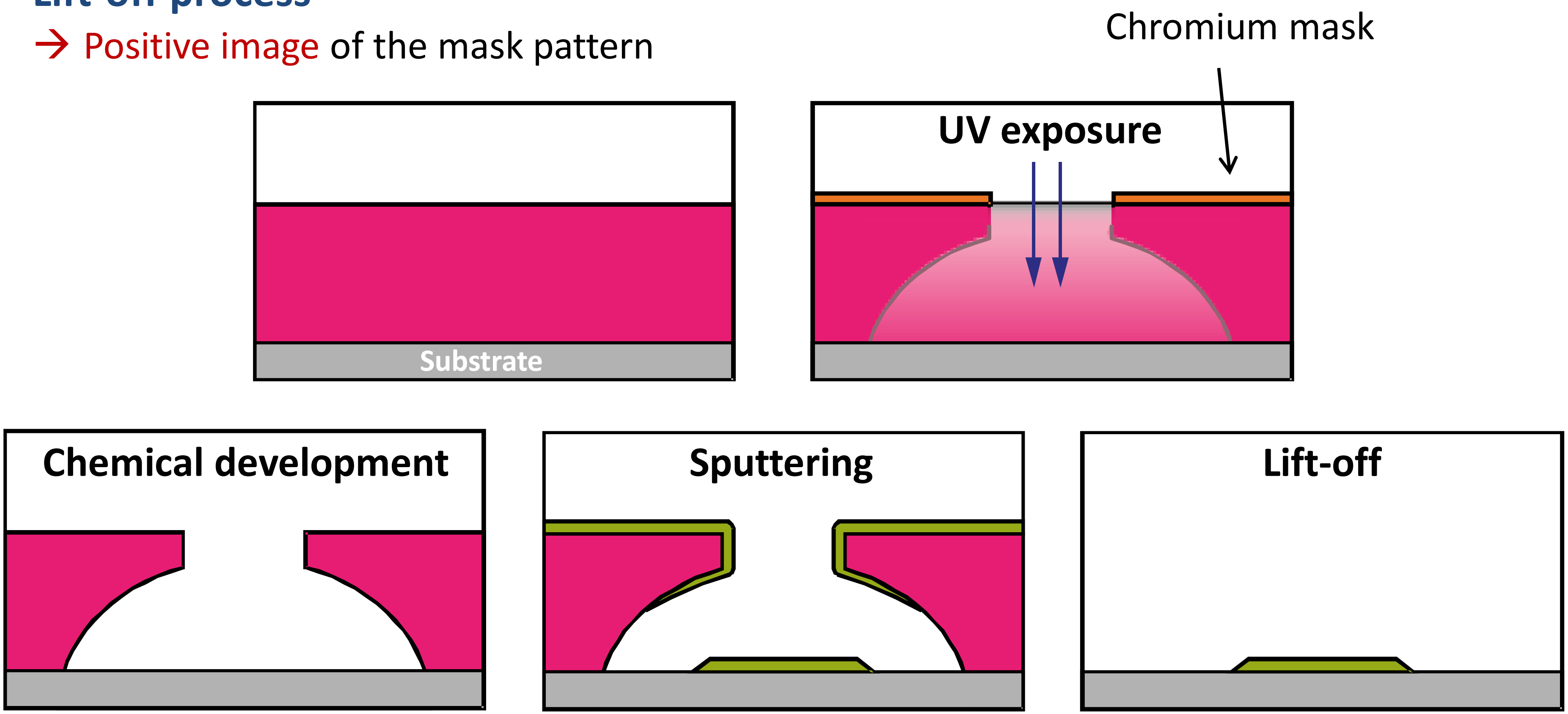
→ Example: Superconducting transmission line (Nb)

→ Etching technique for well-defined edges → Minimize microwave losses



Lift-off process

→ Positive image of the mask pattern



Submicron dimension

→ EBL instead of optical lithography

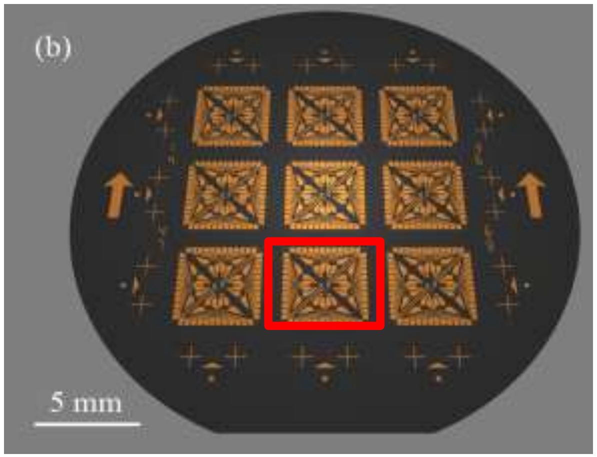
→ Same principle, but resist and exposure different

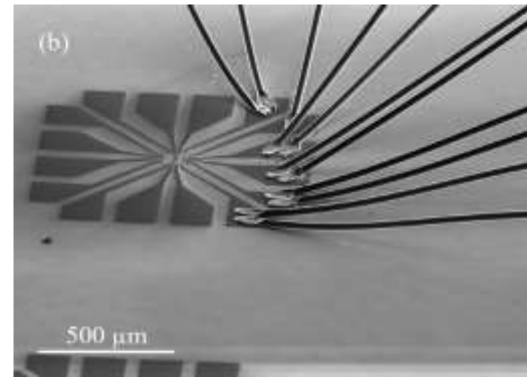
T. Niemczyk, *PhD Thesis* (2011)

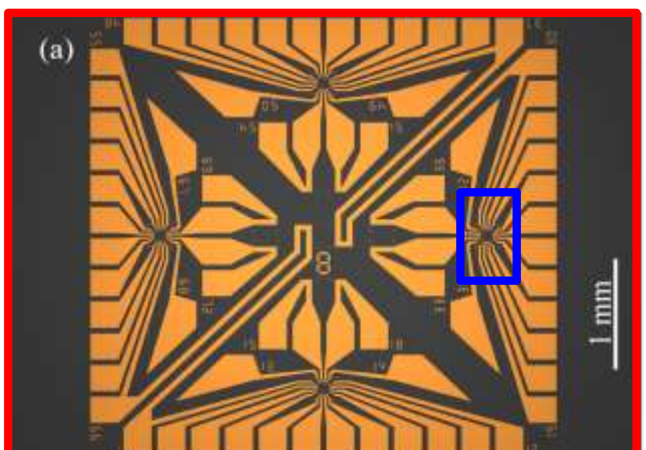
6.1 Fabrication of JJ for quantum circuits

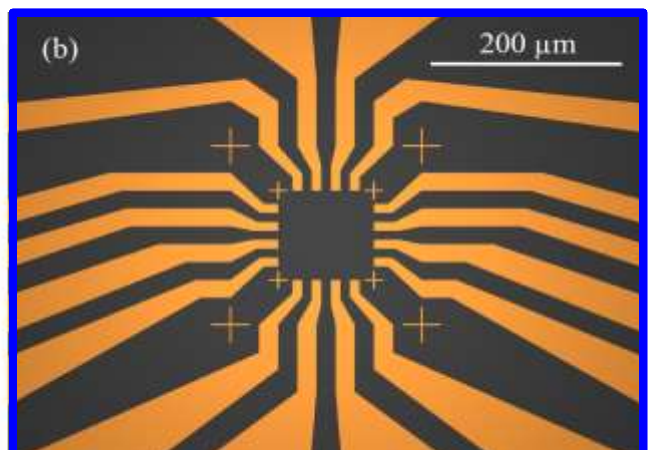
Lift-off process

→ **Example:** Au on-chip wiring for Al junctions and SQUIDs









Etching vs. Lift-off process

	Lift-off	etching
Well-defined edges (no „teeth“)	−	+
Resist choice independent from film growth process	−	+
Remaining substrate undisturbed	+	−

Challenges in micro- and nanofabrication

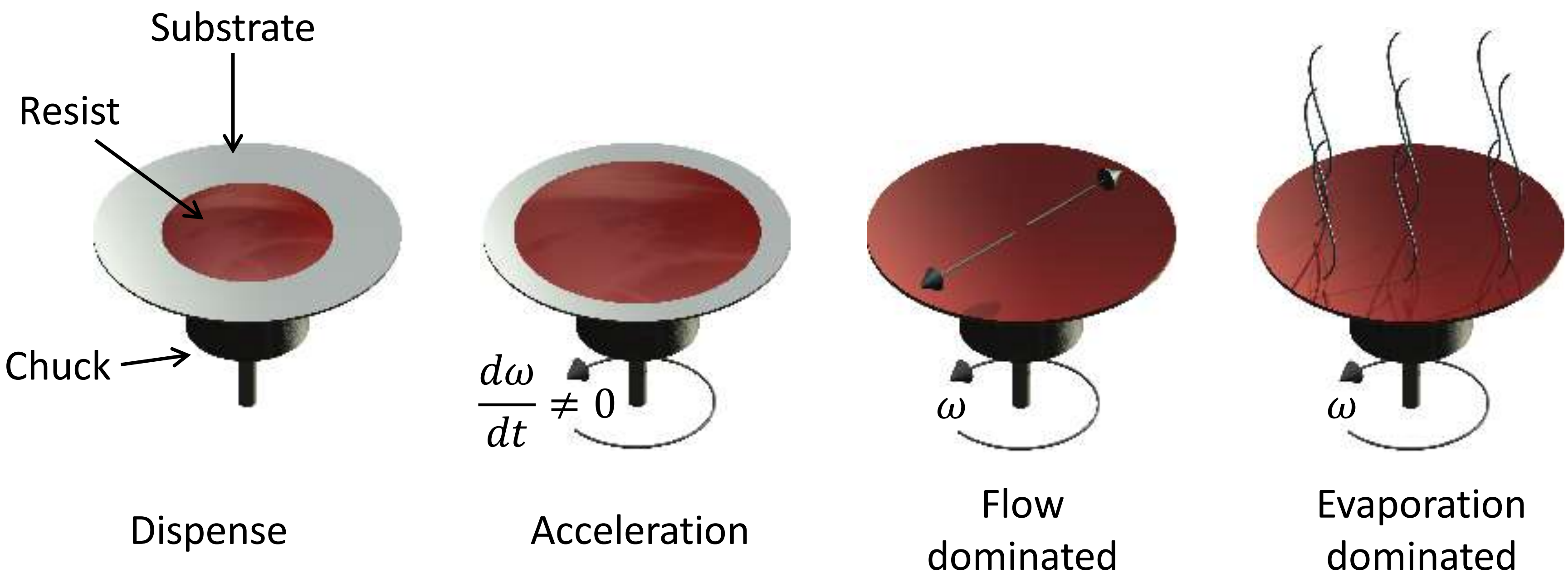
→ Complex procedure with large parameter space
→ Optimization requires controlled and reproducible conditions
→ Cleanroom
  → Low number of dust particles due to special filters & air conditioning
  → Controlled temperature and humidity
→ Small changes to a working process can have a huge impact on the result
  → Highly systematic step-by-step approach mandatory!

Spin coating

Goal → Cover substrate with uniform layer of lithography resist

Principle

→ Distribute resist drop by fast rotation of the substrate
→ Substrate is held in place by vacuum chuck



F. Sterr, *Diploma Thesis* (2011)

6.1 Fabrication of JJ for quantum circuits

Simple spin coating model

Complex process → Simplifying assumptions

→ No resist solvent evaporation
→ Infinitely large substrate
→ Applied liquid radially symmetric
→ Gravitation and Coriolis effects negligible
→ Newtonian liquid (linear shear forces)
→ Appreciable shear resistance only in horizontal planes

$$F_{\text{centrifugal}} = F_{\text{viscous resisting}}$$

$$\rho\omega^2 r = -\eta \frac{\partial^2 v_r}{\partial z^2}$$

ρ → resist density
η → resist viscosity
v_r → radial velocity
h → liquid surface

Integrate with boundary conditions $v_r(z=0) = 0$ and $\left.\frac{\partial v_r}{\partial z}\right|_{z=h} = 0$

$$v_r = \frac{\rho\omega^2 r}{\eta}\left(-\frac{z^2}{2} + hz\right)$$

A. G. Emslie *et al.*, J. of Appl. Phys. **29**, 858-862 (1958)

Overview

$$v_r = \frac{\rho\omega^2 r}{\eta}\left(-\frac{z^2}{2} + hz\right)$$

Radial flow per unit length of circumference

$$q_r = \int_0^h dz\, v_r = Krh^3 \qquad K \equiv \frac{\rho\omega^2}{3\eta} \qquad q_\theta = \mathrm{q_z} = 0$$

Equation of continuity (cylindrical coordinates)

$$\frac{\partial h}{\partial t} = -\boldsymbol{\nabla}\begin{pmatrix} q_r \\ q_\theta \\ q_z \end{pmatrix} = -\frac{1}{\mathrm{r}}\frac{\partial(rq_r)}{\partial r} = -\frac{K}{r}\frac{\partial}{\partial r}(r^2h^3)$$

$$\boldsymbol{\nabla F}(r,\theta,z) = \frac{1}{r}\frac{\partial(rF_r)}{\partial r} + \frac{1}{r}\frac{\partial F_\theta}{\partial\theta} + \frac{\partial F_z}{\partial z}$$

Strong tendency to flatten for arbitrary initial surfaces → $h(r,t) = h(t)$

$$h(t) = \frac{h_0}{\sqrt{1 + 4Kh_0^2 t}} \qquad h_0 \equiv h(t=0) \text{ is initial thickness}$$

Include evaporation → Practical importance, more complicated model

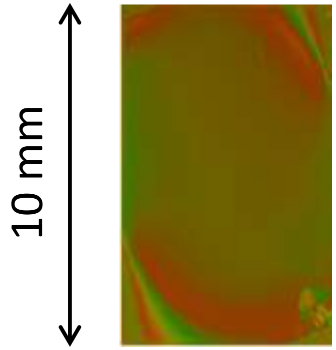
Typical thickness → $50\mathrm{nm} - 1\mu\mathrm{m}$

A. G. Emslie *et al.*, J. of Appl. Phys. **29**, 858-862 (1958)

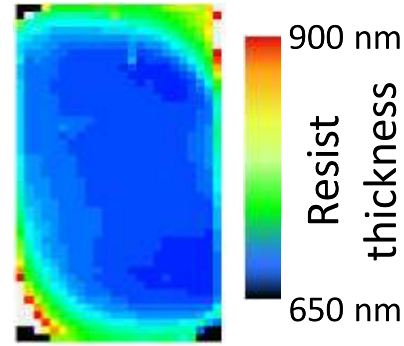
Resist surface defects

Edge beads

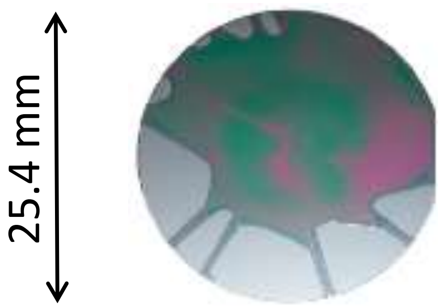
→ Real substrate has finite size
→ Resist thicker near substrate edges
→ Either removal with special mask
→ Or cut small chip after spinnig large substrate



Photograph



Reflectometry measurement

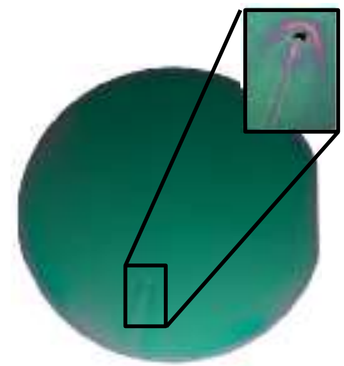


Fingers

→ Not enough resist volume

Air pockets

→ Resist not applied smoothly



Comets

→ Dirt particles on the substrate

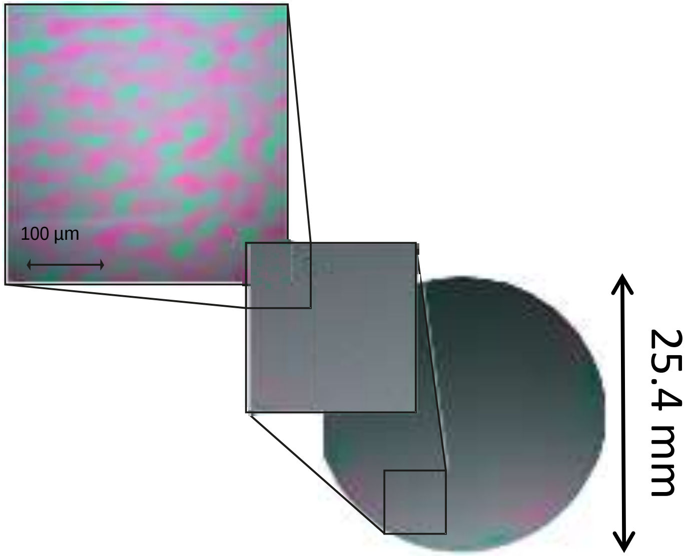
F. Sterr, *Diplom Thesis* (2013)

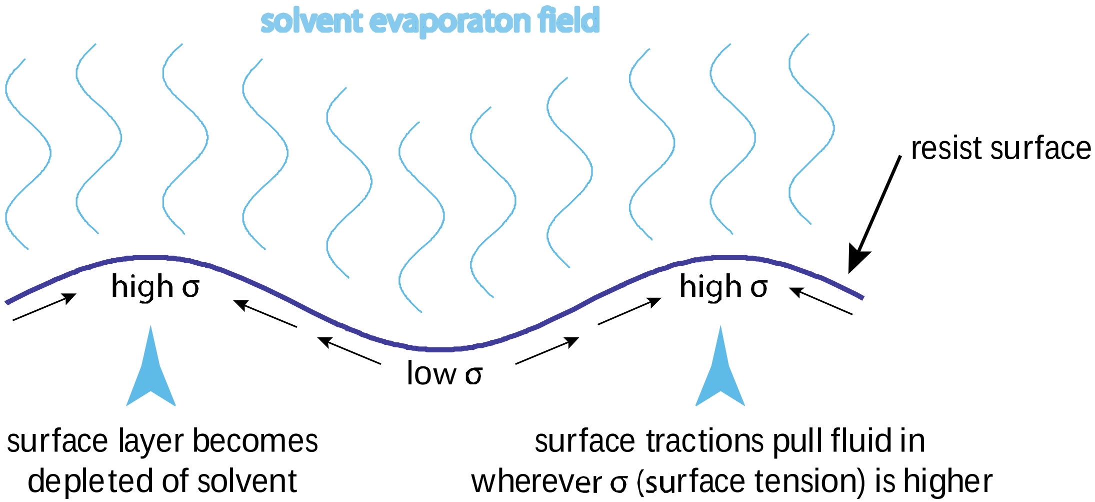
6.1 Fabrication of JJ for quantum circuits

Resist surface defects

Striations

→ Wavy radially oriented resist thickness fluctuations
→ Period: $50 - 200\mu\mathrm{m}$, height: few tens of nm
→ Local evaporation efficiency variations during the transisiton from the flow-dominated to the evaporation-dominated regime
→ Prevention: Increase spin speed, IPA atmosphere, careful resist handling





F. Sterr, *Diplom Thesis* (2013)

Limits of optical lithography

Abbe diffraction limit for far-field imaging systems

$$d = \frac{\lambda}{\underbrace{2(n \sin \theta)}_{\text{Numerical aperture (1.4 in modern optics)}}} \geq \frac{\lambda}{3}$$

λ → wave length
n → refractive index
θ → convergence angle
d → spot size

UV light → d is few hundreds of nm, in practice often $1 - 2\mu\text{m}$
→ Use accelerated electrons instead

Advantages

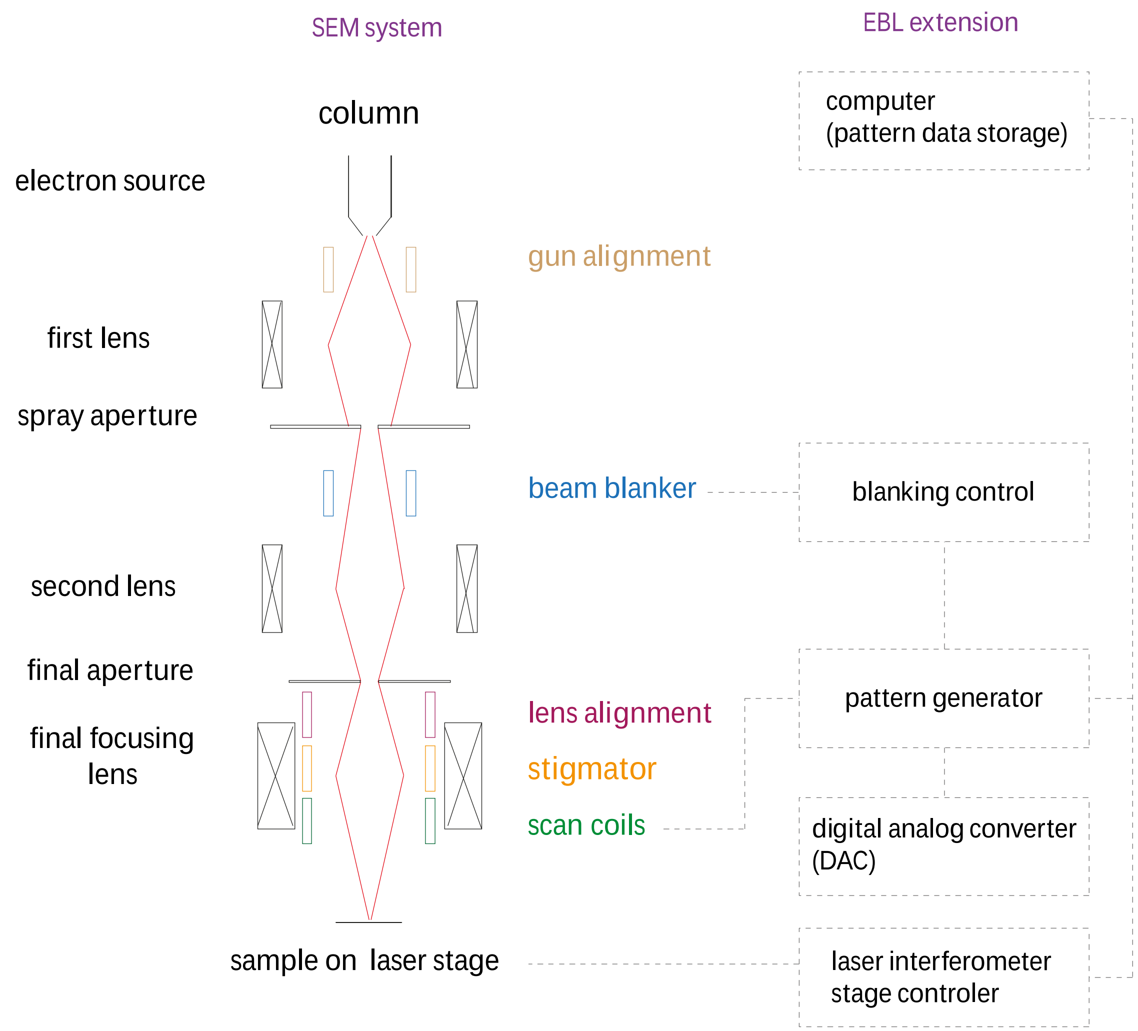
→ At 30 kV acceleration voltage $\lambda_e = h\sqrt{2eVm_e} \approx 0.007\text{nm}$
→ In practice, $d \approx 1$ nm because electrons interact with the substrate
→ "Electron optics" available (magnetic and electrostatic lenses)

Disadvantages

→ Technical complication
→ Lower throughtput
→ Higher cost of operation

Working principle of electron beam lithography (EBL)

Old WMI EBL system: Philipps scanning electron microscope (SEM) XL30sFEG extended with a Raith laser stage



F. Sterr, *Diplom Thesis* (2013)

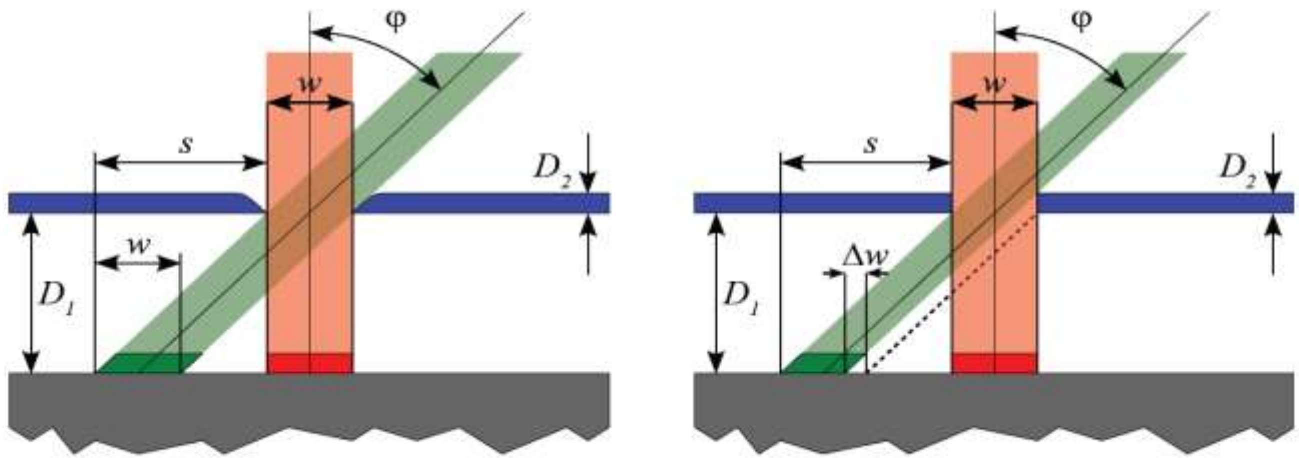
Working principle of electron beam lithography (EBL)

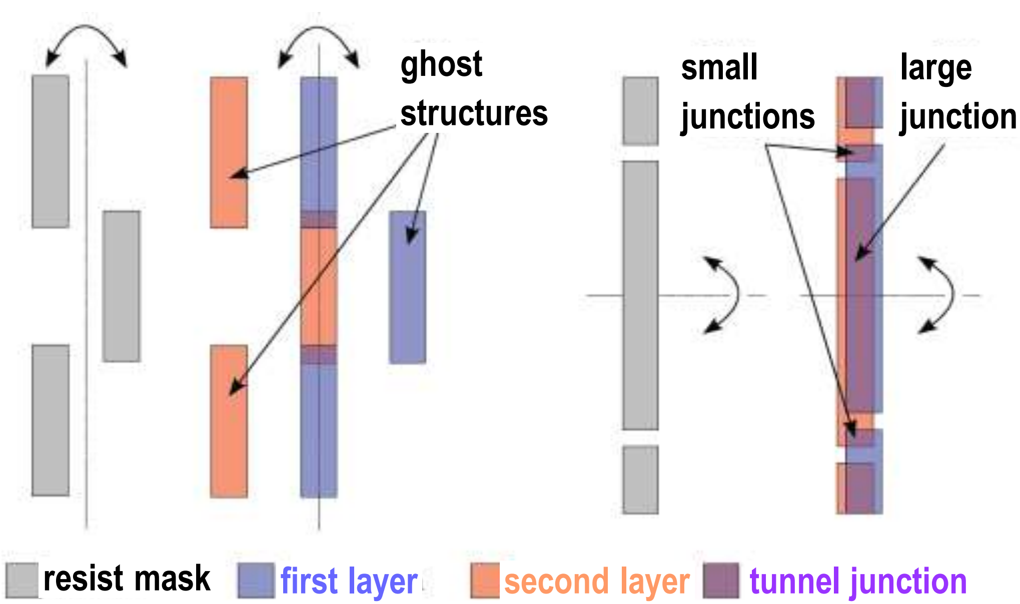
New WMI EBL system

→ Nanobeam nb5
→ Up to $100\ \mathrm{kV}$ acceleration voltage
  → Strongly reduced „natural“ undercut from backscattered electrons
  → Undercut now deliberately designed during the process
→ Large beam current → Fast
→ Few nm resolution (in practice mostly resist limited)
→ Heavily automated (operated „from the office“)
  → Advantage: fewer user-dependent parameers in the process
  → Better reproducibility

Shadow evaporation

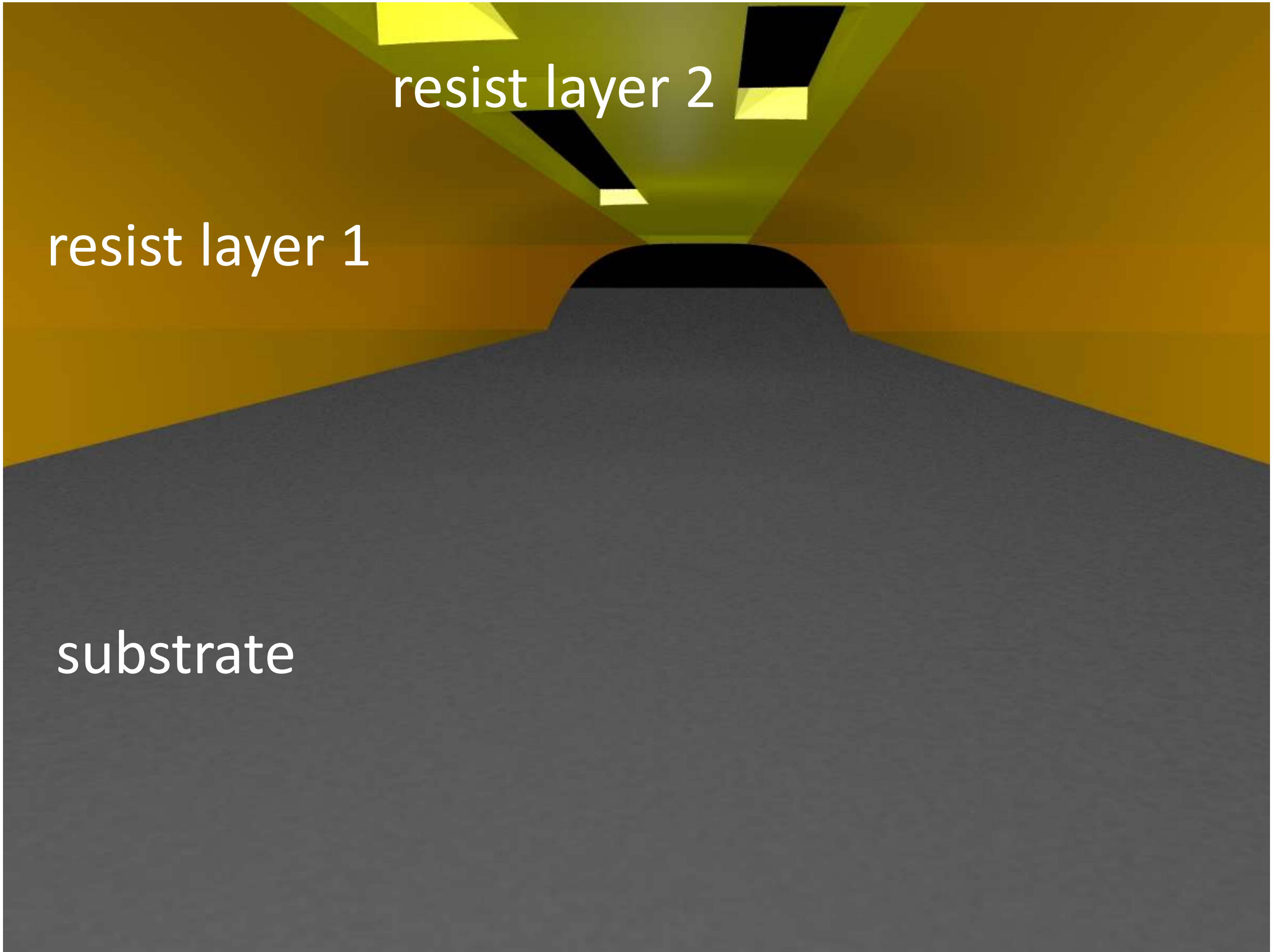
Key fabrication technique for $Al/AlO_x/Al$ Josephson junctions with submicron lateral dimensions





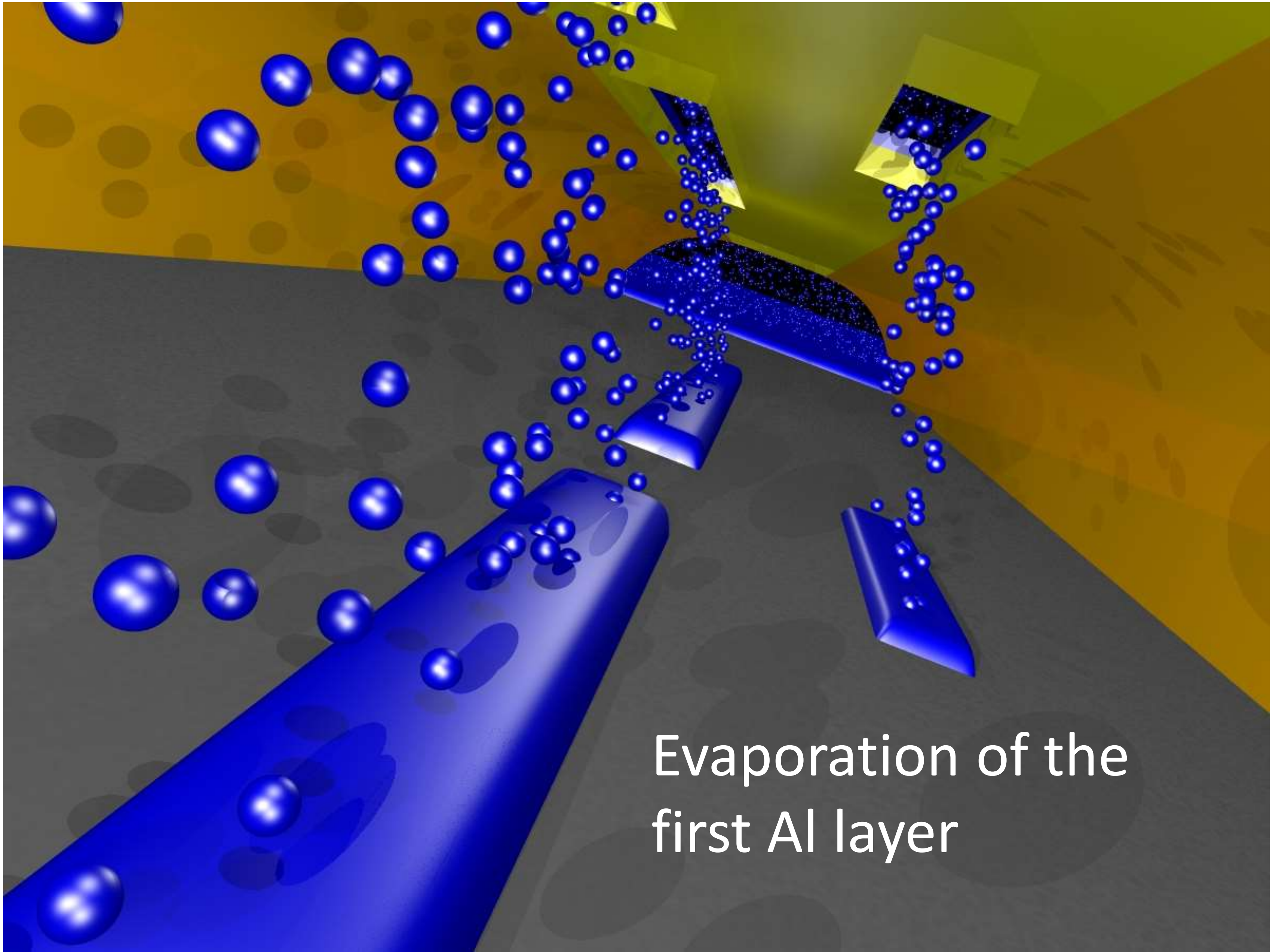
J. Schuler, *PhD Thesis* (2005)

6.1 Fabrication of JJ for quantum circuits

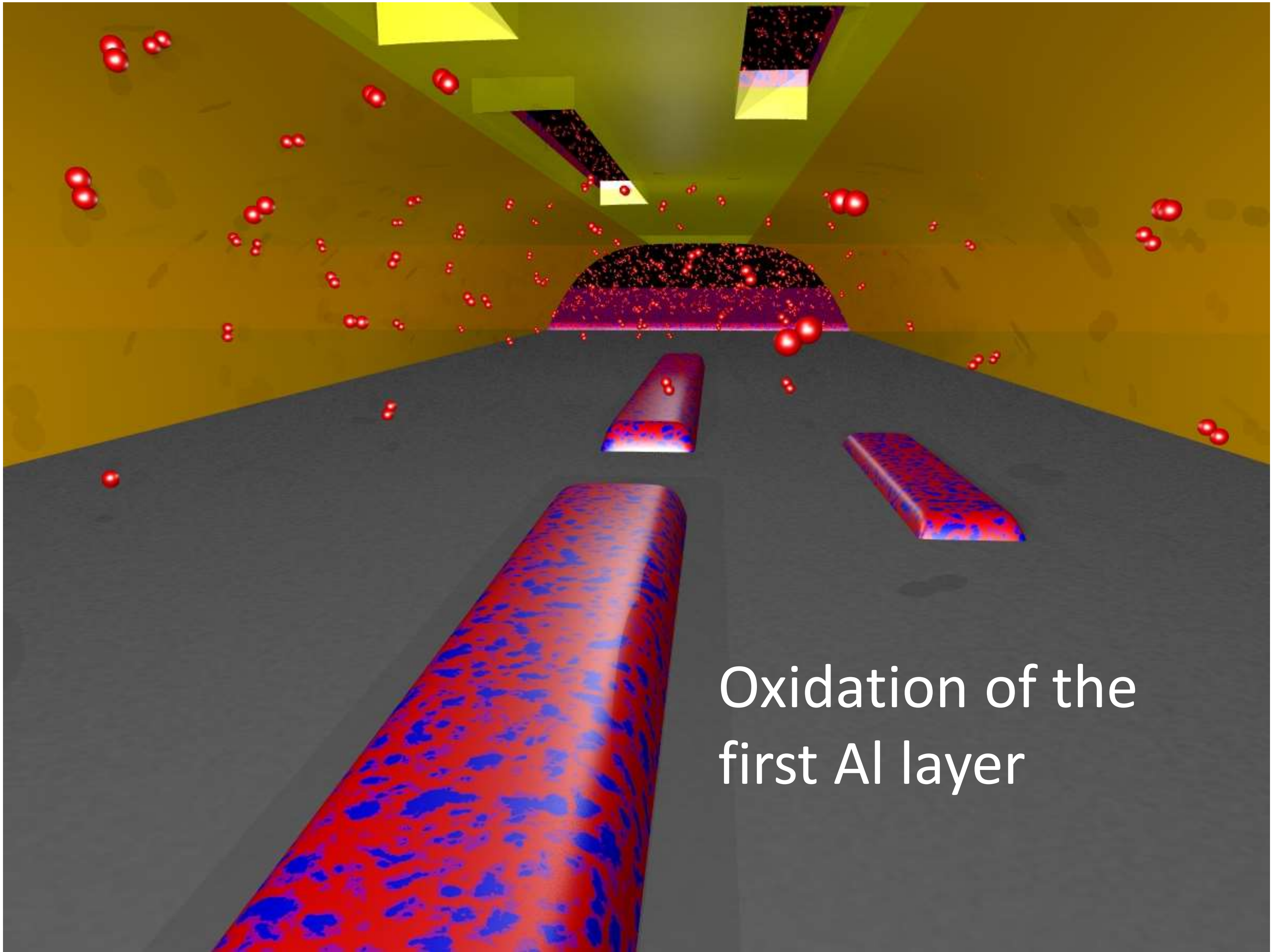


Courtesy of J. Schuler

6.1 Fabrication of JJ for quantum circuits



Courtesy of J. Schuler



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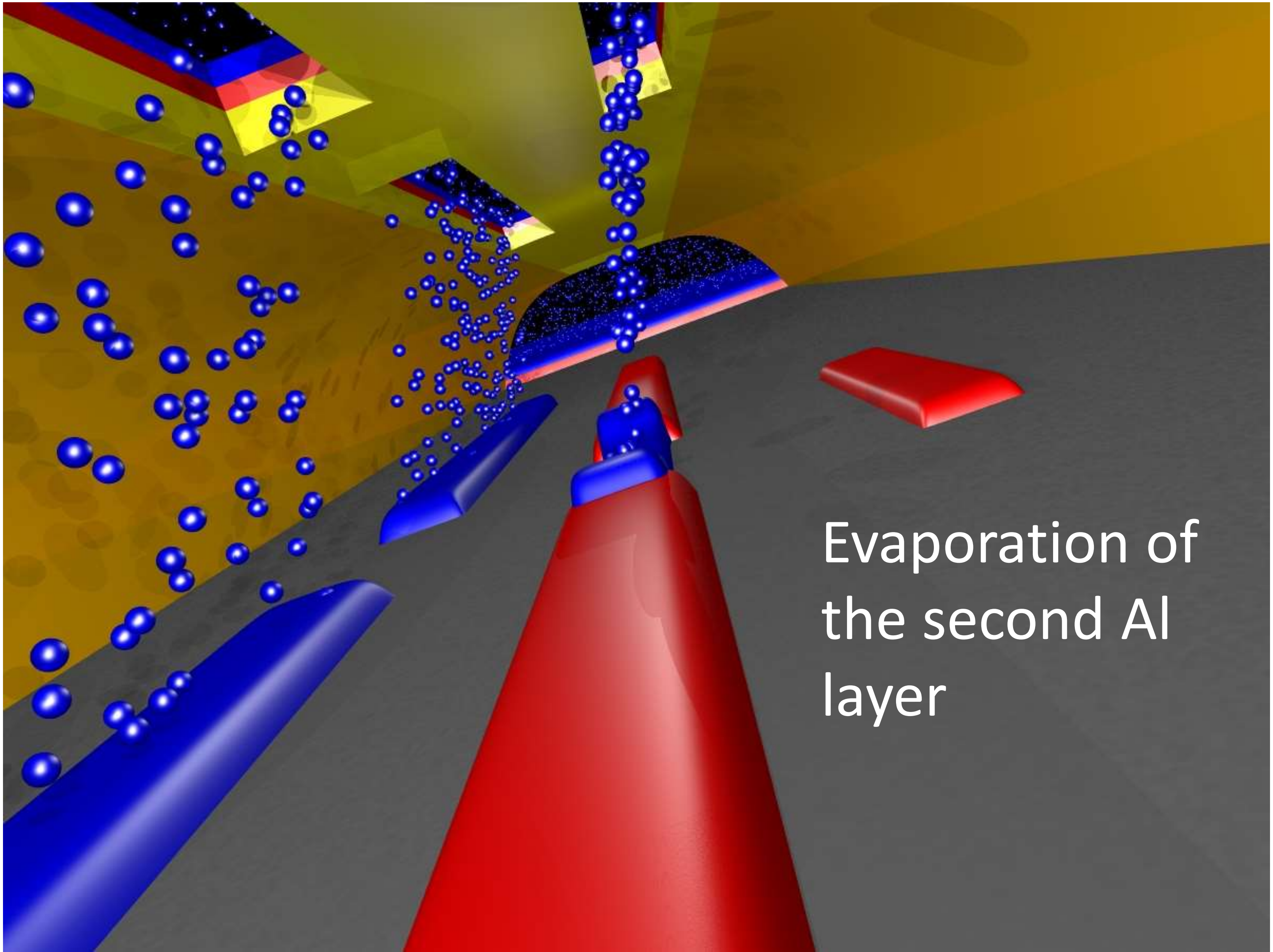
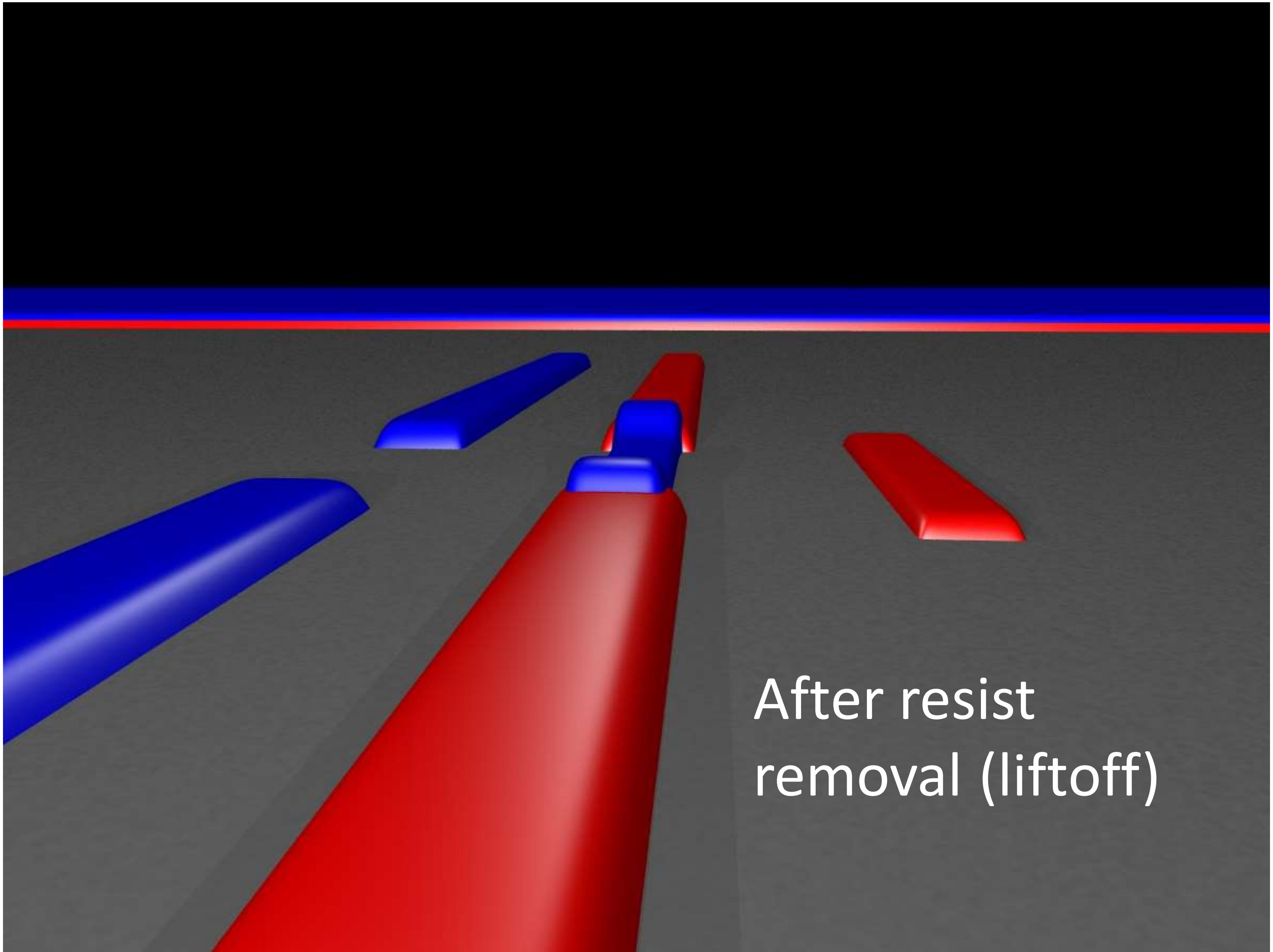


Courtesy of J. Schuler

6.1 Fabrication of JJ for quantum circuits

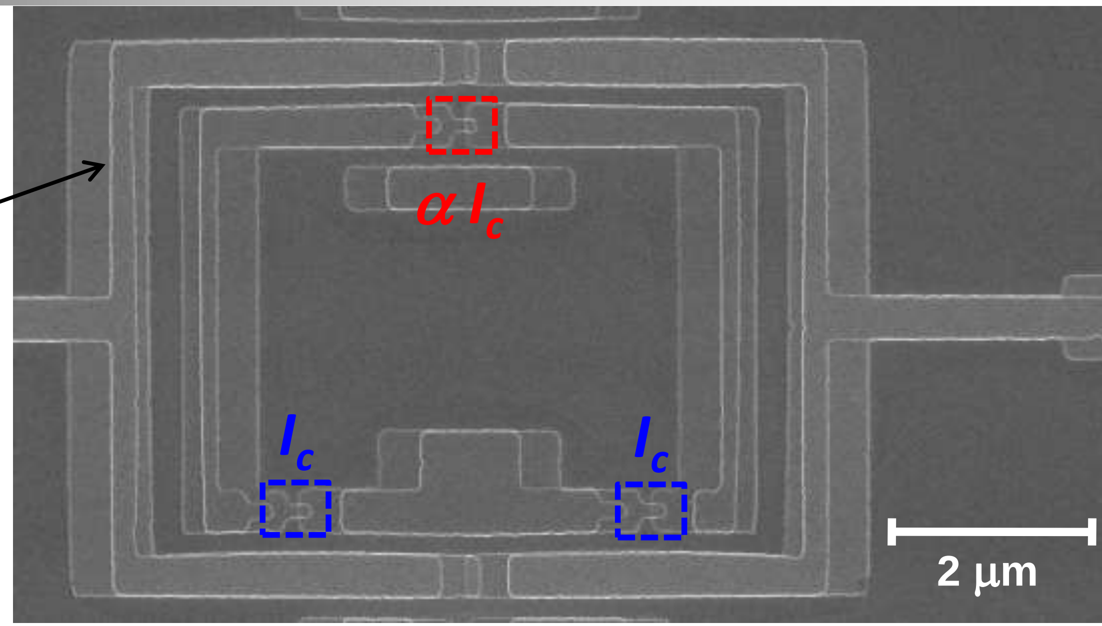


Courtesy of J. Schuler

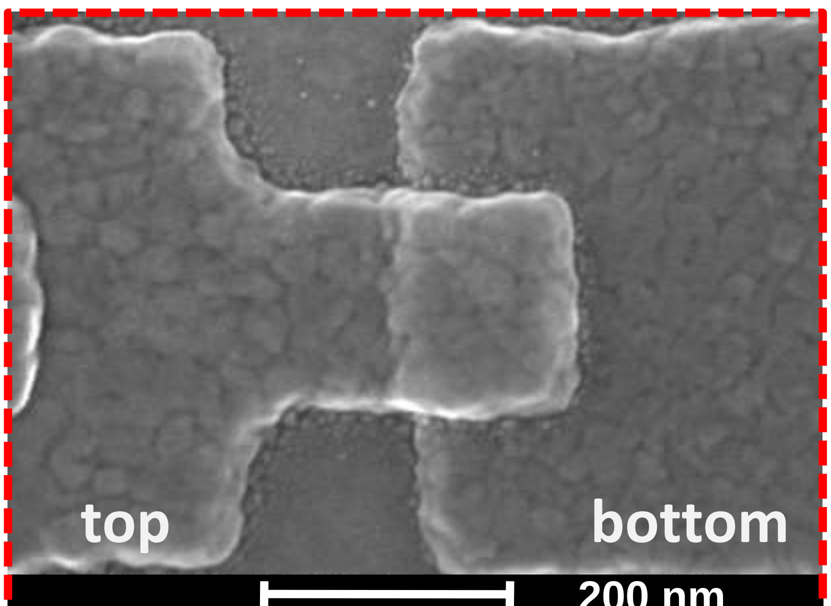
6.1 Fabrication of JJ for quantum circuits

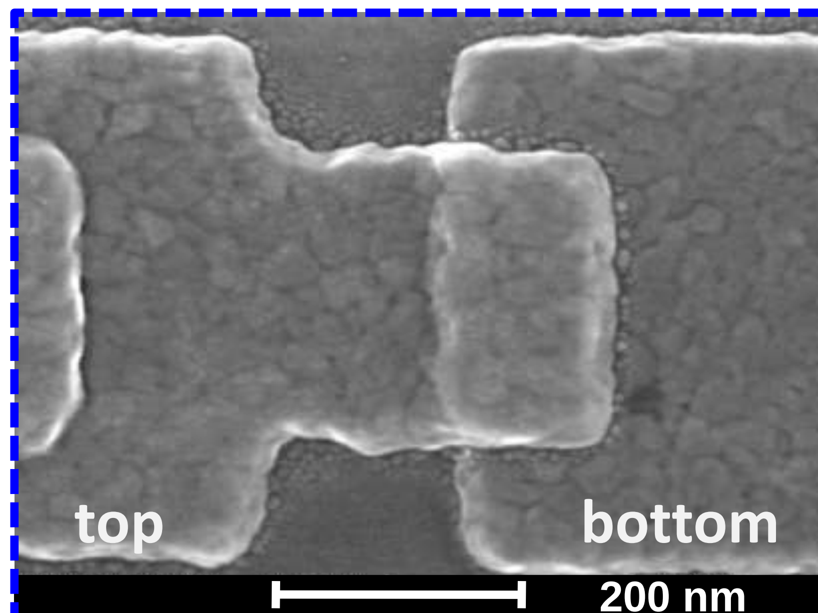
Shadow evaporation of a superconducting flux qubit

Dc SQUID (readout)



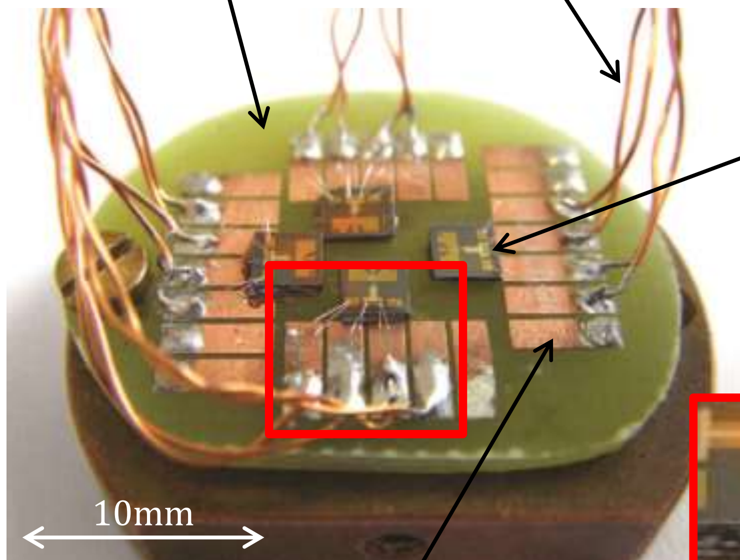
F. Deppe *et al.*,
Phys. Rev. B **76**, 214503 (2007)
T. Niemczyk et al.,
Supercond. Sci. Technol. **22**, 034009 (2009)

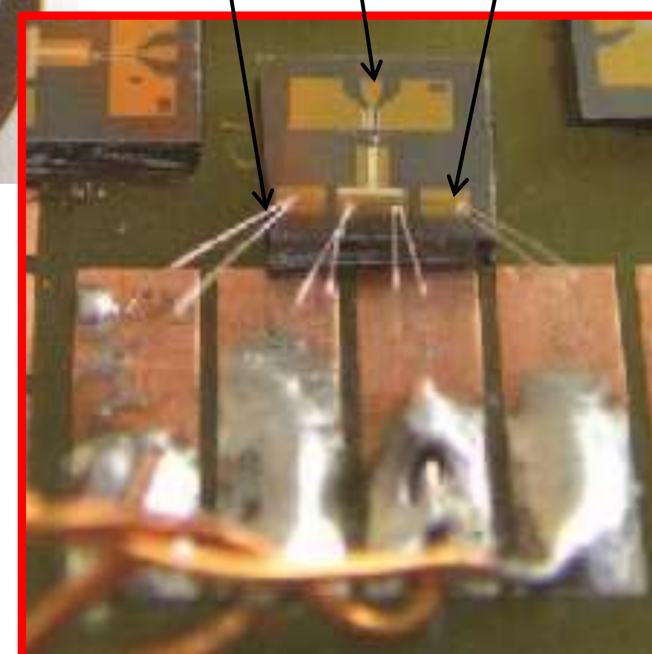




T. Niemczyk, *PhD Thesis* (2011)

Connection techniques





Wire bonding

→ Connect on-chip and off-chip measurement circuit
→ Typically made by thin Al or Au wires or ribbons (diameter $\simeq 25\ \mu$m)
→ Bond wire melted onto contact pad via ultrasonic burst