超伝導量子ビットと共振器の強結合

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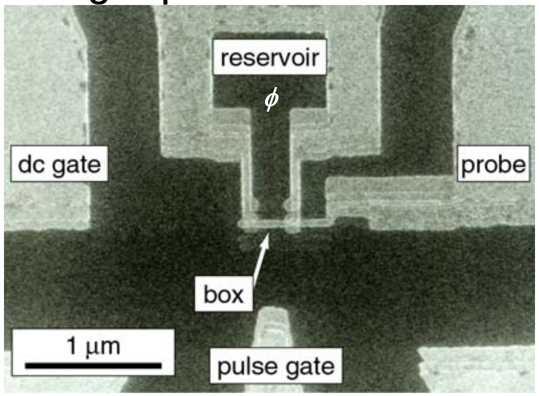
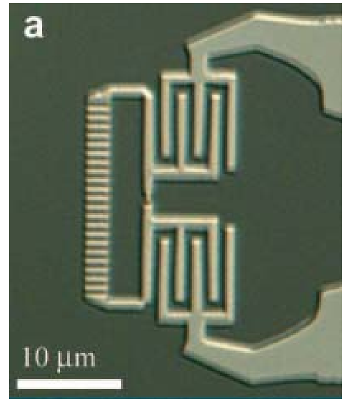
Superconducting qubits – macroscopic artificial atom in circuits

charge qubit/NEC $E_J/E_C \sim 0.3$

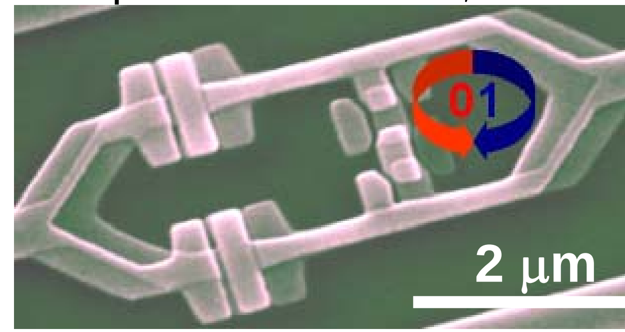


“fluxonium”/Yale

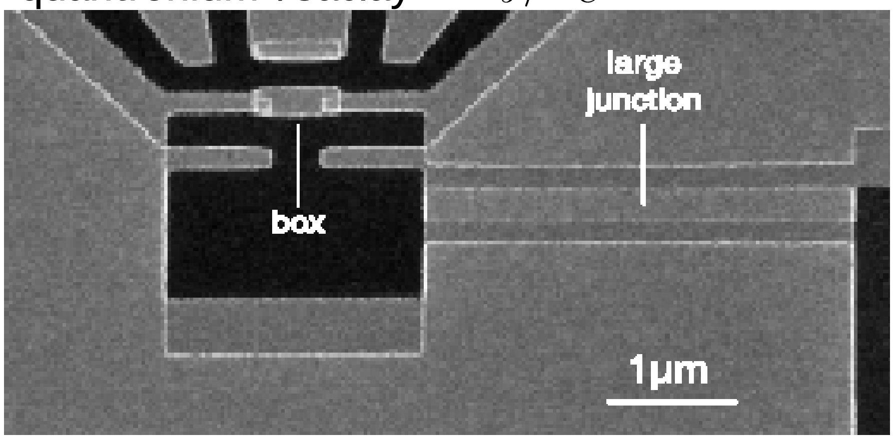


$E_J/E_C \sim 3$

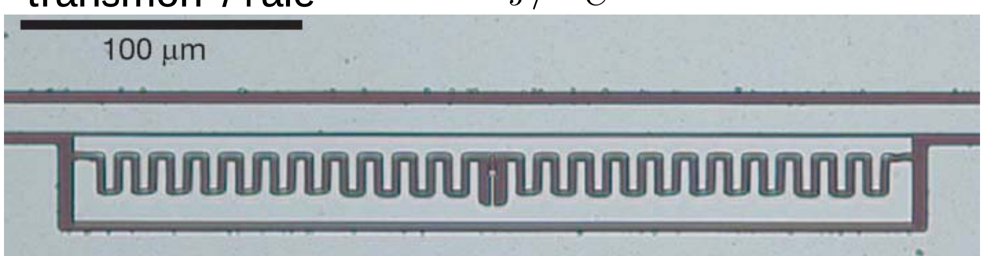
flux qubit/Delft $E_J/E_C \sim 40$



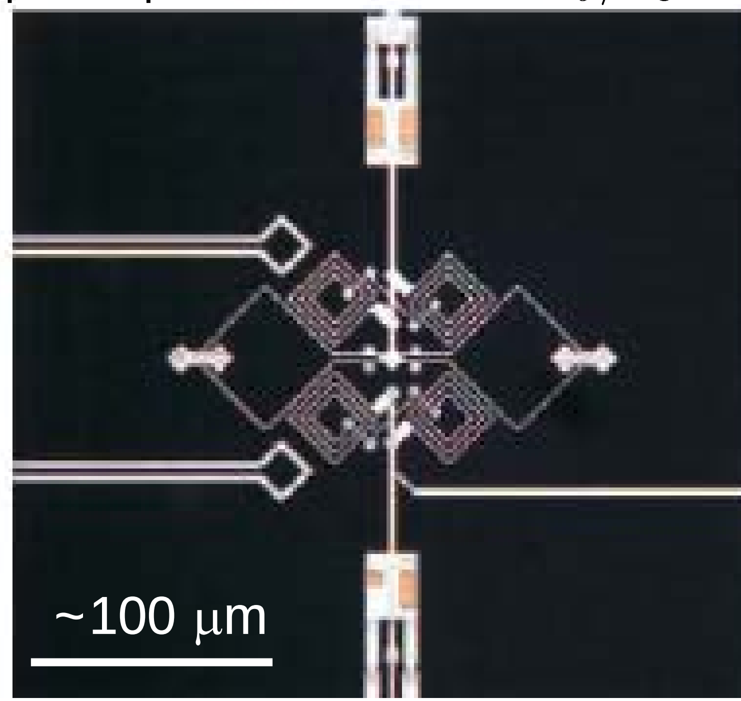
“quantronium”/Saclay $E_J/E_C \sim 5$



“transmon”/Yale $E_J/E_C \sim 50$



phase qubit/NIST/UCSB $E_J/E_C \sim 10^4$



Superconducting qubits/circuits

Cons:

- Low energy photons (microwave ~ 1-10 GHz)
- Low temperature (~10 mK) required
- Limited coherence time (typically ~ 1 μs)
- Vulnerable to optical photons — quasiparticle excitations

Superconducting qubits/circuits

Pros:

- Small dissipation
- Large nonlinearity of Josephson junctions

- High-fidelity quantum circuits
  - Deterministic and fast single-qubit and two-qubit gates
  - Single-shot readout
  - On-chip multi-qubit scalability
  - Flexible design — qubits, resonators, transmission lines
  - Well-developed microwave and cryogenic engineering
- Large dipole moment
  - Strong coupling to EM modes/charges/spins/NEMS
- Improved coherence time (~10-100 μs)

- Squeezing/parameteric amplification
- Single photon source/detector

Strong coupling between a flux qubit and a superconducting resonator via capacitance

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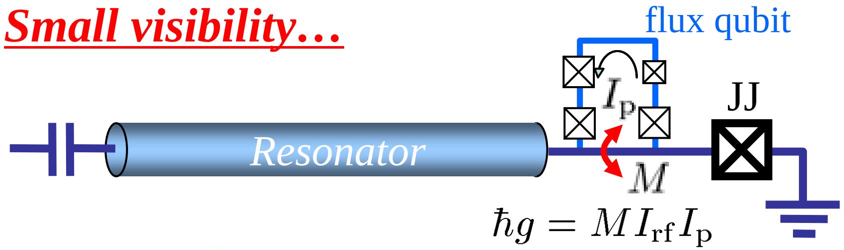
a: Advanced Science Institute, RIKEN
b: Green Innovation Research Labs., NEC

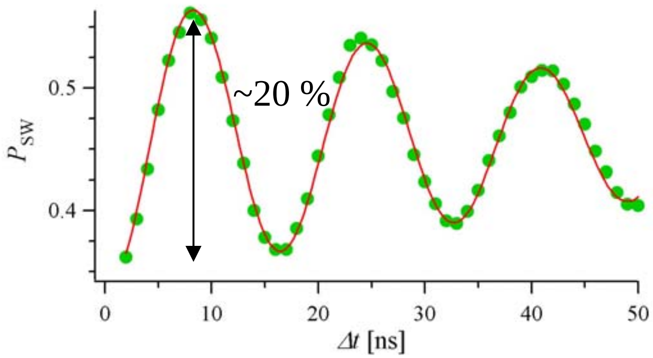
Poster No.7

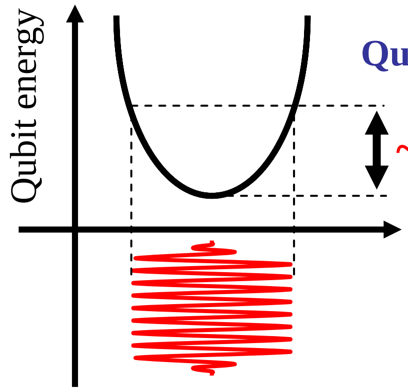
Motivation

Small visibility…



$$\hbar g = M I_{rf} I_p$$



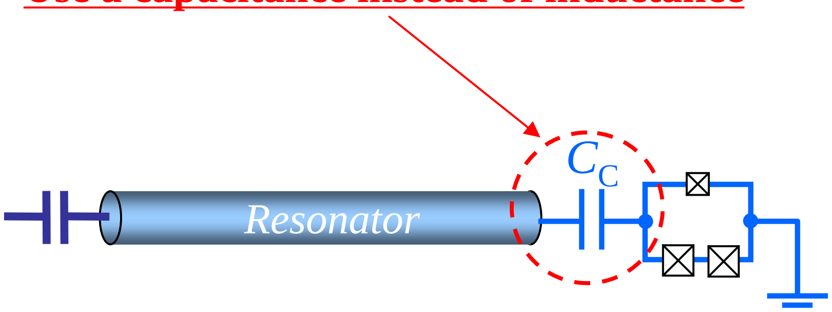


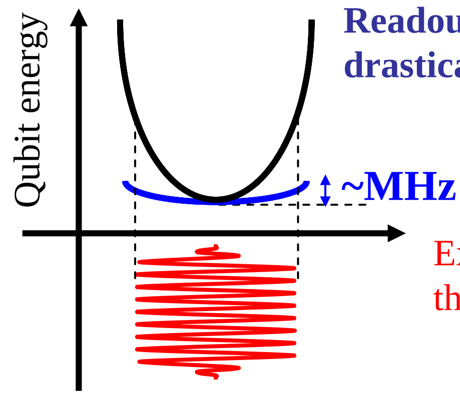
Current in a resonator

Qubit is shaken by readout pulses.

- LZ tunneling
- Energy exchange with TLSs.

Use a capacitance instead of inductance



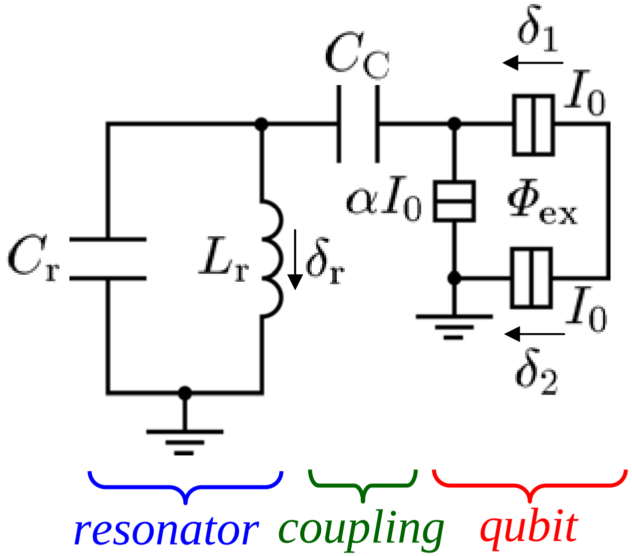


Voltage in a resonator

Readout backaction should be drastically small.

Expect an improvement of the visibility

Flux qubit capacitively coupled to a LC resonator



Circuit diagram

$\delta_1,\ \delta_2,\ \delta_r$: Phase differences

I_0 : Critical current of a larger JJ

Φ_{ex} : External flux bias

C_C : Coupling capacitor

C_r : Resonator capacitor

L_r : Resonator inductor

Total Hamiltonian of this system

$$\mathcal{H} = \mathcal{H}_q + \mathcal{H}_r + \mathcal{H}_c .$$

qubit ($\mathcal{H}_q$) resonator ($\mathcal{H}_r$) coupling ($\mathcal{H}_c$)

$$\begin{aligned}\mathcal{H}_q &= 4E_c\frac{1+\alpha+\beta}{1+2\alpha+2\beta}(n_1^2+n_2^2) + 8E_c\frac{\alpha+\beta}{1+2\alpha+2\beta}n_1 n_2 \\ &\quad -E_J\cos\delta_1 - E_J\cos\delta_2 - \alpha E_J\cos(\delta_1-\delta_2+2\pi f)\end{aligned}$$

$$\mathcal{H}_r = \frac{E_r}{\sqrt{1+\gamma}}(a^\dagger a + \tfrac{1}{2})$$

$$\mathcal{H}_c = \frac{2i}{1+2\alpha+2\beta}\sqrt{\frac{\beta\gamma}{(1+\gamma)^{3/2}}}\sqrt{E_r E_c}(n_1-n_2)(a^\dagger - a)$$

$$\begin{aligned}\beta &= C_c/C_J \\ \gamma &= C_c/C_r \\ E_r &= \hbar/\sqrt{L_r C_r}\end{aligned}$$

Dispersive shift in Jaynes-Cummings Hamiltonian

Jaynes-Cummings Hamiltonian

$$\mathcal{H}_{\mathrm{JC}} = \hbar \frac{\omega_{\mathrm{a}}}{2}\sigma_{\mathrm{z}} + \hbar\omega_{\mathrm{r}}(\hat{a}^\dagger\hat{a} + 1/2) + \hbar g(\hat{a}\sigma^+ + \hat{a}^\dagger\sigma^-)$$

In the dispersive limit, $g \ll |\omega_{\mathrm{a}} - \omega_{\mathrm{r}}| \ (= |\Delta|)$

$$\mathcal{H}_{\mathrm{JC}} \sim \hbar(\omega_{\mathrm{r}} + \underline{\frac{g^2}{\Delta}}\sigma_{\mathrm{z}})(\hat{a}^\dagger\hat{a} + 1/2) + \hbar\omega_{\mathrm{a}}\sigma_{\mathrm{z}}/2$$

$$\equiv \chi$$

Effective resonant frequency of the resonator

$\omega_{\mathrm{r}} - \frac{g^2}{\Delta}$ for qubit |g>

$\omega_{\mathrm{r}} + \frac{g^2}{\Delta}$ for qubit |e>

Generalized Jaynes-Cummings model

$$\mathcal{H} = \hbar \sum_j \omega_j |j\rangle\langle j| + \hbar\omega_\mathrm{r}\hat{a}^\dagger\hat{a} + \hbar \sum_{i,j} g_{ij}|i\rangle\langle j|(\hat{a}+\hat{a}^\dagger)$$

In the dispersive limit, $g_{ij} \ll |\omega_{ij} - \omega_\mathrm{r}|, \ (\omega_{ij} = \omega_j - \omega_i)$

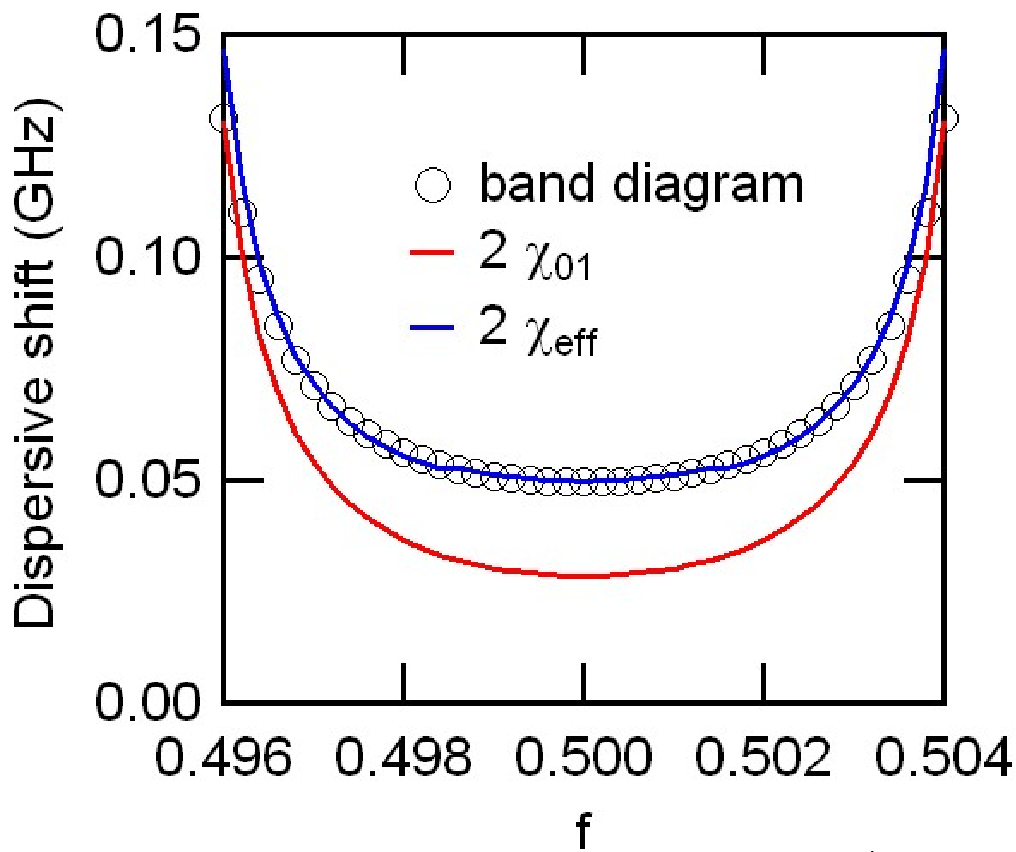
$$\mathcal{H}_\mathrm{eff} = \hbar(\omega_\mathrm{r}' + \chi_\mathrm{eff}\sigma_\mathrm{z})\hat{a}^\dagger\hat{a} + \hbar\omega_{01}'\sigma_\mathrm{z}/2$$

$$\chi_\mathrm{eff} = \chi_{01} - \chi_{10} + \frac{1}{2}\sum_{j=2}(\chi_{j1} - \chi_{1j} - \chi_{j0} - \chi_{0j})$$

effect of higher states

$$\chi_{ij} = \frac{g_{ij}g_{ji}}{\omega_{ij} - \omega_\mathrm{r}}, \ g_{ij} = \langle i|\mathcal{H}_\mathrm{c}|j\rangle$$

Dispersive shift

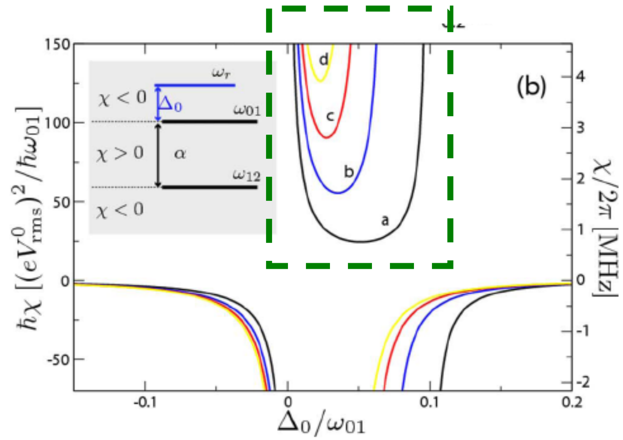


$$\chi_{\text{eff}} = \chi_{01} - \chi_{10} + \frac{1}{2}\sum_{j=2}^{4}(\chi_{j1} - \chi_{1j} - \chi_{j0} - \chi_{0j})$$

“Straddling” regime

$$\chi_{\rm eff} = \chi_{01} + \frac{1}{2}(\chi_{21} - \chi_{12})$$

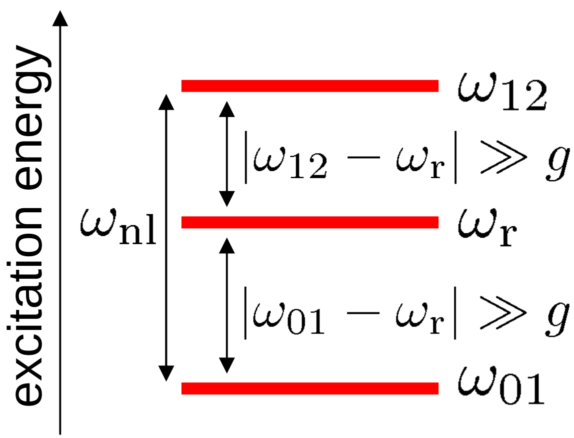
$$\chi_{ij} = \frac{-|g_{ij}|^2}{\omega_{ij} - \omega_{\rm r}}, \;\; \omega_{ij} = \omega_j - \omega_i$$



cf. transmon
Koch *et al*., PRA **76**, 042319 (2007)

$$\omega_{01} < \omega_{\rm r} < \omega_{12}$$

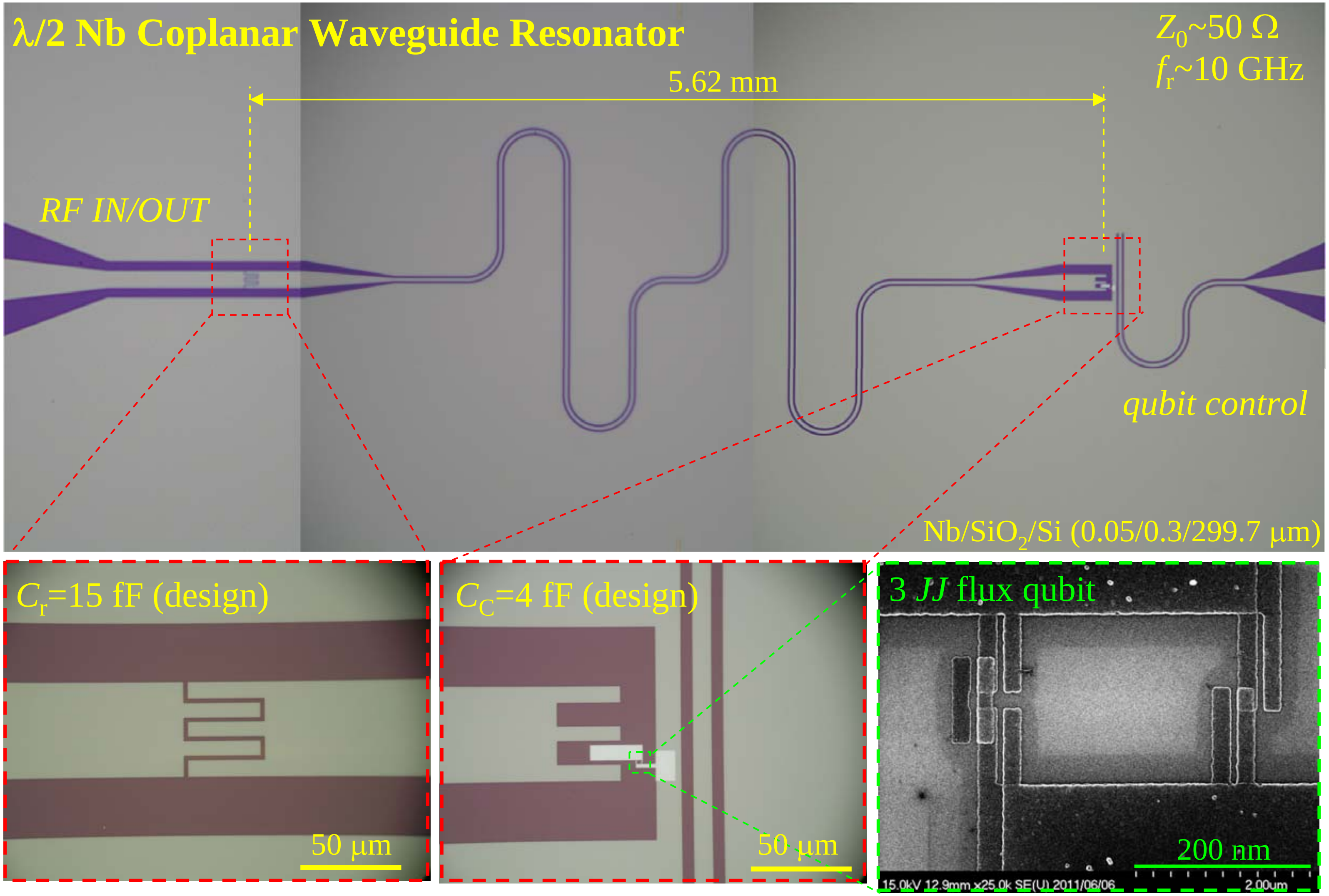
required condition



$$g \ll \omega_{\rm nl}$$

transmon
$\omega_{\rm nl}$ ~ 100 MHz
flux qubit
$\omega_{\rm nl}$ ~ 10 GHz

Sample Images



Unpublished data ...

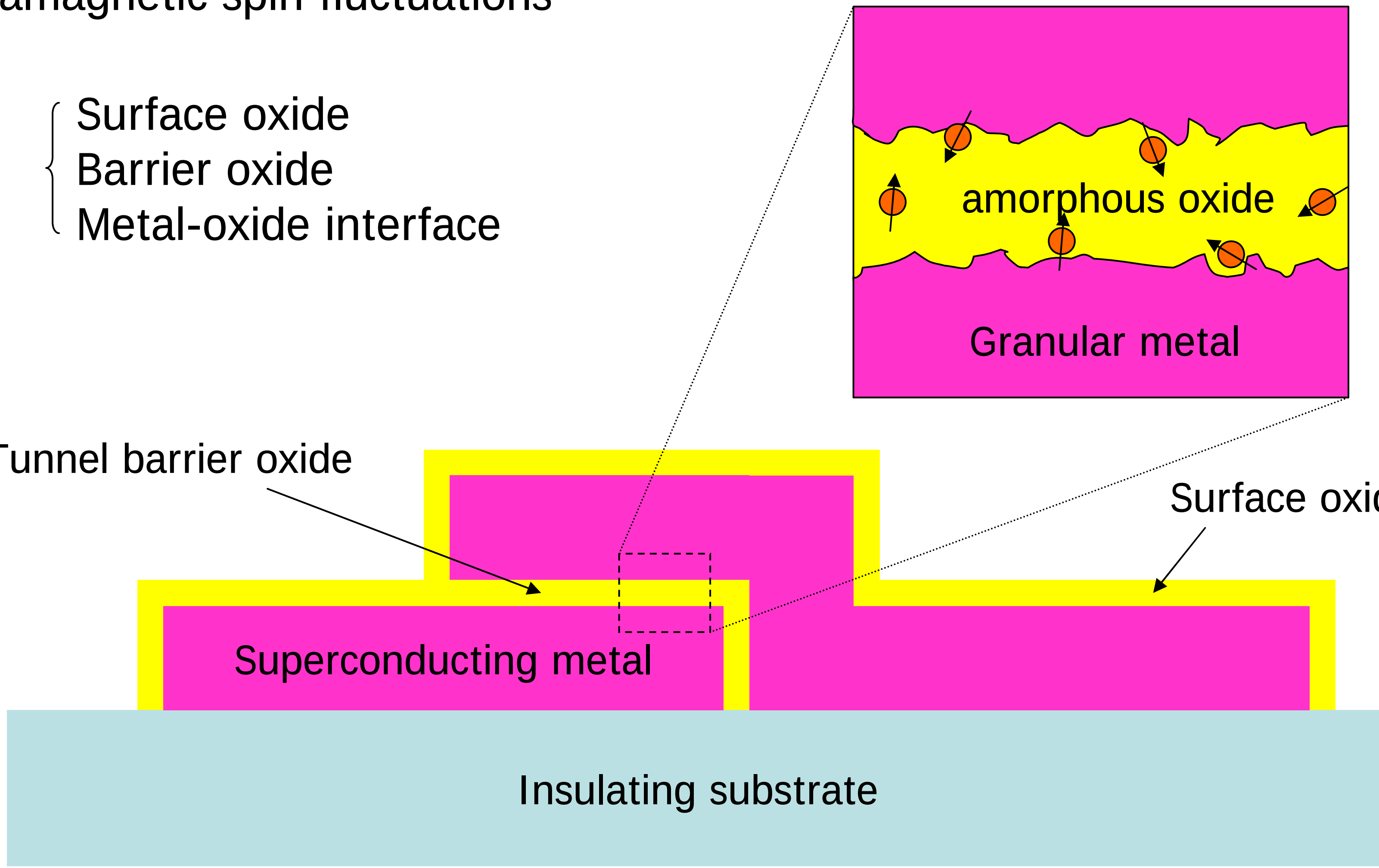
Superconducting qubits with epitaxial junctions

In collaboration with H. Terai, Qiu Wei, Zhen Wang (NICT)

Amorphous oxides in the barrier, on the surface

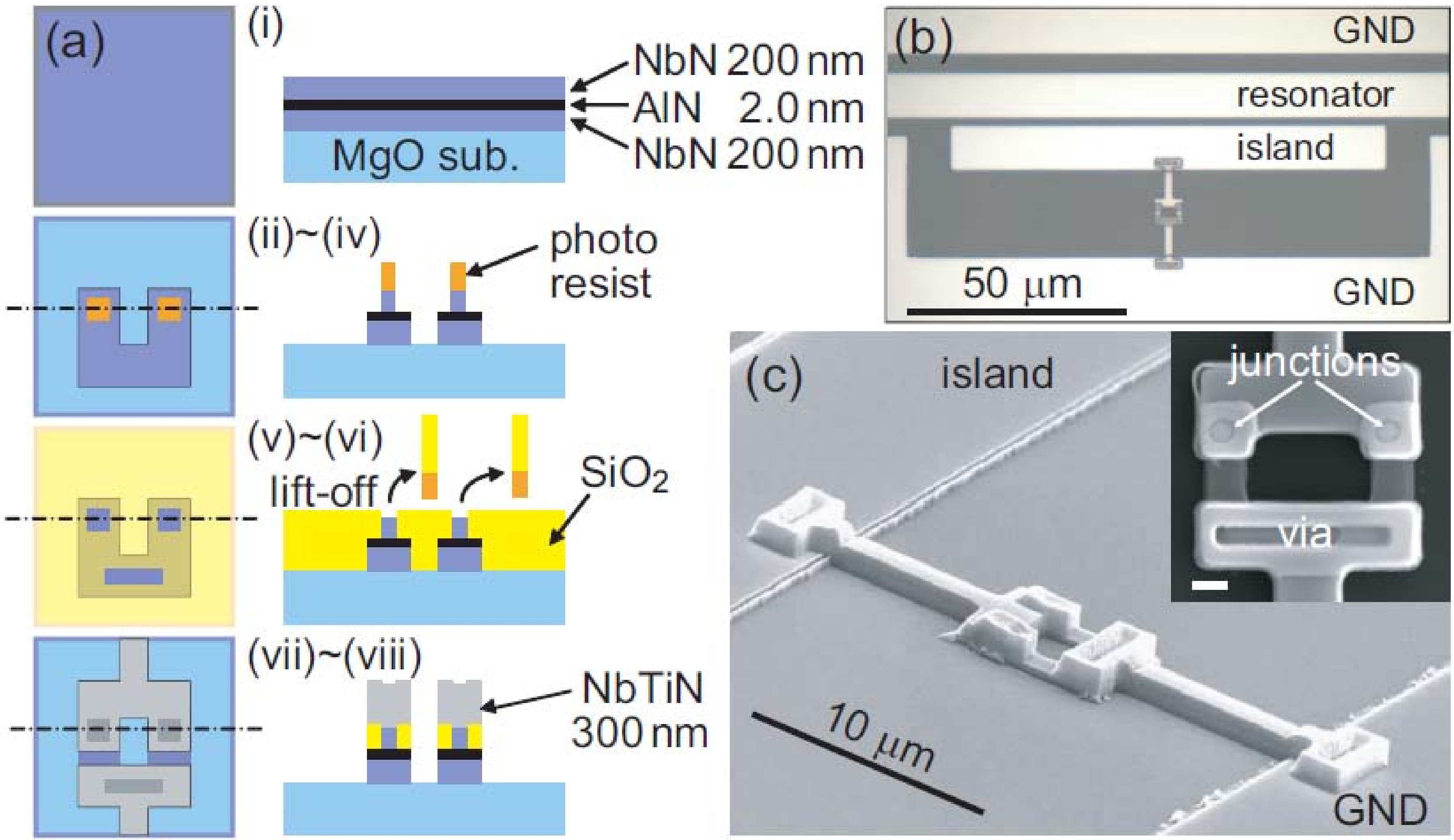
Charge fluctuations
Josephson-energy fluctuations
Paramagnetic spin fluctuations

- Surface oxide
- Barrier oxide
- Metal-oxide interface

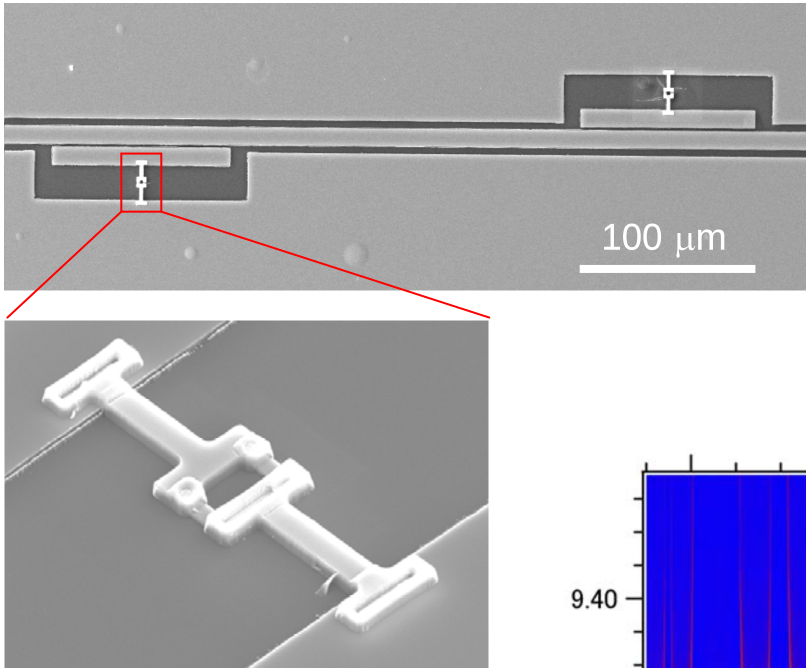


Transmon qubit fabrication

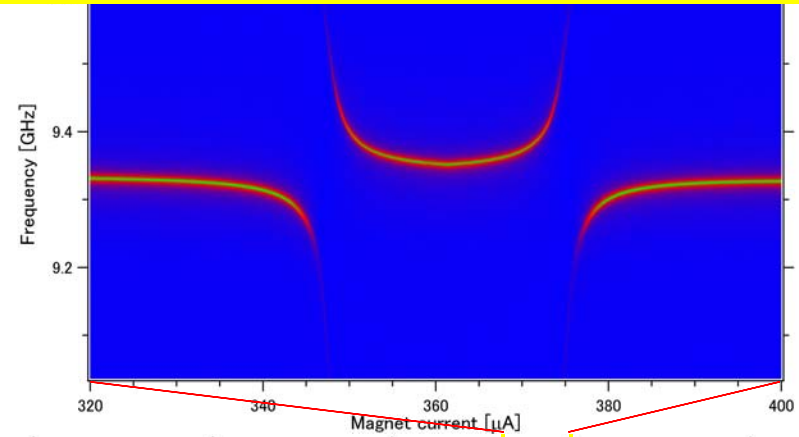
Hirotaka Terai (NICT)

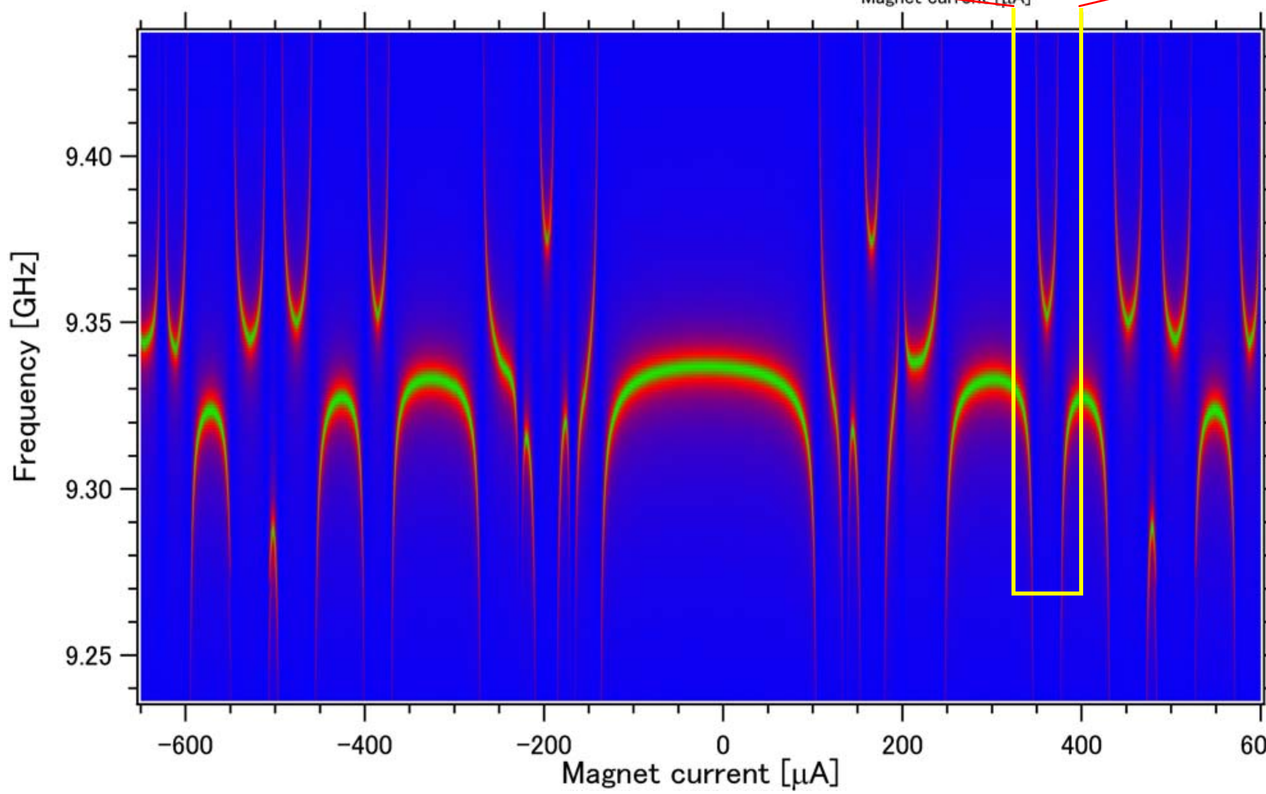


Vacuum Rabi splitting



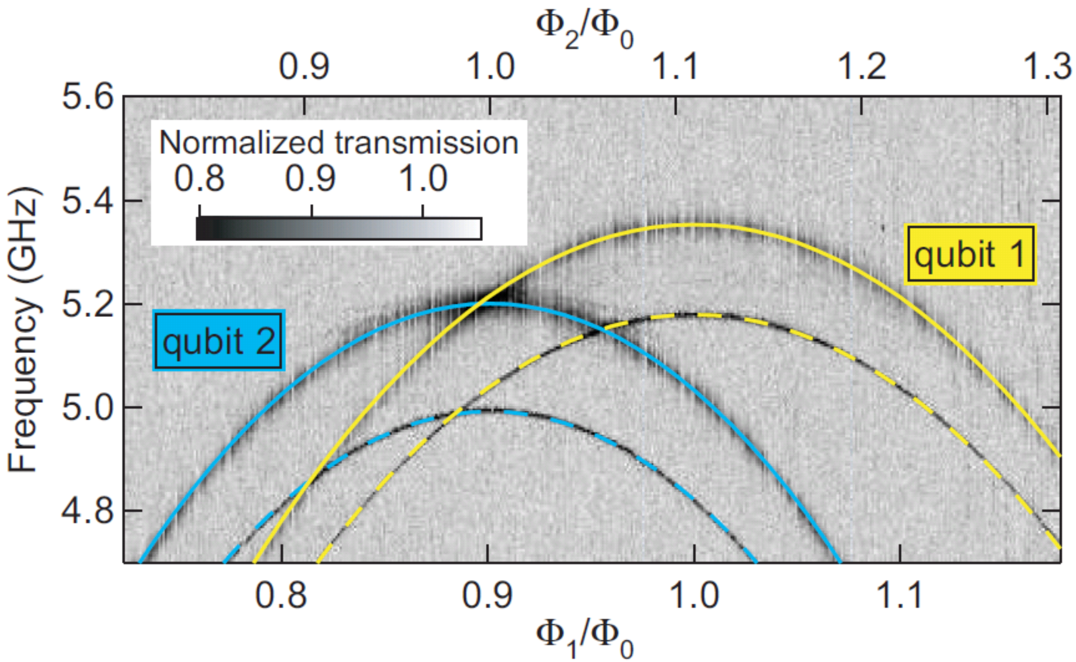
Vacuum Rabi splitting: g/h ∼150 MHz

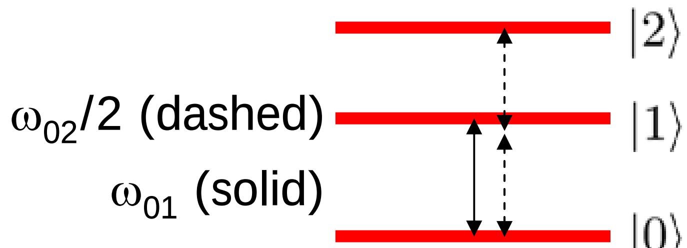




4 transmons coupled with a resonator

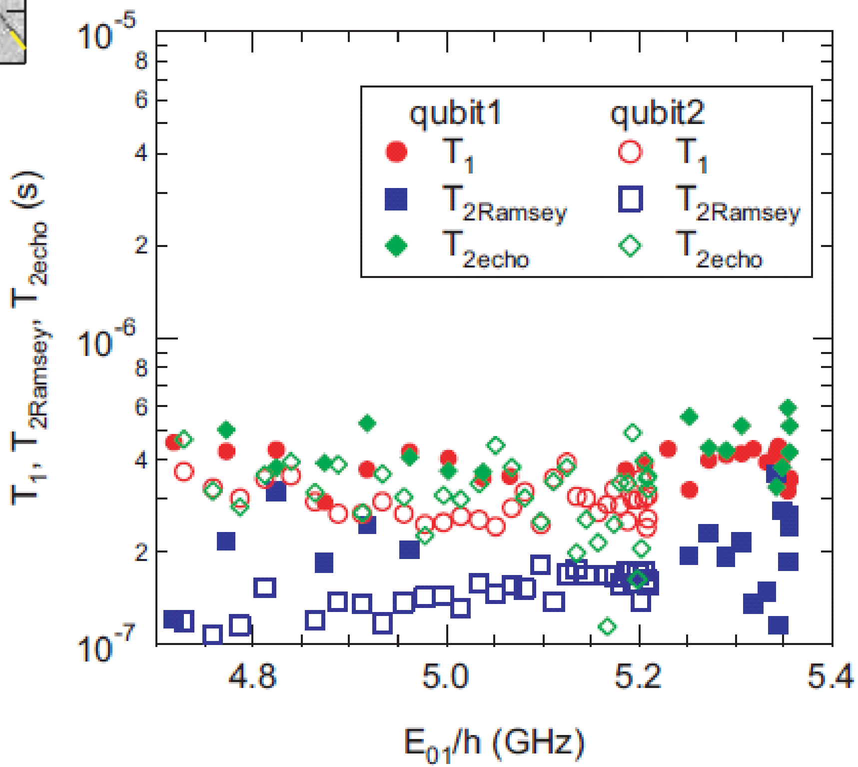
Qubit spectroscopy & decoherence time





$\omega_r/2\pi$ ~ 9.19 GHz

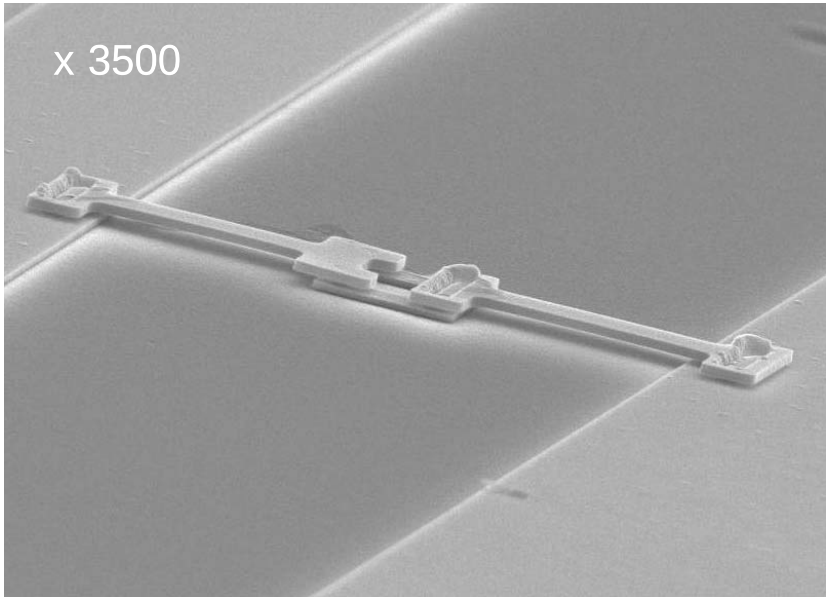
qubit 1: E_J/h = 13.4 GHz, E_c/h = 0.30 GHz
qubit 2: E_J/h = 11.7 GHz, E_c/h = 0.34 GHz
qubit-cavity coupling: g/h ~ 0.17 GHz

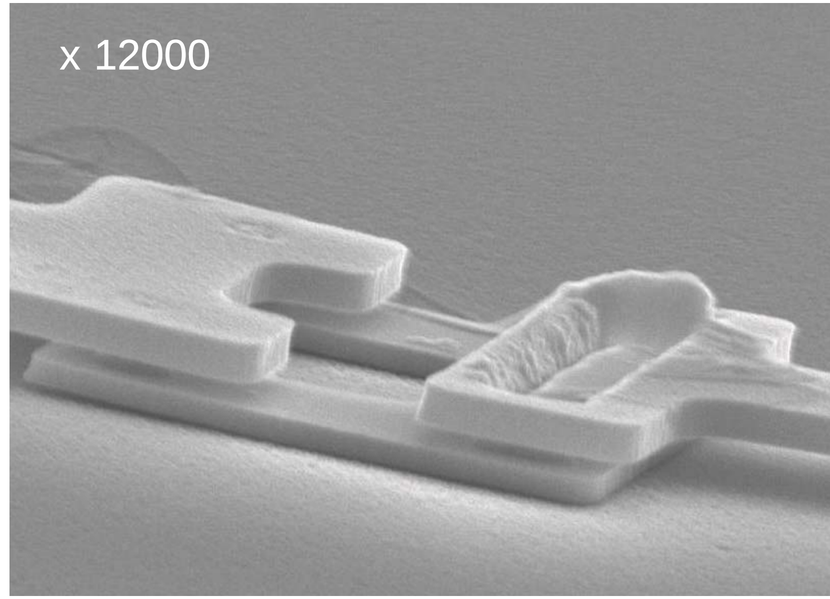


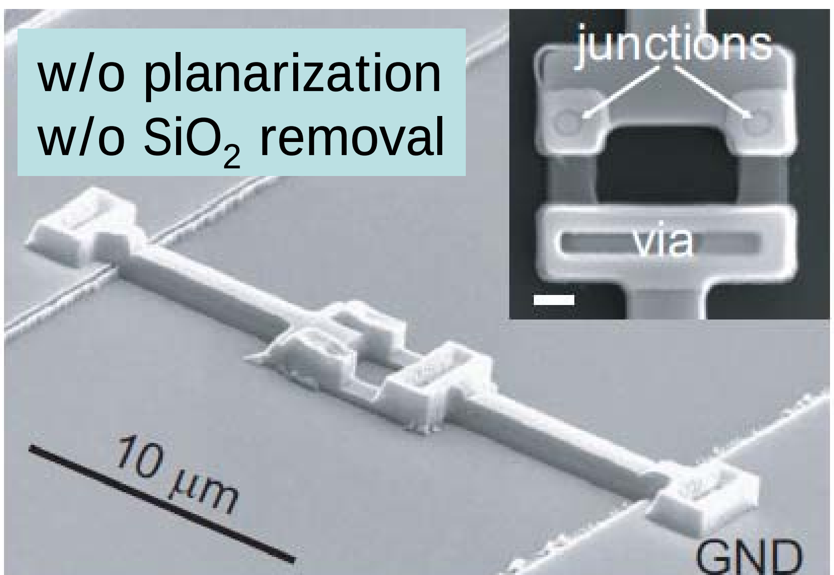
T_1	~ 250-450 ns
$T_{2Ramsey}$	~ 100-300 ns
T_{2echo}	~ 200-600 ns

Planarization and SiO_2 removal

H. Terai (NICT)







To be clarified:

- Defect density in the junctions
- Effect of dielectric removal
- Smaller junctions by e-beam lithography
- Dielectric loss of MgO substrate
- Other choice of substrate