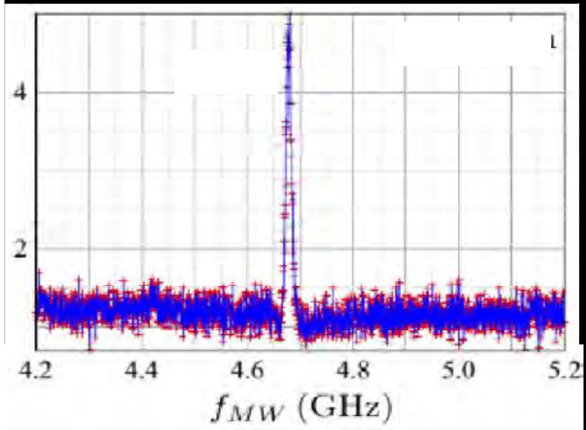
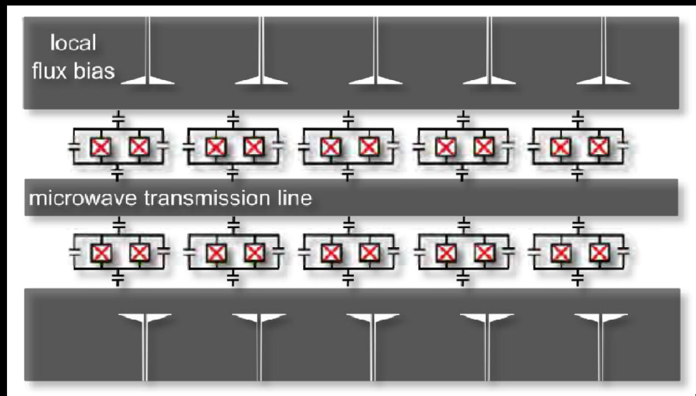
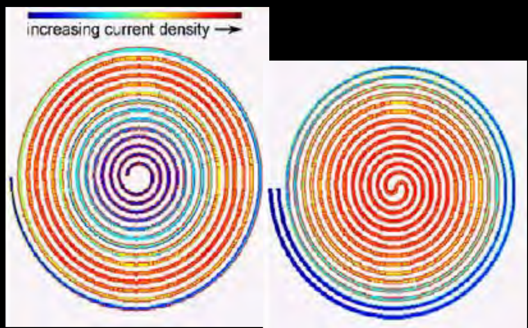
Quantum bits based on superconducting circuits

Martin Weides, Karlsruhe Institute of Technology

$|0\rangle \leftrightarrow |1\rangle$







Brief history experimental SC qubits

1999 Charge (NEC)+flux (Delft) qubits

2002 Phase qubit (NIST)

2004 cQED with qubits (Yale)

2007 Lasering (NEC)

QND (Delft)

2008 Fock states (UCSB)

2009 Grover and Deutsch–Jozsa (Yale)

Arbitrary quantum states (UCSB)

Bell inequality (UCSB)

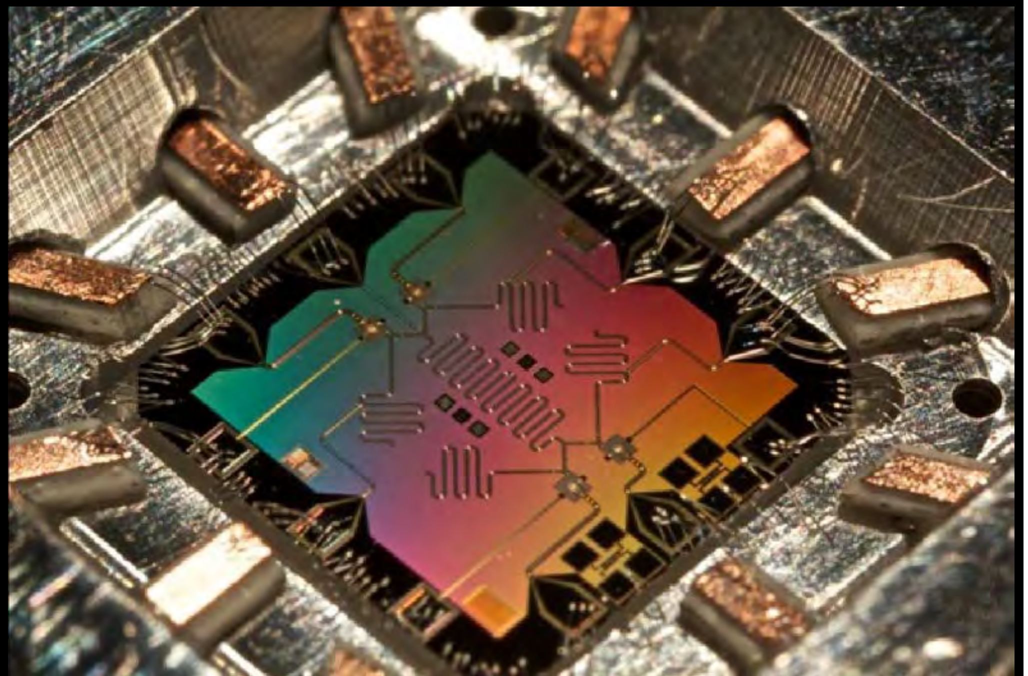
2010 3-qubit entanglement (UCSB & Yale)

2011 Quantum von Neumann architecture (UCSB)

2012 4 qubits and

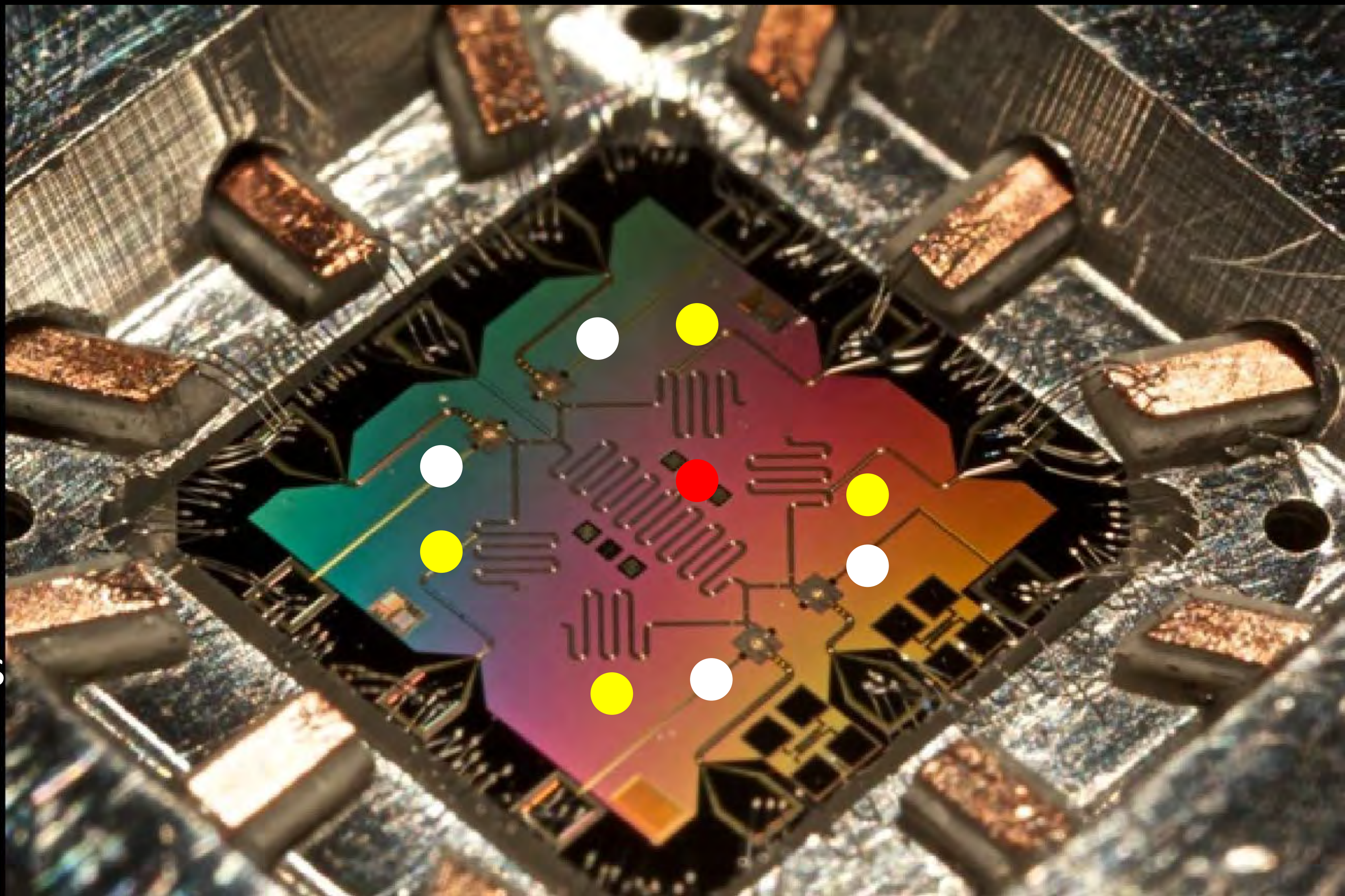
5 resonators (UCSB)

Shor, '15=5x3'



Microstructured quantum processor

(University of California, Santa Barbara)



- Qubit
- Memory
- Signalbus

5 mm

Lucero *et al.*, Nature 2012

Basic potentials

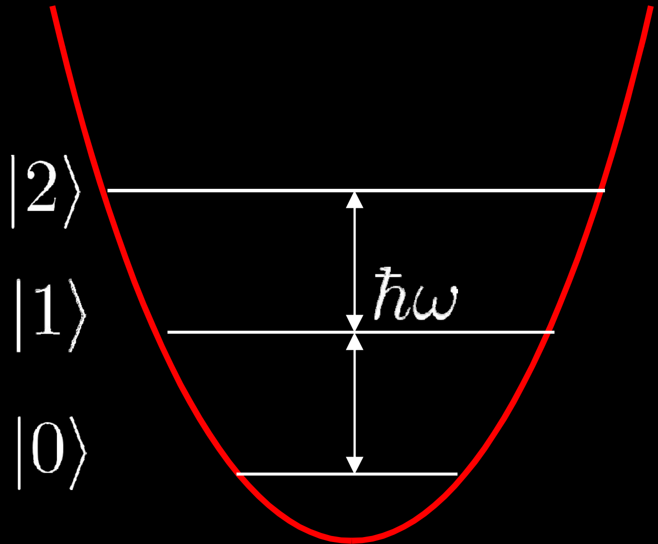
Harmonic oscillator

Photons in cavity, atom oscillation

Energy levels equidistant

Energy eigenstate $|n\rangle$

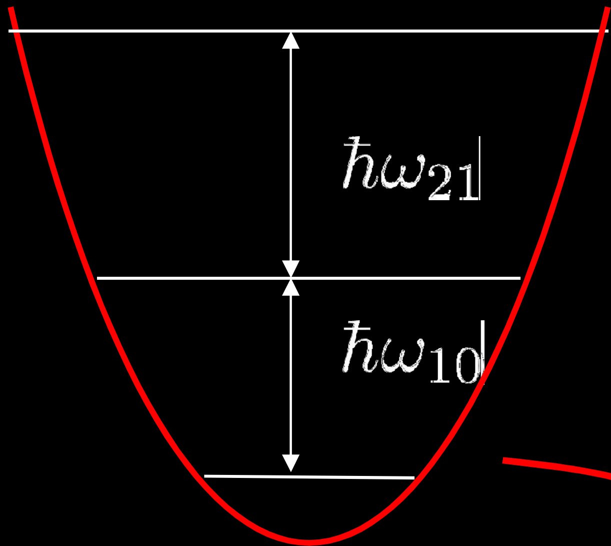
$$\hat{H}_{\mathrm{cavity}} = \left(a^\dagger a + \tfrac{1}{2}\right)\hbar\omega$$



Anharmonic oscillator

Large excitation amplitudes

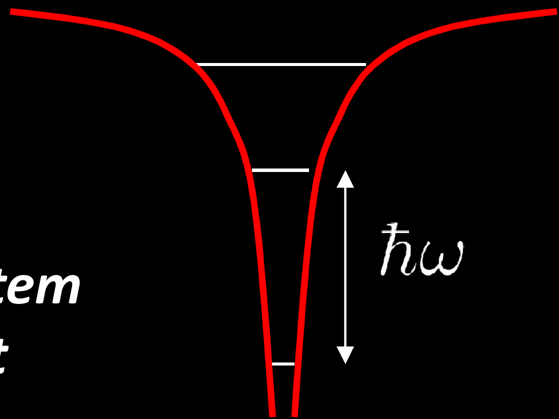
$$\Delta = \omega_{n+1,n} - \omega_{n,n-1}$$



Two level system

if $|\Delta/\omega| >> 0$ → ***two level system***

atomic transition, spin, qubit



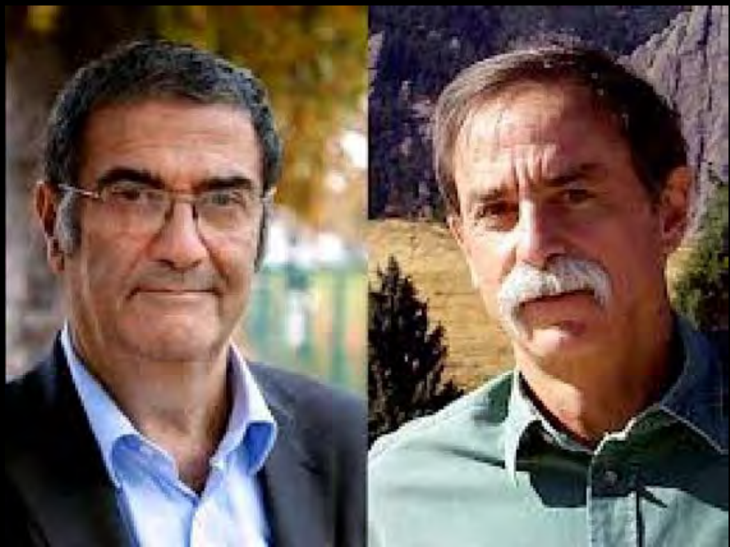
$$\hat{H}_{\mathrm{TLS}} = \hbar\omega\frac{\hat{\sigma}_z}{2}$$

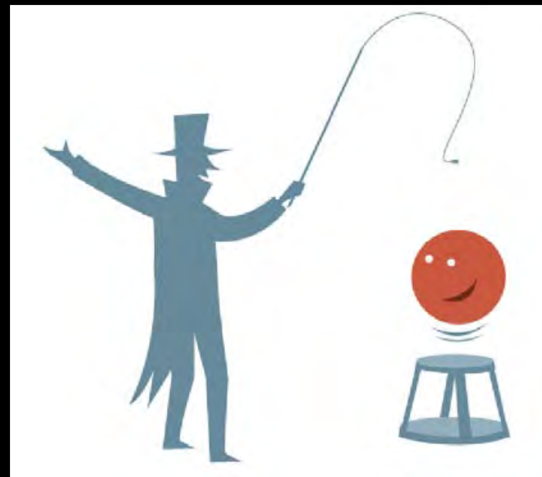
Nobel price 2012

Nobel Prize in Physics 2012 was awarded jointly to

Serge Haroche and David J. Wineland

"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"





Controlling a quantum particle (atoms or ions)

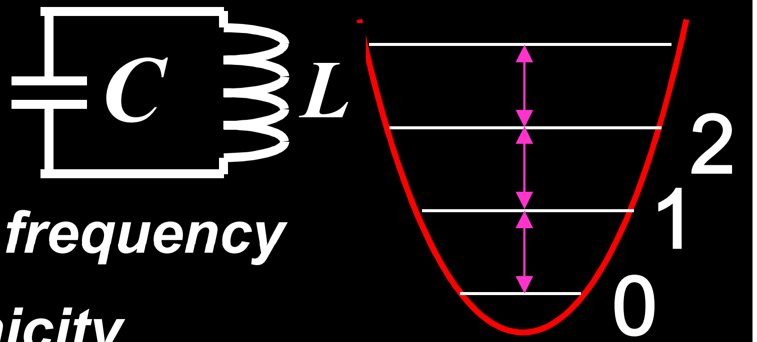
$$\hat{H} = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_a \frac{\hat{\sigma}_z}{2} + \frac{\hbar\Omega}{2}\hat{E}\hat{S}$$

Jaynes–Cummings
Cavity-qubit system

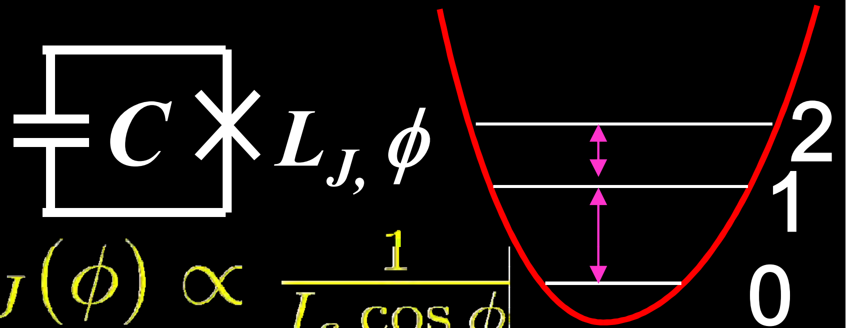
Quantum information processing, Q-simulation, collective Q-phenomena

Artificial atoms for quantum matter require

- Large interaction strength → ***dipole moment***
- Tunability → ***tune transition frequency***
- Frequency selection → ***large anharmonicity***
- Long coherence → ***low loss***
- High integration density → ***scalability***



linear LC oscillator



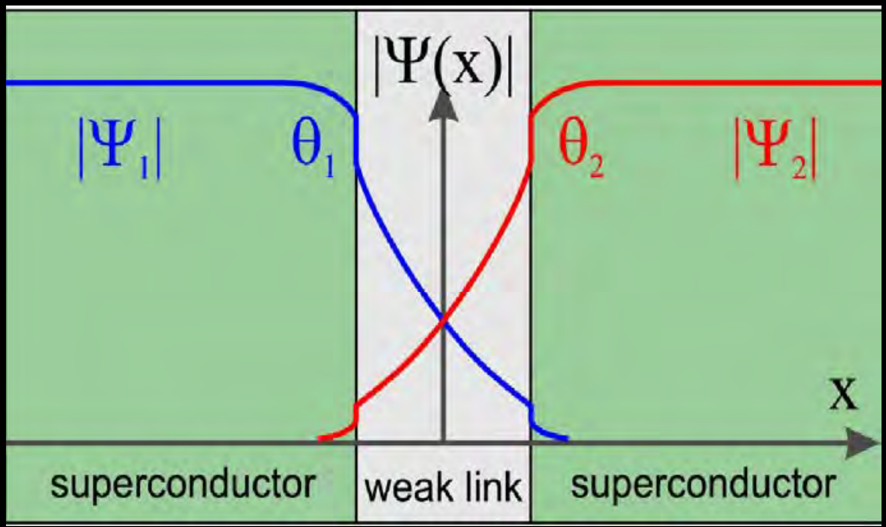
$$L_J(\phi) \propto \frac{1}{I_c \cos\phi}$$

non-linear LC oscillator

Superconducting quantum circuit

- Strong coupling w/ EM field, long coherence, fast & local detuning
- simple resonant circuit design, straightforward scalability
- high density, integration w/ std. electronics

Josephson junction → non-linear inductor



$$\Psi = |\Psi| \exp(i\theta)$$

Phase difference

$$\phi = \theta_1 - \theta_2$$

1st Josephson eq.: $I_J = I_c \sin\phi$ (DC)

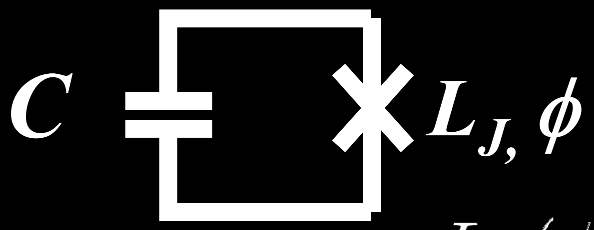
2nd Josephson eq.: $V = \frac{\Phi_0}{2\pi}\frac{\partial\phi}{\partial t}$ (AC)

From DC: $\frac{\partial I_J}{\partial\phi} = I_c \cos\phi$

Insert in AC: $V = \frac{\Phi_0}{2\pi}\frac{1}{I_c\cos\phi}\frac{\partial I_J}{\partial t} = L_J\frac{\partial I_J}{\partial t}$

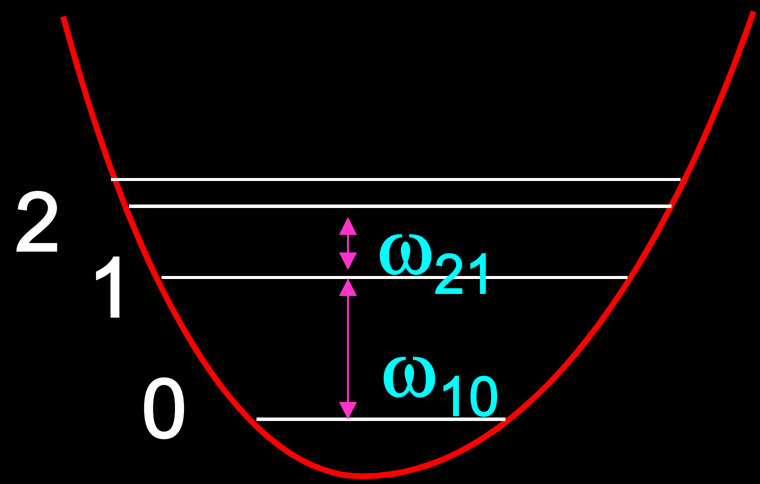
→ non-linear inductance: $L_J(\phi) = \frac{\Phi_0}{2\pi}\frac{1}{I_c\cos\phi}$

Capacitively shunted Josephson junction → Anharmonic oscillator

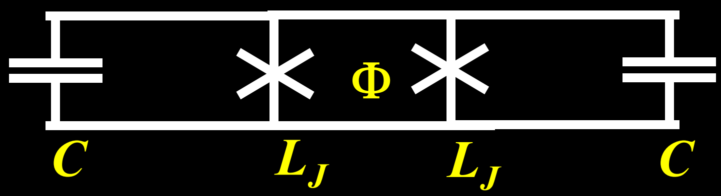


$$L_J(\phi) \propto \frac{1}{I_c \cos\phi}$$

non-linear LC oscillator

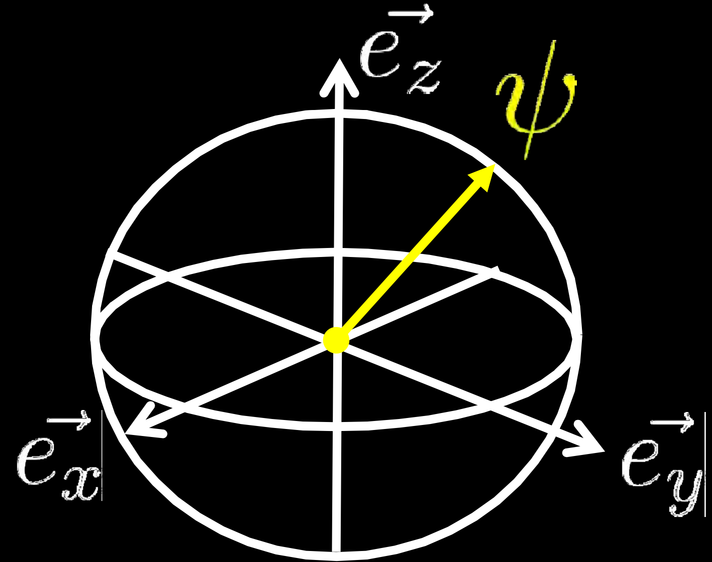


Restrict to two lowest states → **Bloch sphere**



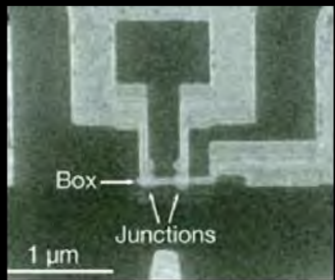
Magnetic flux Φ changes $L_J(\phi)$

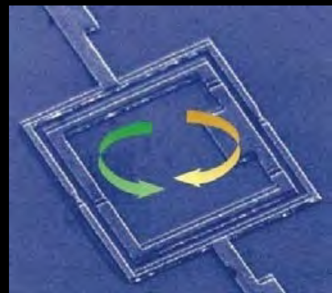
$$\omega_{10} = 1/\sqrt{C L_J(\Phi)}$$

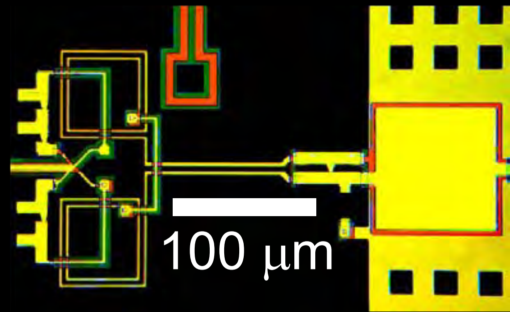


Superconducting qubit 'zoo'

	Charge	Flux	Phase
$[\hat{q}, \hat{\phi}] = i\hbar$			
$E_J/E_C = \frac{I_c \Phi_0}{2\pi} / \frac{e^2}{2C}$	1	10^2	10^4
Junction area (μm^2)	0.01	0.1-1	1-100

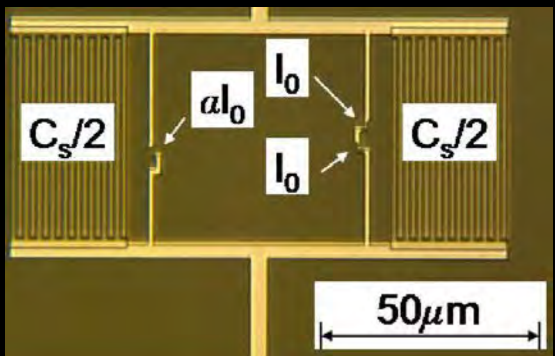




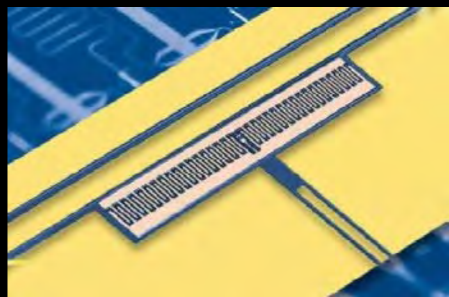


Modern designs

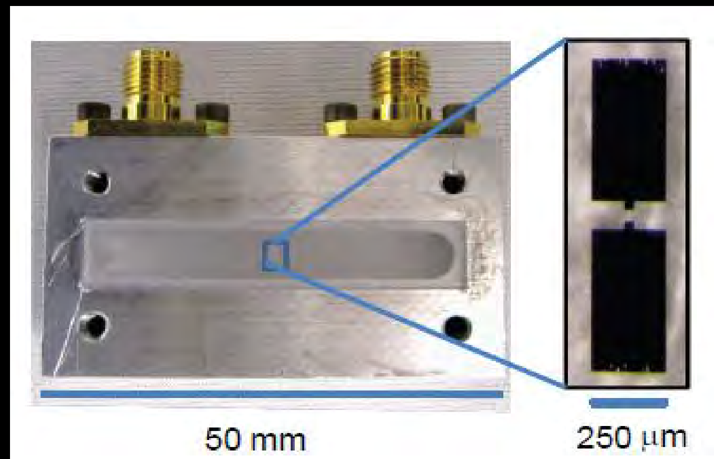
C-shunted flux qubit



Transmon=
C-shunted charge qubit



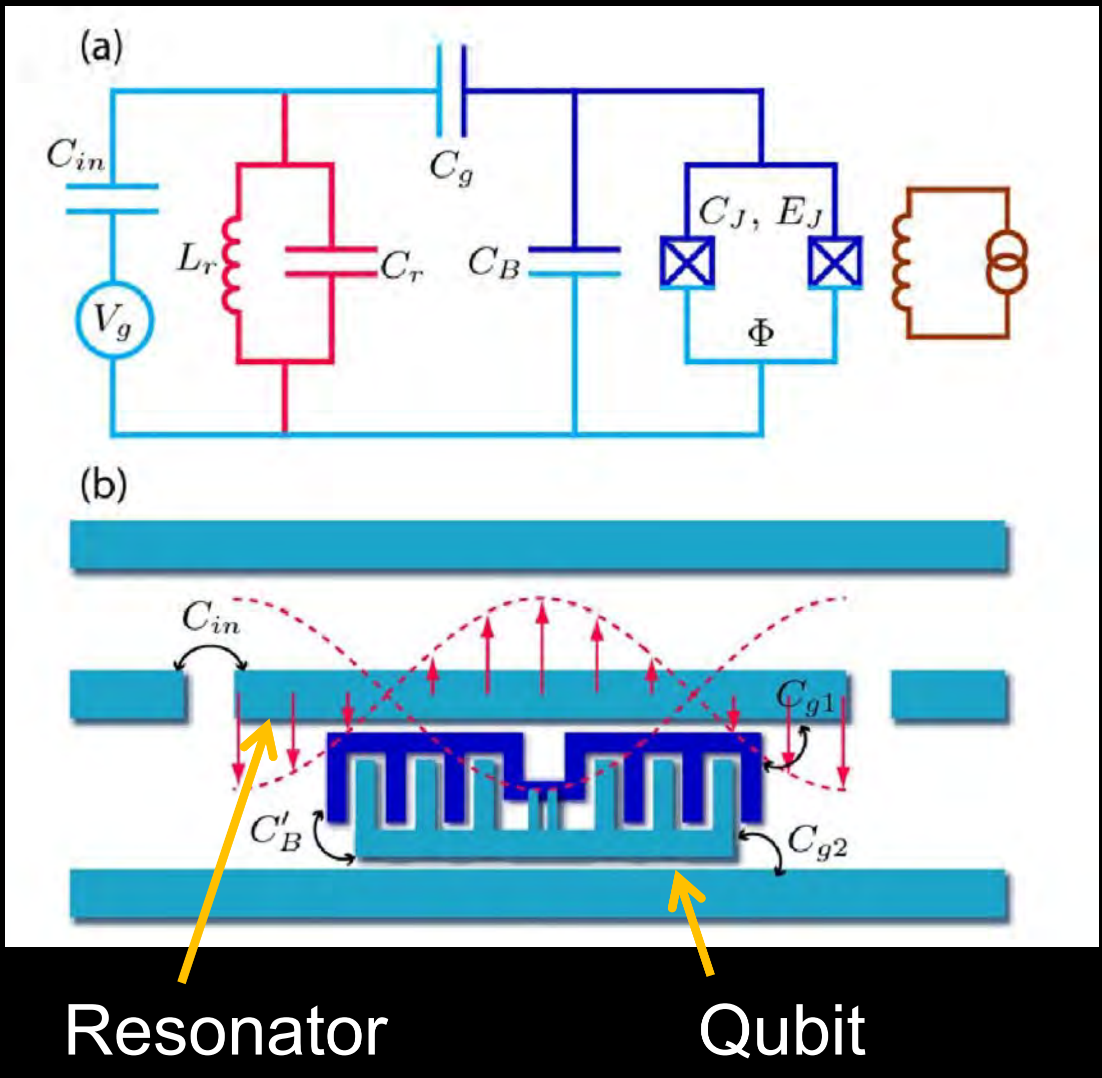
3d transmon



circuit quantum electrodynamics (cQED): artificial atom (qubit) coupled to resonator

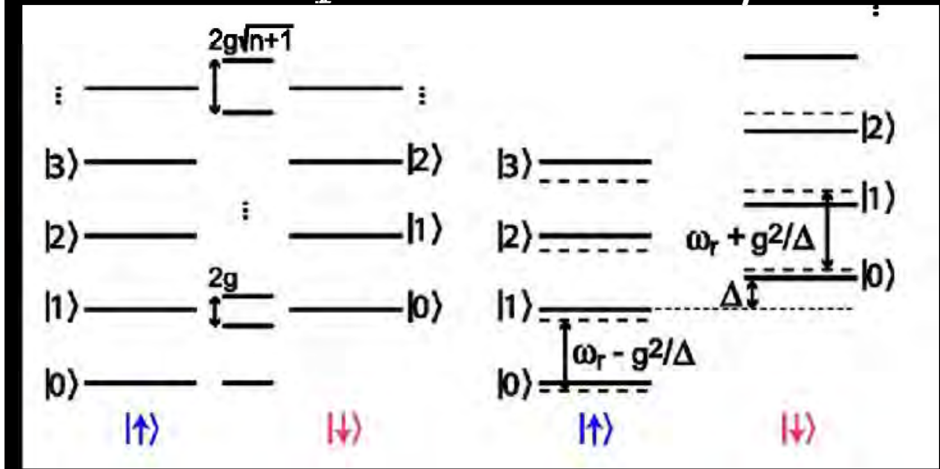
$$\hat{H} = \hbar\omega_r \hat{a}^\dagger \hat{a} + \hbar\omega_q \frac{\hat{\sigma}_z}{2} + \frac{\hbar\Omega}{2}\hat{E}\hat{S}$$

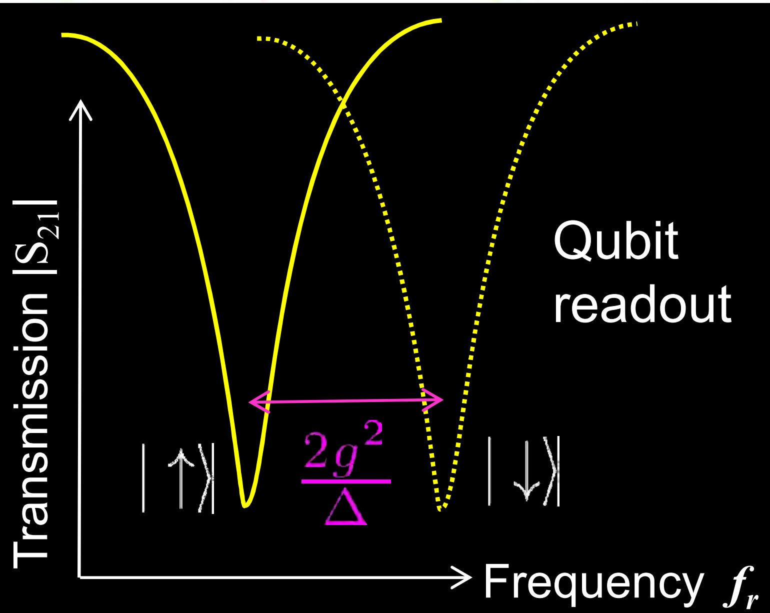
Strong coupling regime possible



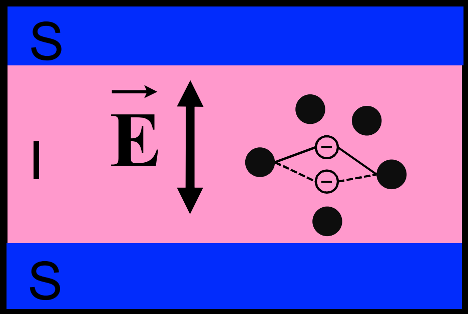
Koch *et al.* PRA 2007, Blais *et al.* PRA 2004

$\omega_r = \omega_q$ $\omega_r = \omega_q - \Delta$

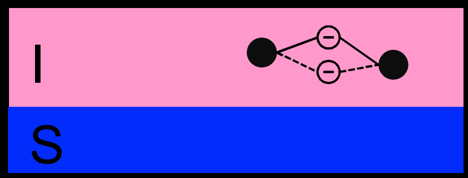




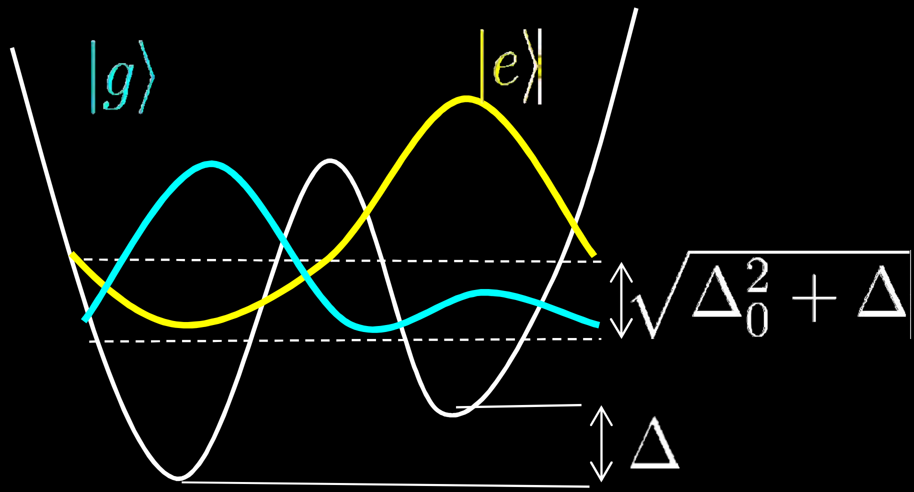
Parasitic two level systems (TLS) in dielectrics



Josephson tunnel junction



resonator



Amorphous oxides loaded with uncompensated charges ~ $10^{16}/\mathrm{cm}^3$

Range of energies, coherence and Rabi frequencies Δ, T_1, T_2, Ω

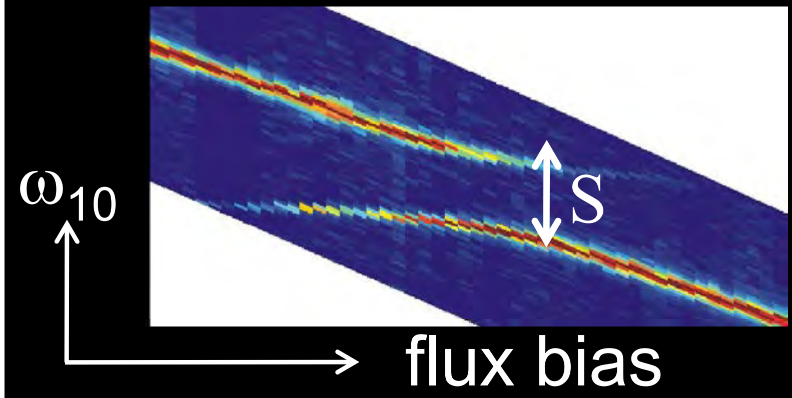
Absorption probability goes as ~ $\dfrac{\tanh\left(\frac{\hbar\omega}{2k_BT}\right)}{\sqrt{1+\left(\frac{E}{E_c}\right)^2}}$

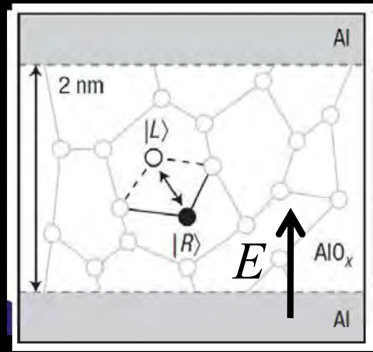
Maximized at low E, T

→ Dominating loss at low T & E

Schickfus, Hunklinger (1975)
Katz *et al.*, PRL (2010)

Decoherence due to TLS

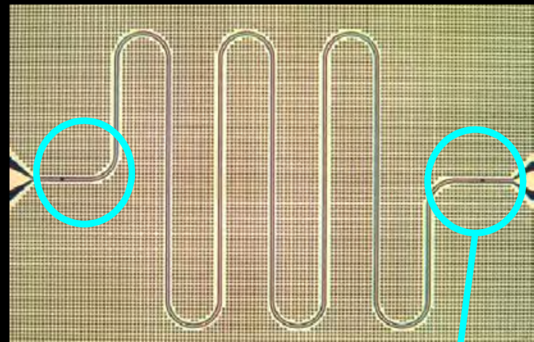




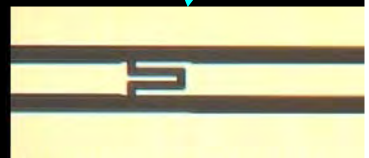
interaction S lifts degeneracy

Qubit spectroscopy and time domain

TLS located in *tunnel barrier oxide*



coupler



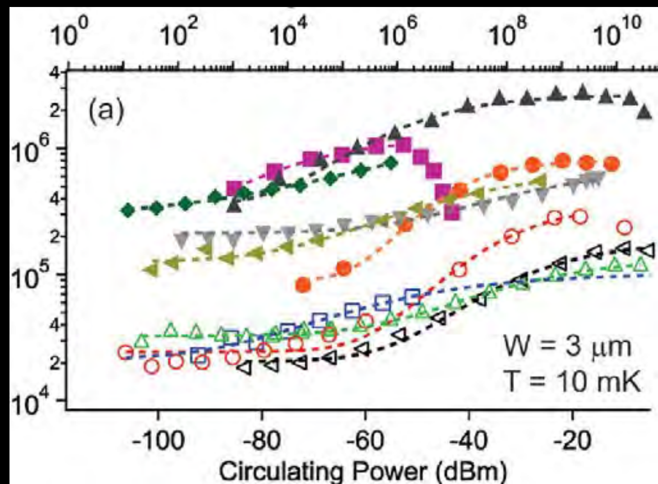
Resonator quality factor

power dependence (TLS saturation)

$$Q^{-1} = Q^{-1}_{\mathrm{TLS}}(E) + Q^{-1}_{\mathrm{P.I.}}$$

$$Q^{-1}_{\mathrm{TLS}} \propto \frac{\tanh\left(\frac{\hbar\omega}{2k_BT}\right)}{\sqrt{1+\left(\frac{E}{E_c}\right)^2}}$$

$Q = 1/\tan\delta$



Sage *et al.* JAP '10

Coherence threshold quantum error correction

Min. requirement: 0.1‰ error per gate (10 nsec)→ 100 μsec

Relaxation T_1 $|1\rangle \rightarrow |0\rangle$

Limited by: *Capacitive and inductive loss, quasiparticles, environmental coupling, microscopic defect states (TLS)*

Dephasing T_2^*, T_2 $|\psi\rangle \rightarrow |\psi\rangle e^{i\phi}$

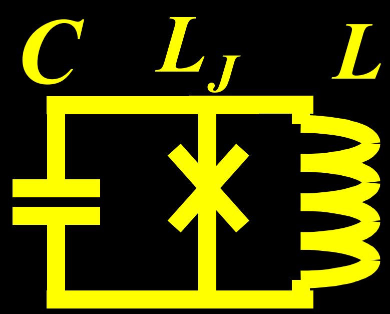
$T_2 \approx 2T_1$ (@ sweet spot), usually shorter

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{\tau_\phi}$$

Limited by: *1/f noise (charge, flux)*

Materials limited:

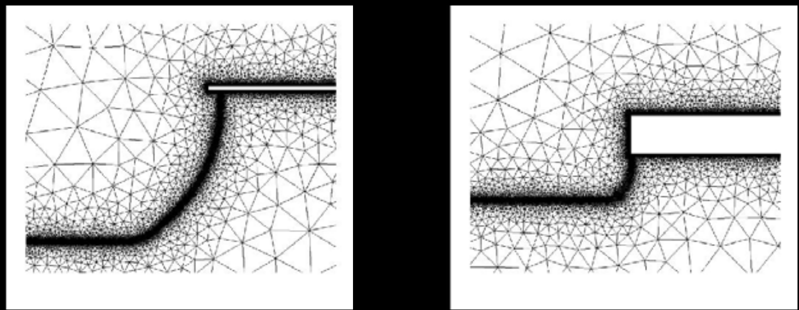
→***Junctions, inductors, capacitors***



Field distribution, filling factor of stored energy

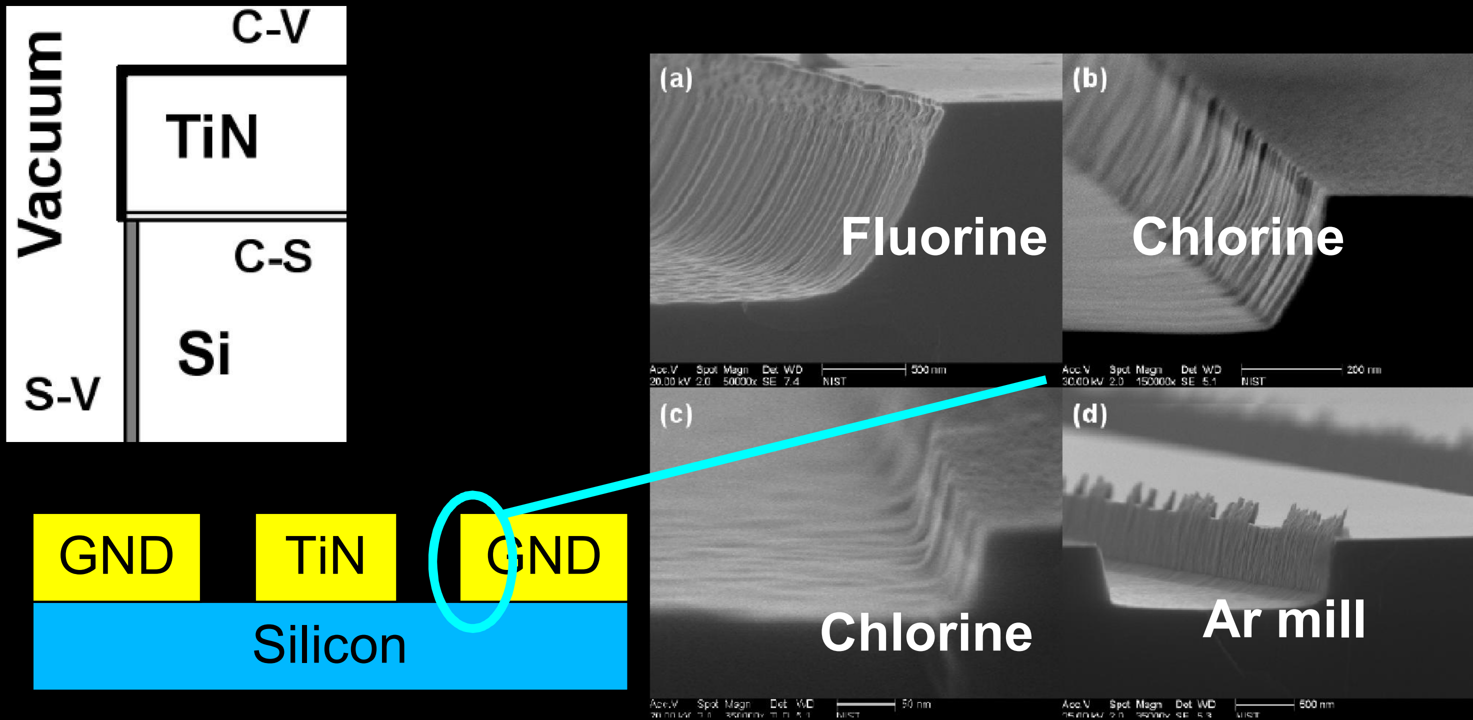
→ Etched surface matters, microscopic structure, E-field

→ Implications for resonant quantum circuits



Filling factor:

$$F_{\mathrm{V}} = \frac{\int_{\mathrm{V}} \epsilon_{\mathrm{V}} |E(r)|^2 dv}{\int_{\mathrm{V_{tot}}} \epsilon(r) |E(r)|^2 dv}$$

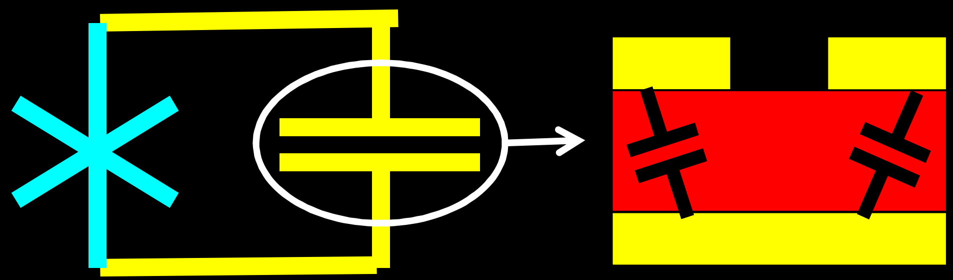


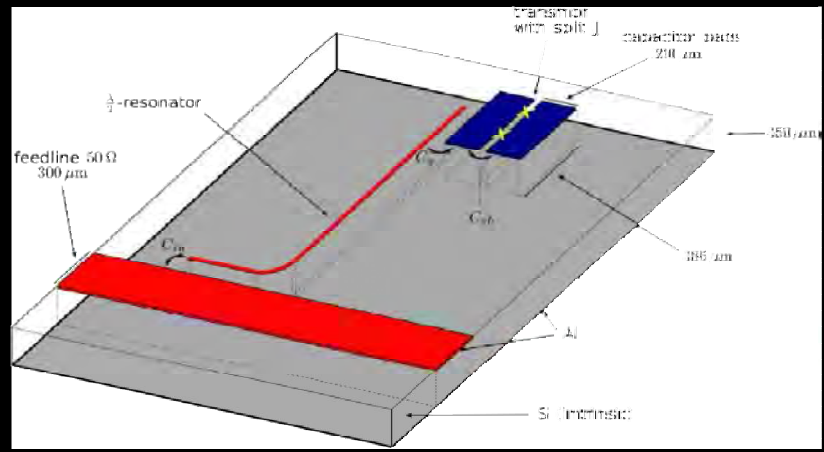
Sandberg *et al.*
APL 2012

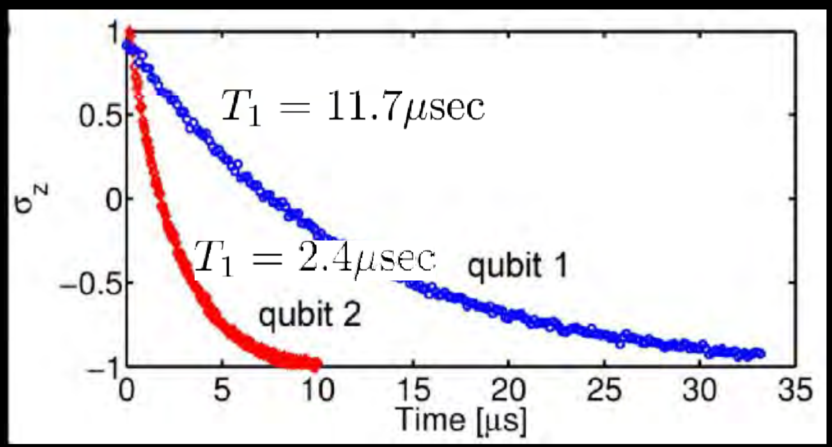
Microstrip transmon qubit

1. Best Josephson junction (T_1) → Sub-micron Al-AlO_x-Al
2. Best capacitor (δ) → TiN microstrip w/ low loss silicon substrate
3. Negligible Al/TiN interface loss → Merge sub-micron junctions and TiN capacitor

Loss participation analysis: → expected lifetime dominated by TiN







qubit 1: Purcell limit 20 μsec

Radiation limit 17 μsec

Combined limit 9.7 μsec

qubit 2: Purcell limited

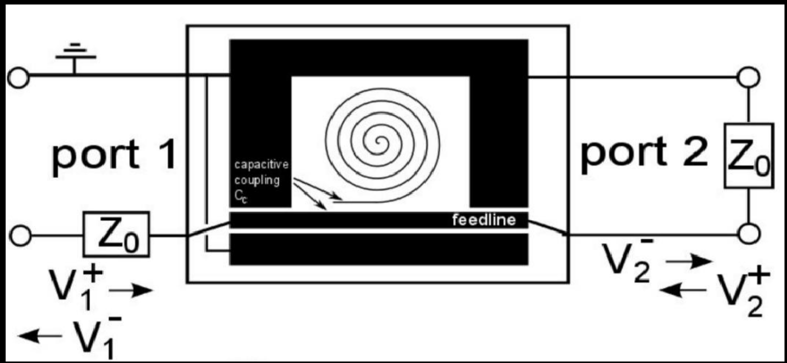
Re-designed qubit T_1=40 μsec

expect >100 μsec (error correction threshold)

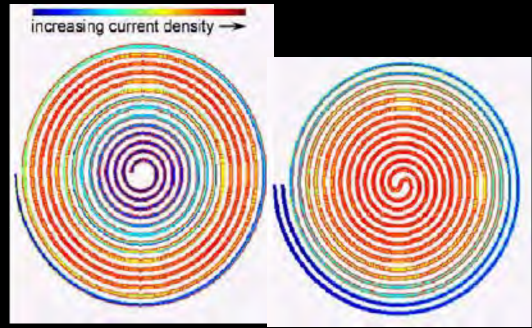
Sandberg *et al.*, APL 2013

Engineered quantum elements

Resonator design and simulation

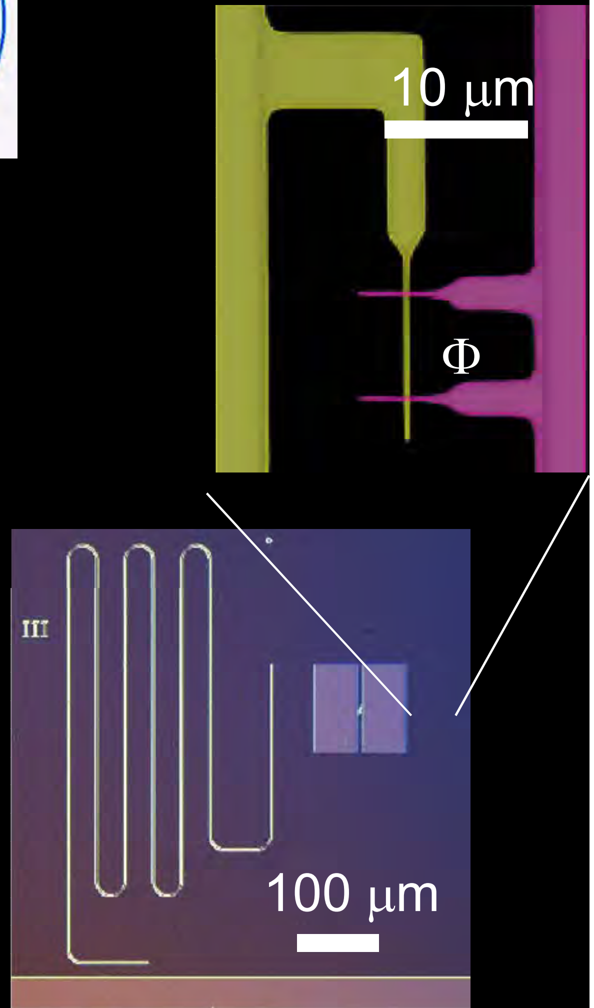


Current distribution

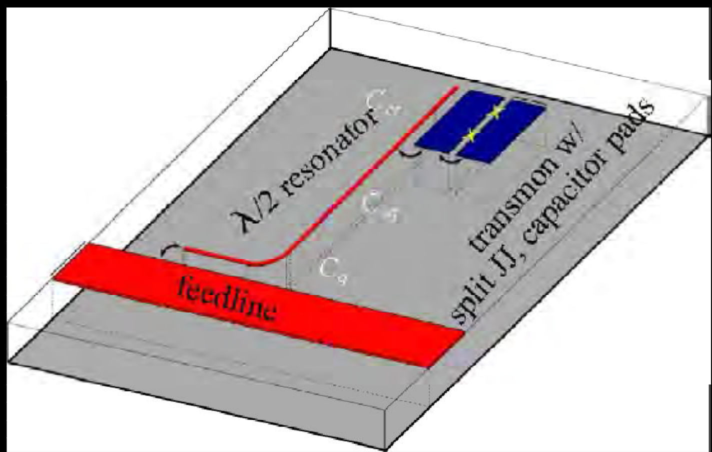


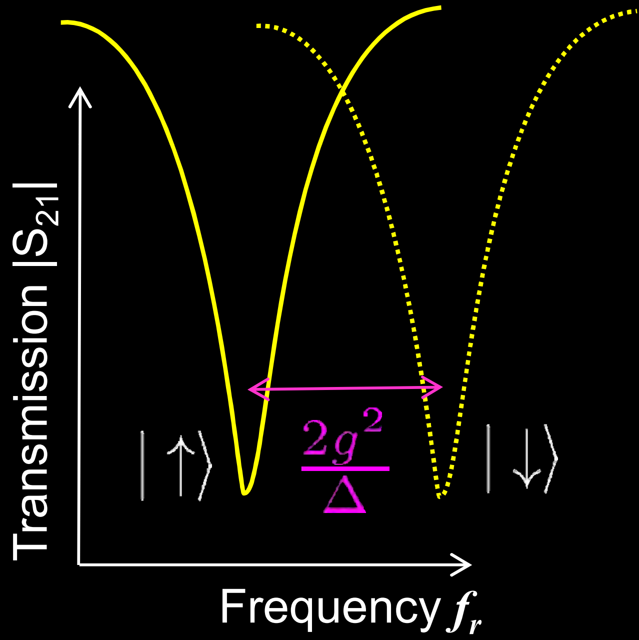
Kiselev, BA thesis '13

Flux tunable junction



Qubit (Transmon) coupled to resonator





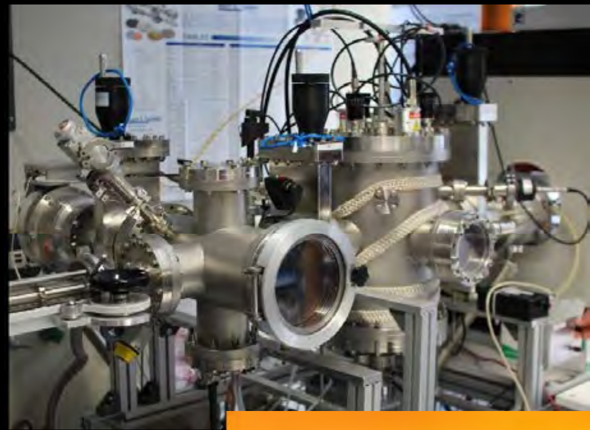
Braumüller, MA thesis '13

Deposition tools

Fast turnaround, flexibility, reliability, good control

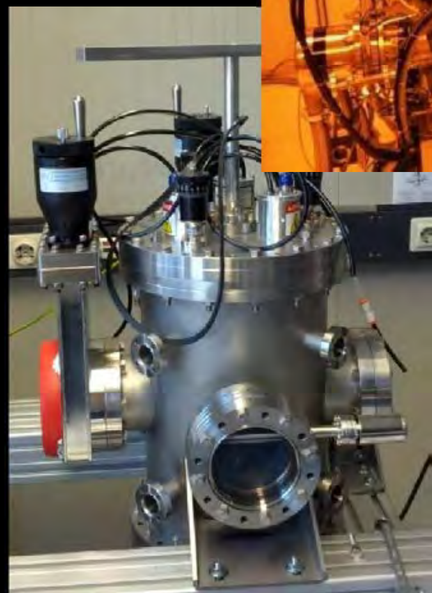
Deposition, cleaning, oxidation

Al-AlO_x-Al tunnel junctions



- **Sputter tool** Plasma 1
  - Al, Nb, NbN, AlO_x resonators

- **Shadow evaporation tool** Plassys
  - E-beam evaporator
  - Al-shadow evaporated junctions
  - Ti/Au markers, AuPd resistors



- **Sputter tool** Plasma 2
  - Nitride superconductors
  - Heating stage (500°C)

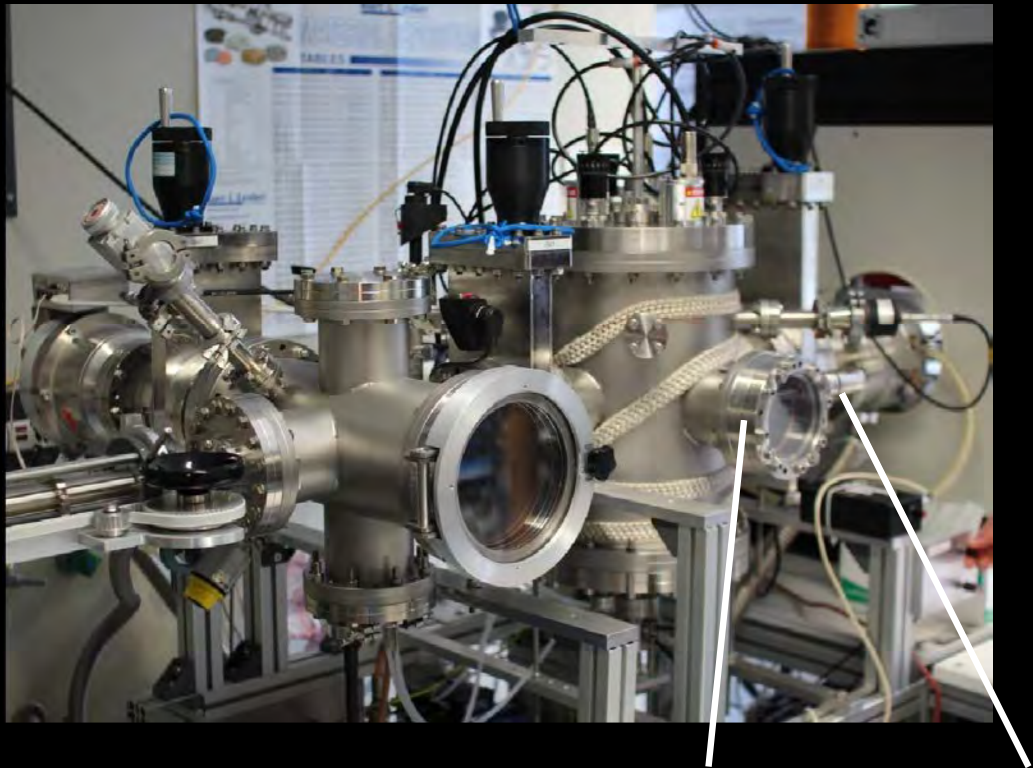
Sputtered thin films

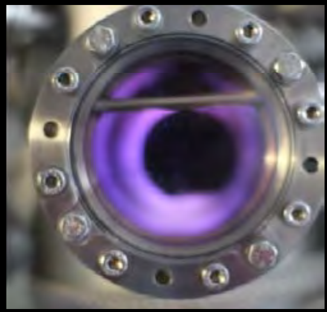
- Fast turnaround, flexibility, reliability, good control

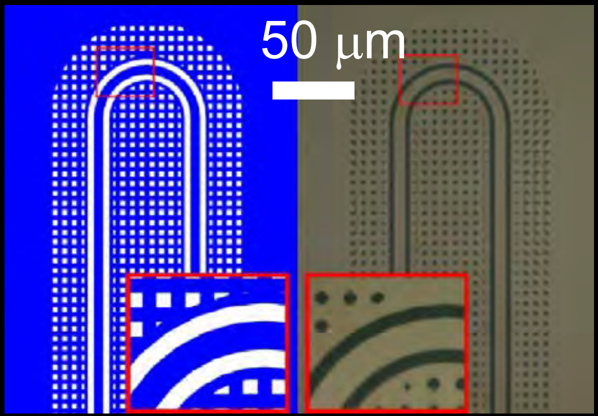
- Deposition
- Cleaning
- Oxidation

- Al, Nb, NbN, AlO_x resonators
- Al-AlO_x-Al tunnel junctions

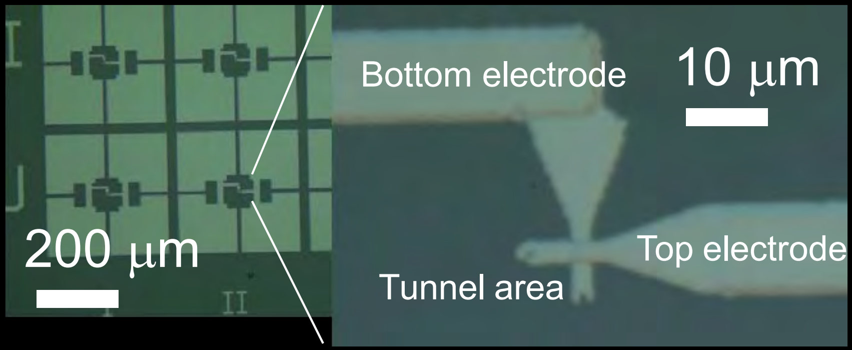
- Toolbox of designs and materials



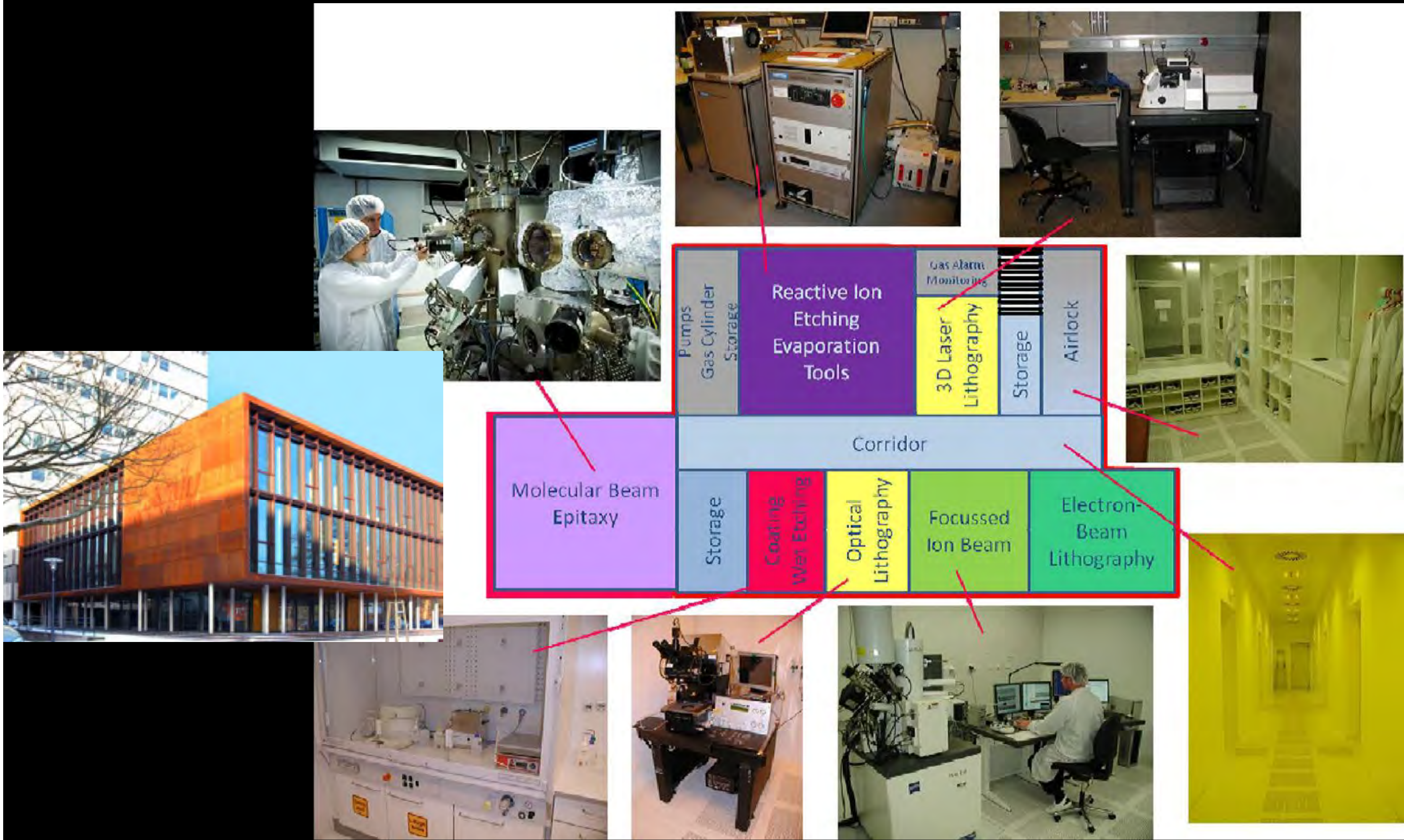




Neuwirth, BA thesis '13

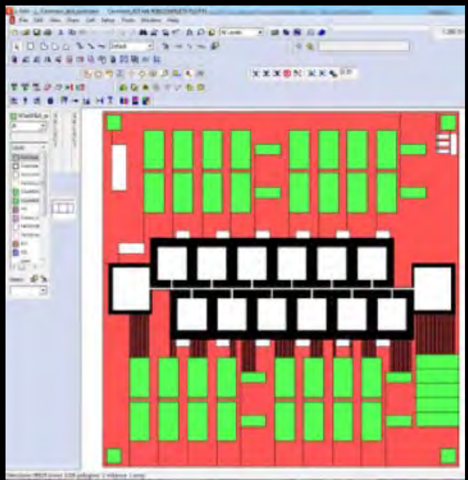


DFG Center for Functional Nanostructures
Nanostructure Service Laboratory

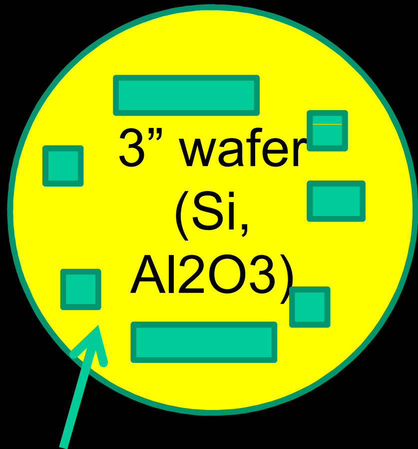


Schematic fabrication

1. Design software

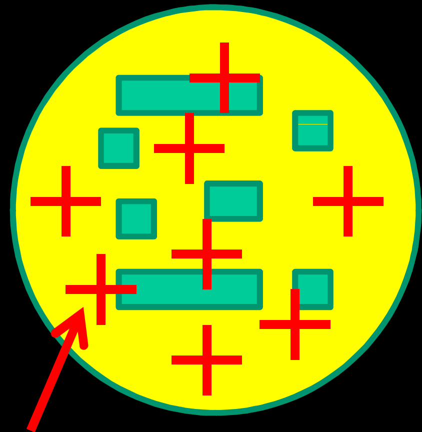


2. Film deposition, optical litho, etch



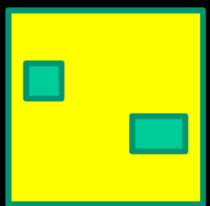
Inductor, capacitor, flux bias…
(1 µm+ feature sizes)

3. E-beam markers optical litho



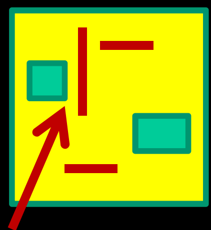
Markers (crosses etc.)

4. Dice into $20x20\ mm^2$



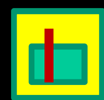
Get 6 chips w/
same designs

5. E-beam litho, Al-AlO_x-Al shadow evaporation



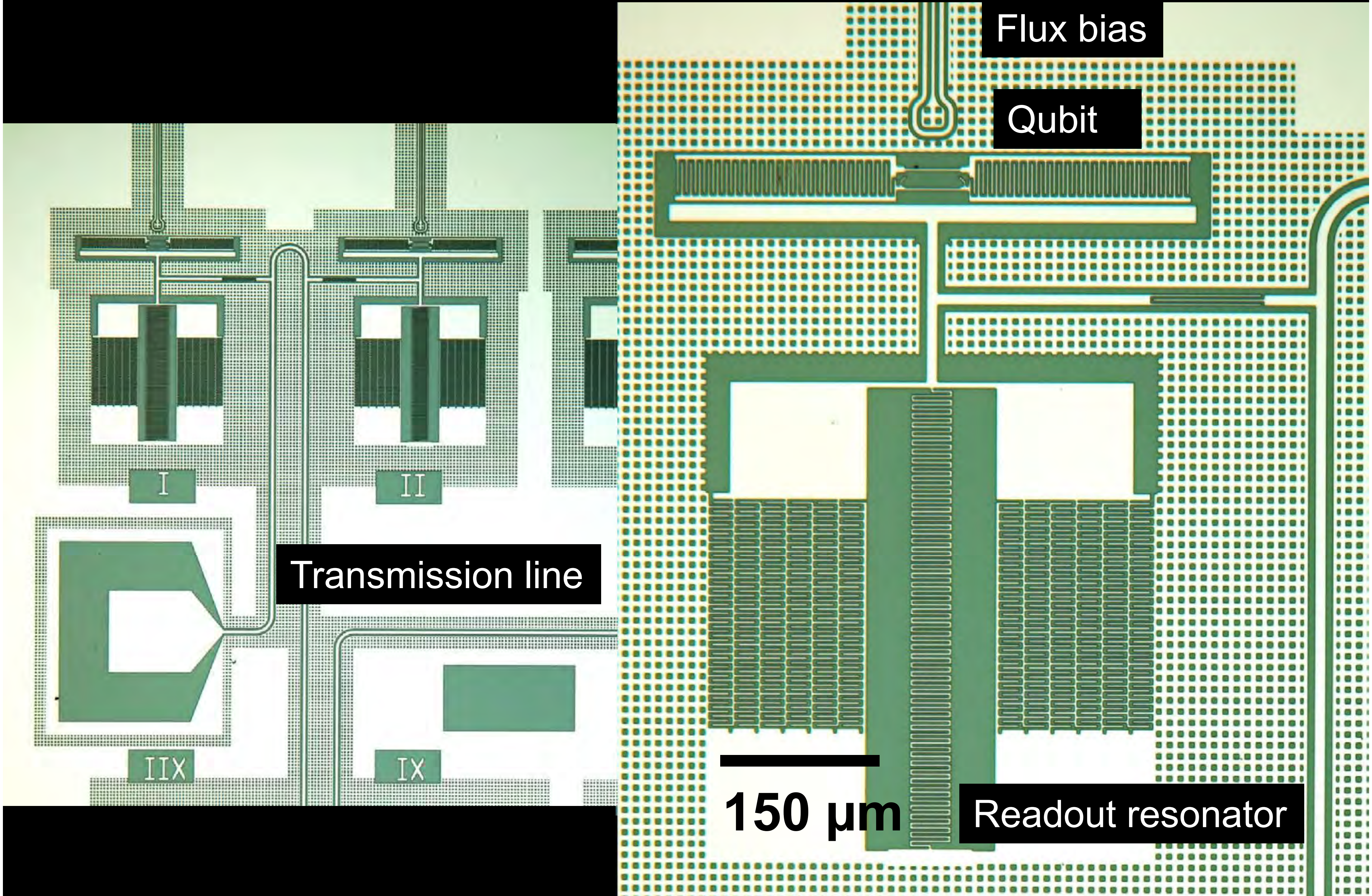
‘Dolan’ bridges,
Tunnel junctions, …

6. Dice into $5x5mm^2$



Get 9 chips w/
different designs

12 qubit chip ‘cavemon’



$^3He/^4He$ dilution refrigerator

400 mm cold plate

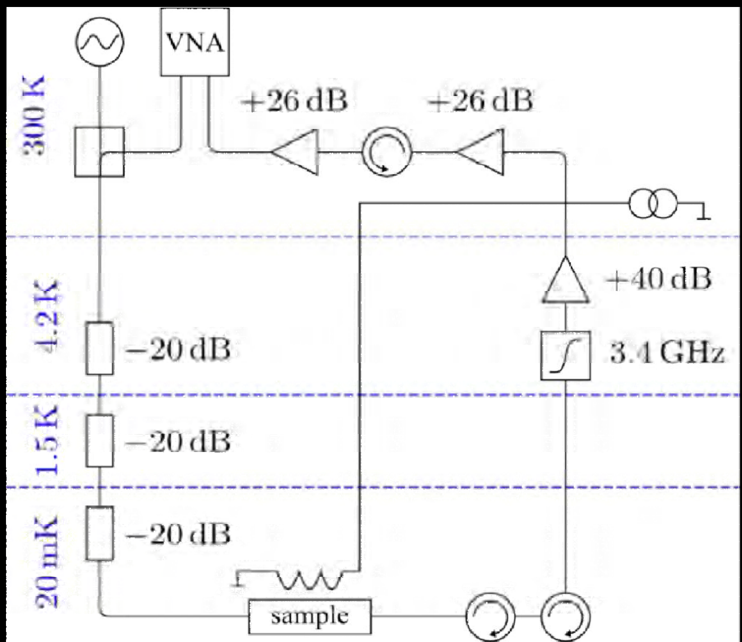
18 coax lines, 24 filtered DC lines

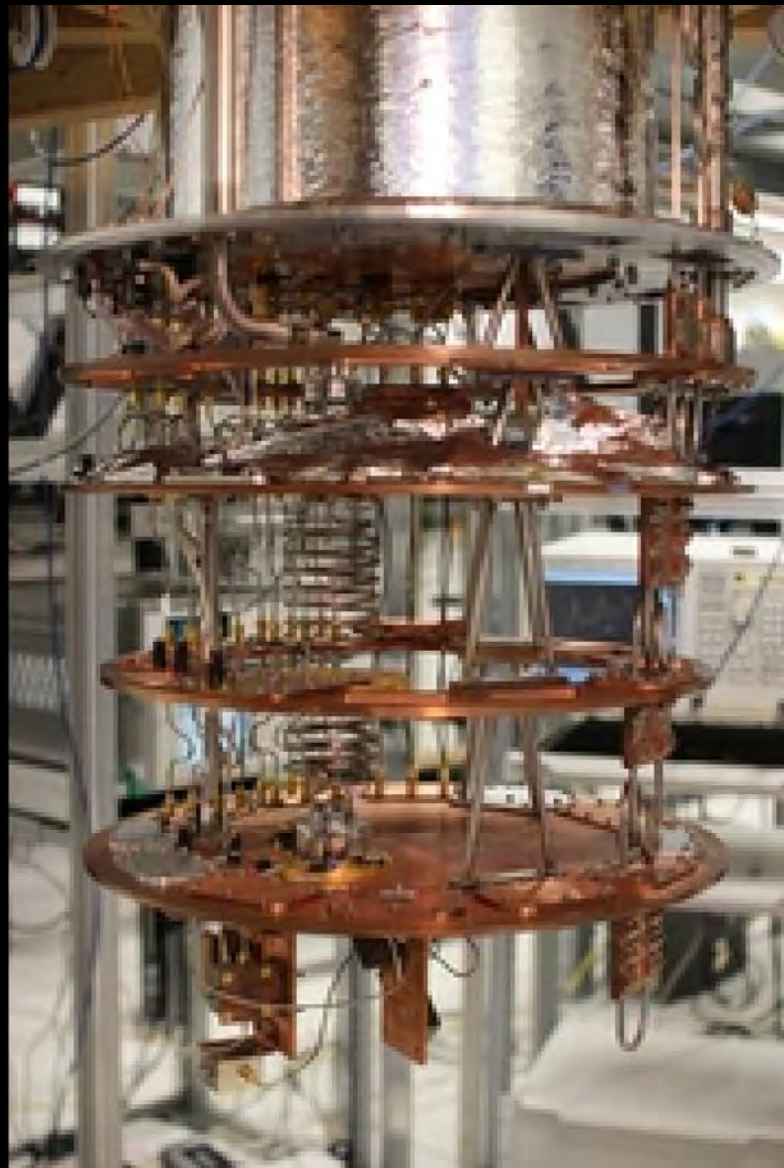
6 HEMTs (2x LNF)

2-port, 4-port microwave switches, circulators, filters, infrared shield…

Fits 9 samples

Multi-tone spectroscopy, flux bias, time domain measurements





Materials for quantum circuits
- specific properties for capacitive and inductive regions -

Superconductors

- Aluminium
- Niobium
- Niobium nitride
- Aluminium oxide

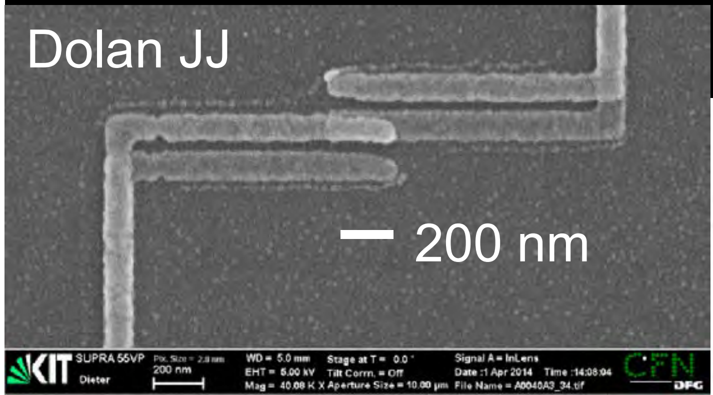
Josephson junctions

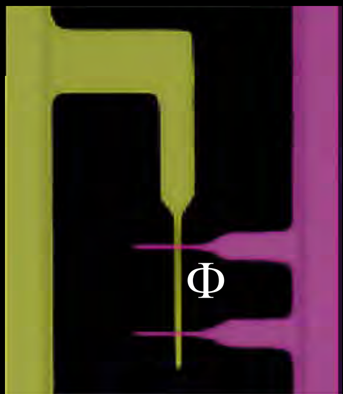
- Cross junctions (optical & e-beam, sputtered)
- Shadow junctions (e-beam, evaporated)

Josephson tunnel junctions

$Al\text{-}AlO_x\text{-}Al$ junctions

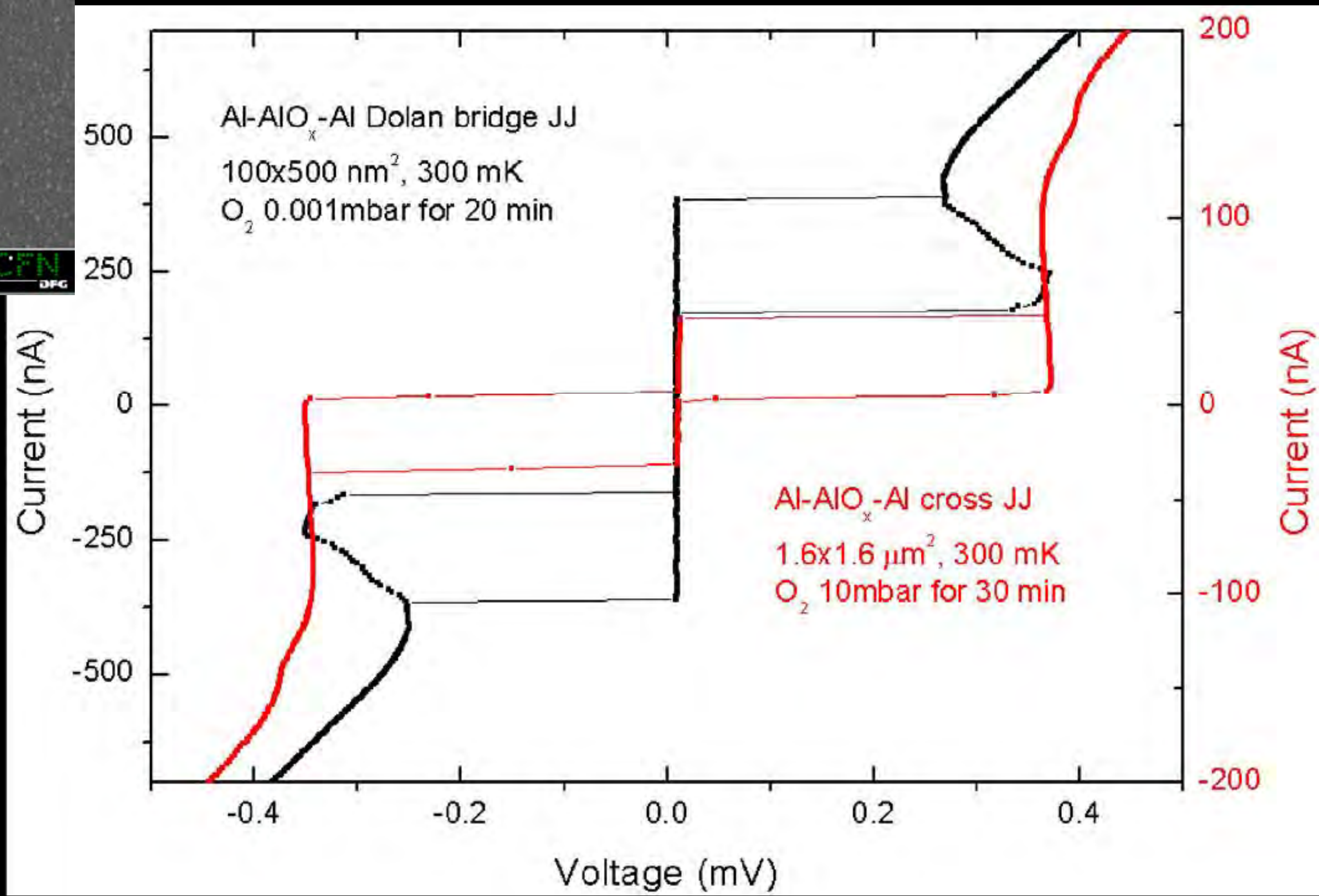
- Ultra-small shadow evaporated (aka *Dolan* JJs)
- Micron-sized *cross* JJs, evaporated and sputtered





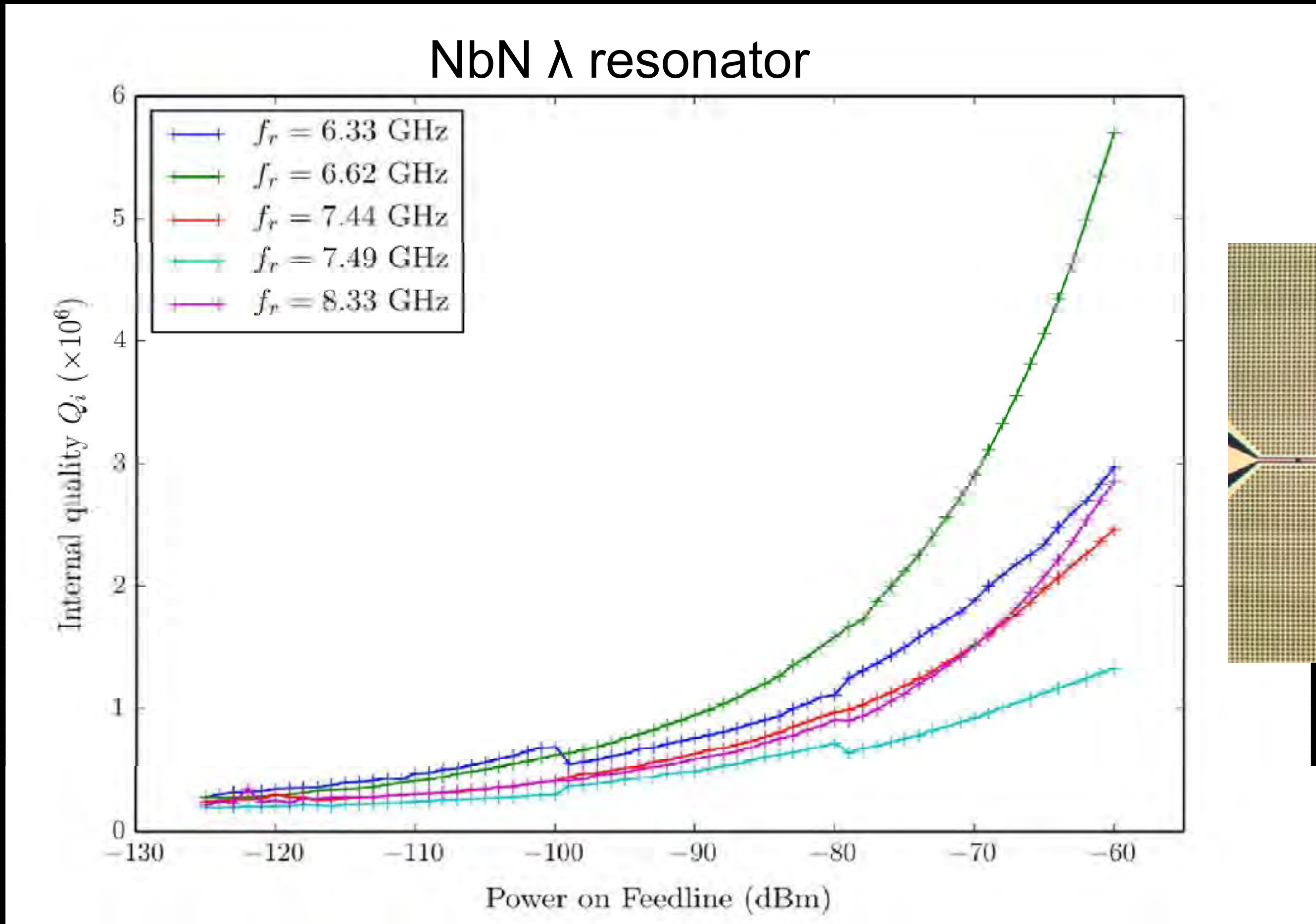
Cross JJ

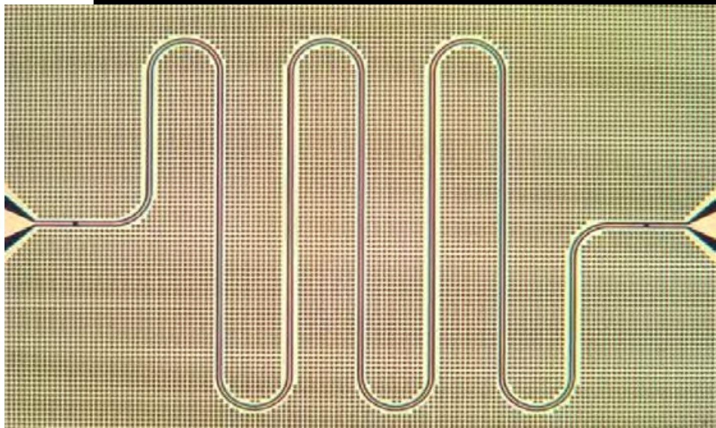
Current-voltage characteristic at 300mK



Microwave resonators

Internal quality factor versus power



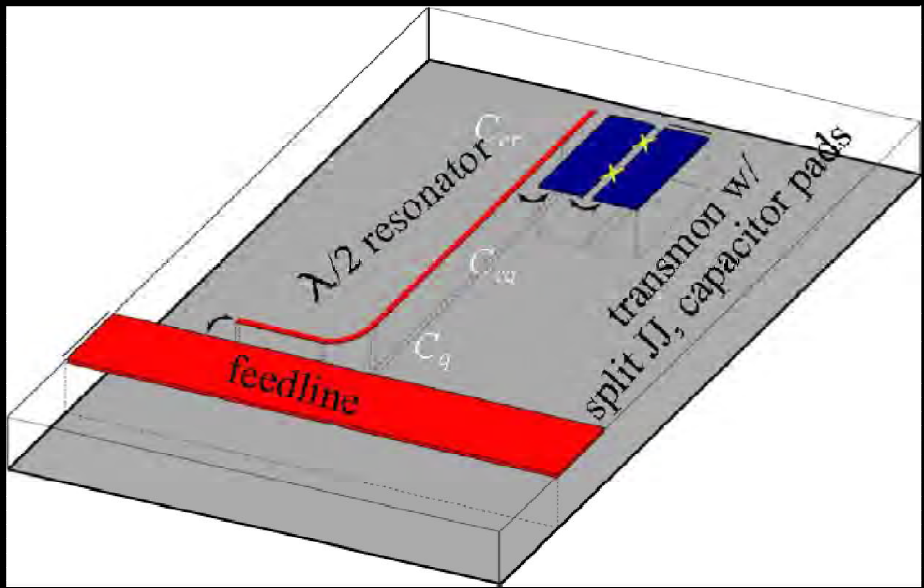


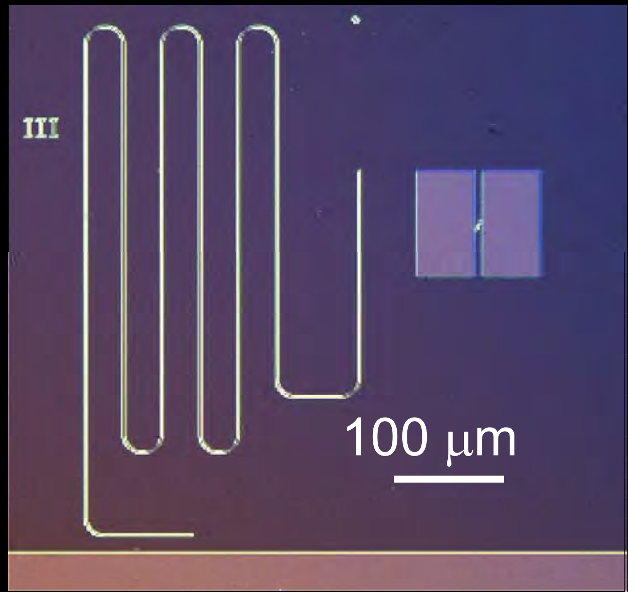
Al, Nb, NbN, and AlO_x resonators

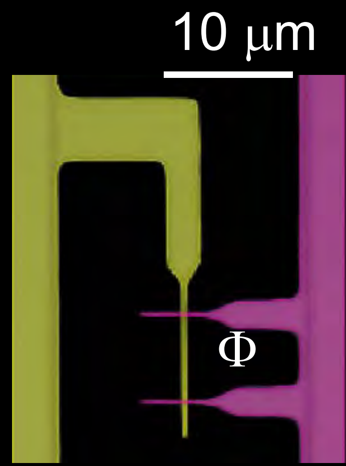
quality factors Q:100k @single photon, 1M+ @high power

Designs: Geometric, lumped element, spiral, coplanar waveguide, microstrip

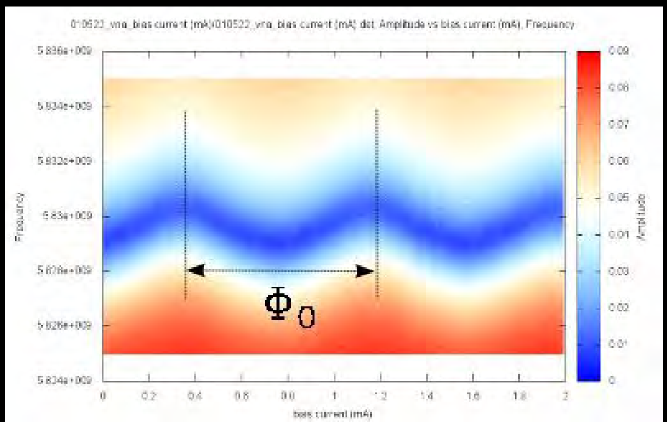
Microstrip transmon qubits (non-tunable and tunable)





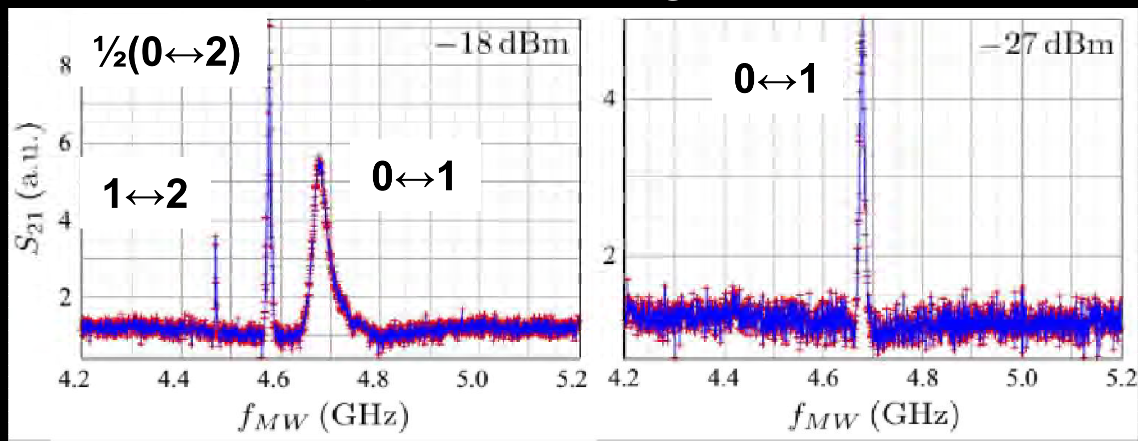


Flux Φ to qubit resonator response



Qubit spectroscopy

Increase drive power → higher level visible



Braumüller, MA thesis '13

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Thanks for your attention