Coherence in Josephson-Junction Qubits

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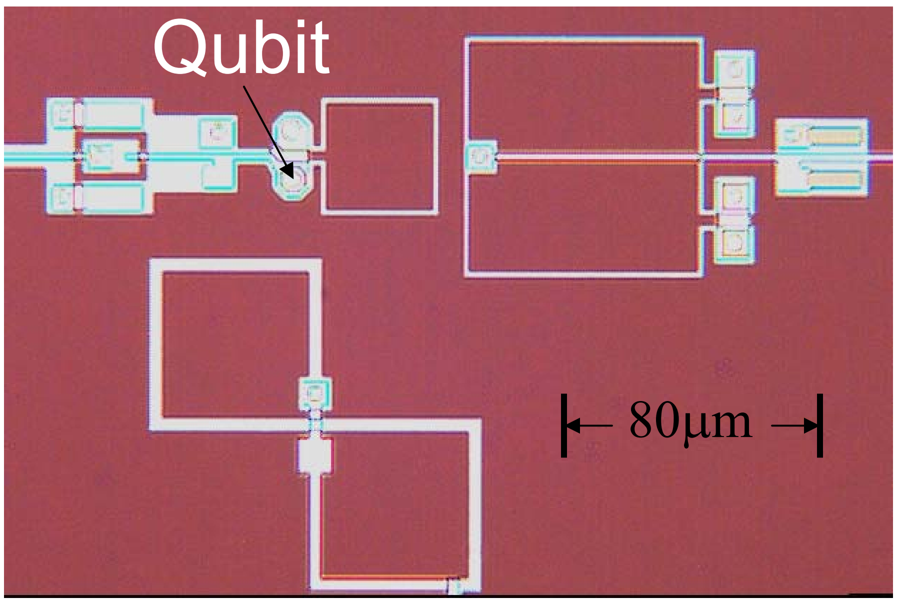

- "Atom" based on nonlinear microwave resonator
- Scalable system using IC fabrication

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Outline & Key Concepts

Introduction

- Superconductors : Intrinsically low dissipation
- Josephson Junctions : Strong non-linear element

Circuits work

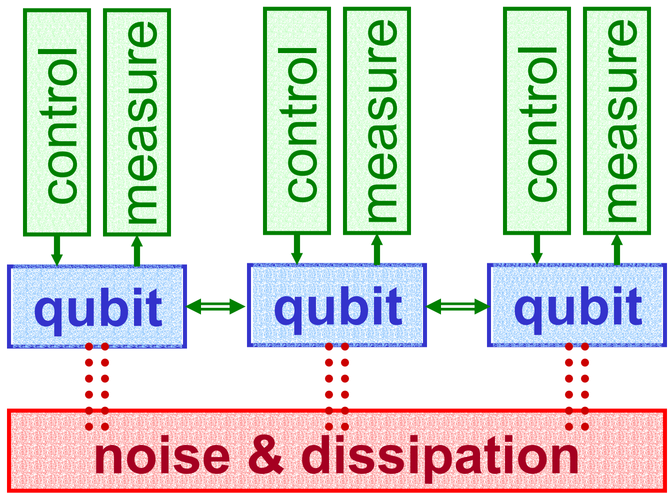
- 1-qubit logic : controlled with bias current
- 2-qubit gates : use linear coupling
- Impedance transformers : decouple qubit from leads
- Low dissipation qubit circuit, Rabi oscillations

Coherence

- New mechanism for decoherence – junction resonances
- Microscopic model (connects: I-V, 1/f noise, decoherence)
- Improve junction fabrication for better coherence
- *Preliminary* tests of coupled-qubits, time-domain

Circuits work well enough that we can study & improve coherence!

Challenge: Coupling vs. Decoherence



Experimental challenge:
Couple qubits to each other,
control, & measure,
not noise and dissipation

Experimental Systems

Atoms

Feynmann (1985):
"it seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms, and quantum behavior holds sway."

atomic

- Ions
- Neutral Atoms
- NMR

mesoscopic

- Spin
- Semiconductor spin
- Quantum Dot

Experimental Systems

Feynmann (1985):
"it seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms, and quantum behavior holds sway."

Atoms | **EM modes**

- Photons

atomic

- Ions
- Neutral Atoms
- NMR

mesoscopic

- Spin
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- Quantum Dot

microscopic

- Superconductor SET
- 2-Degenerate SSET
- 3 Junction SQUID
- RF SQUID
- Josephson Junctions (this work)

Coherence easier

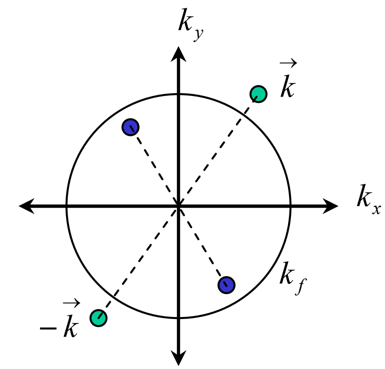
Coupling easier

Charge
(NEC, Chalmers)
(Saclay)

(Delft)
Flux
(MIT)

Phase
(NIST, Kansas)

Quantum Integrated Circuits



- No Dissipation: Superconductivity

  Phase degree of freedom: ϕ

  Cooper pairs – states of zero momentum

  Only remaining degree of freedom is ϕ

  Supercurrent: $j_s \propto \nabla \phi$

  Energy gap of excitations: $2\Delta \approx 3.5\ kT_c$

  No dissipation for $\mathrm{hf} < 2\Delta$ (80 GHz for Al)

$$\Psi = \prod_k \left(u_k + v_k e^{i\phi} c_k^+ c_{-k}^+ \right) |\ 0\ \rangle$$

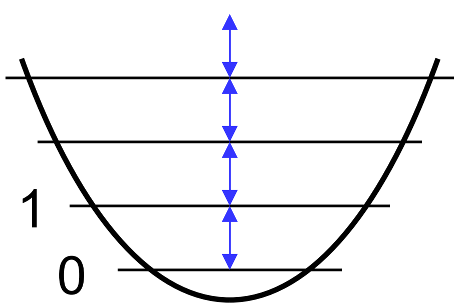
- Suppression of Thermal Noise: kT << hf

  Dilution refrigeration: 20 mK << 0.5 K (10GHz)

- Non-linearity: Josephson effect

$$\phi_L - \phi_R = (2\,e/\hbar) \int V dt$$

$$= (2\pi/\Phi_0)\ \Phi$$



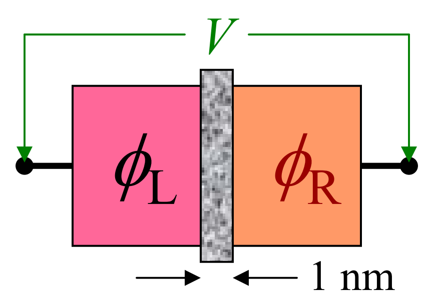
$$I \propto \left\langle \Psi \middle| T c_{kL} c_{-kL} c_{kR}^+ c_{-kR}^+ \middle| \Psi \right\rangle - c.c.$$

$$\propto e^{i\phi_L} e^{-i\phi_R} - c.c.$$

$$= I_0 \sin(\phi_L - \phi_R)$$

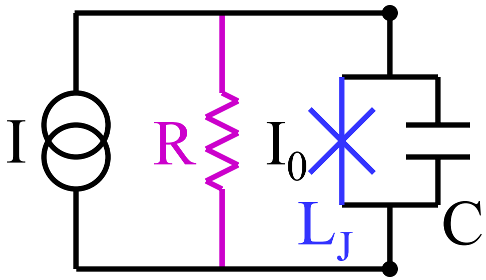
$$I = I_0 \sin(\ \Phi\ 2\pi/\Phi_0\ )$$

Non-linear Inductor



Large Δ gives no dissipation from junction imperfections

Qubit: Nonlinear LC resonator



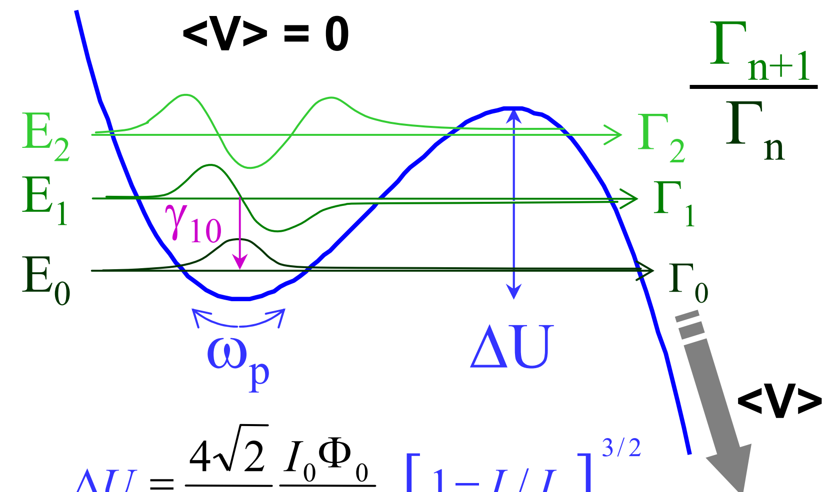
$$I = I_0 \sin\delta$$

$$V = \frac{\Phi_0}{2\pi}\dot{\delta}$$

$$\dot{I}_j = I_0 \cos\delta \ \dot{\delta} \equiv (1/L_J)V$$

$L_J = \Phi_0/2\pi I_0 \cos\delta$
nonlinear inductor

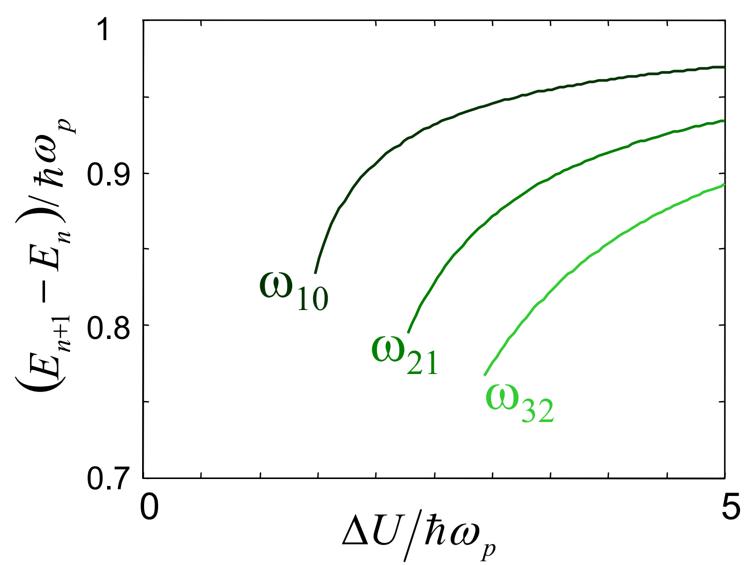
U(δ)



$$\frac{\Gamma_{n+1}}{\Gamma_n} \sim 1000$$

$$\Delta U = \frac{4\sqrt{2}}{3}\frac{I_0\Phi_0}{2\pi}\left[1 - I/I_0\right]^{3/2}$$

$$\omega_p = \left(\frac{2\sqrt{2}\pi}{\Phi_0}\frac{I_0}{C}\right)^{1/2}\left[1 - I/I_0\right]^{1/4}$$

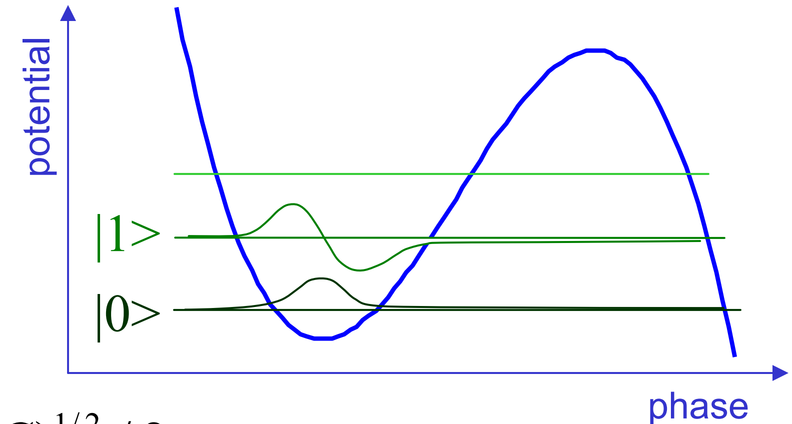


$\gamma_{10} \cong 1/RC$ Lifetime of state |1>

Josephson-Junction Qubit

- State Preparation

  Wait $t > 1/\gamma_{10}$ for decay to $|0>$



- Qubit logic with bias control

$$I = I_{dc} + \delta I_{dc}(t) + I_{\mu wc}(t)\cos\omega_{10}t + I_{\mu ws}(t)\sin\omega_{10}t$$

$$\begin{aligned} H_{(2)} &= \sigma_x \bullet I_{\mu wc} \bullet (\hbar / 2\omega_{10}C)^{1/2} / 2 \\ &+ \sigma_y \bullet I_{\mu ws} \bullet (\hbar / 2\omega_{10}C)^{1/2} / 2 \\ &+ \sigma_z \bullet \delta I_{dc}(t) \bullet (\partial E_{10}/\partial I_{dc})/2 \end{aligned}$$

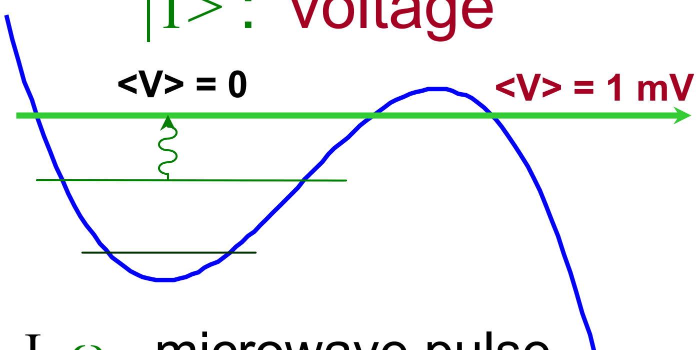
- State Measurement (Junction acts as "photomultiplier")

  $|0>$: zero voltage

  $|1>$: voltage

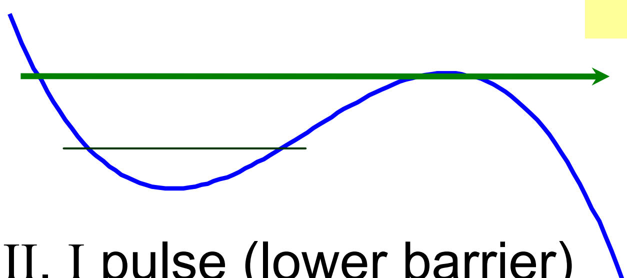
With $\Gamma_i/\Gamma_{i-1} \sim 500$

Expect fidelity > 95-99+% !!



I. ω_{21} microwave pulse

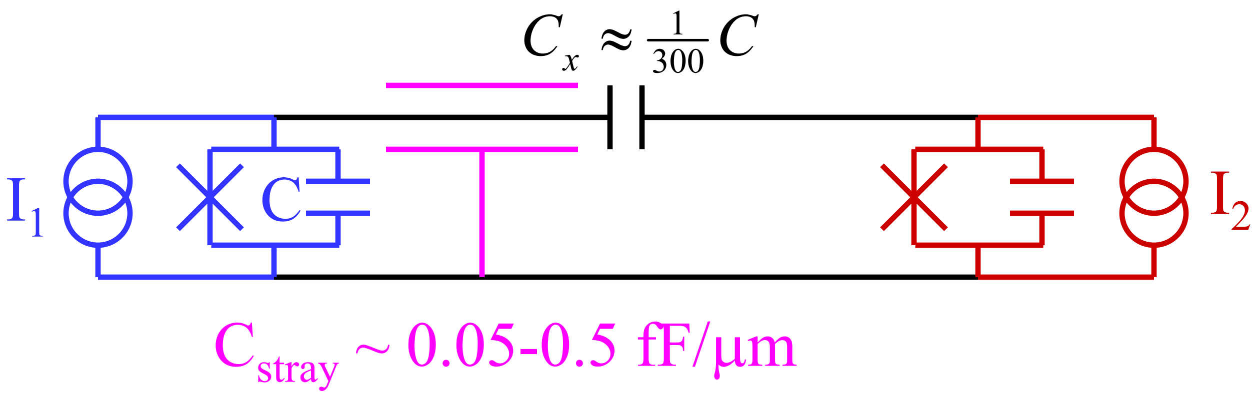
τ_{meas} ~100 ns, Fidelity ~90%



II. I pulse (lower barrier)

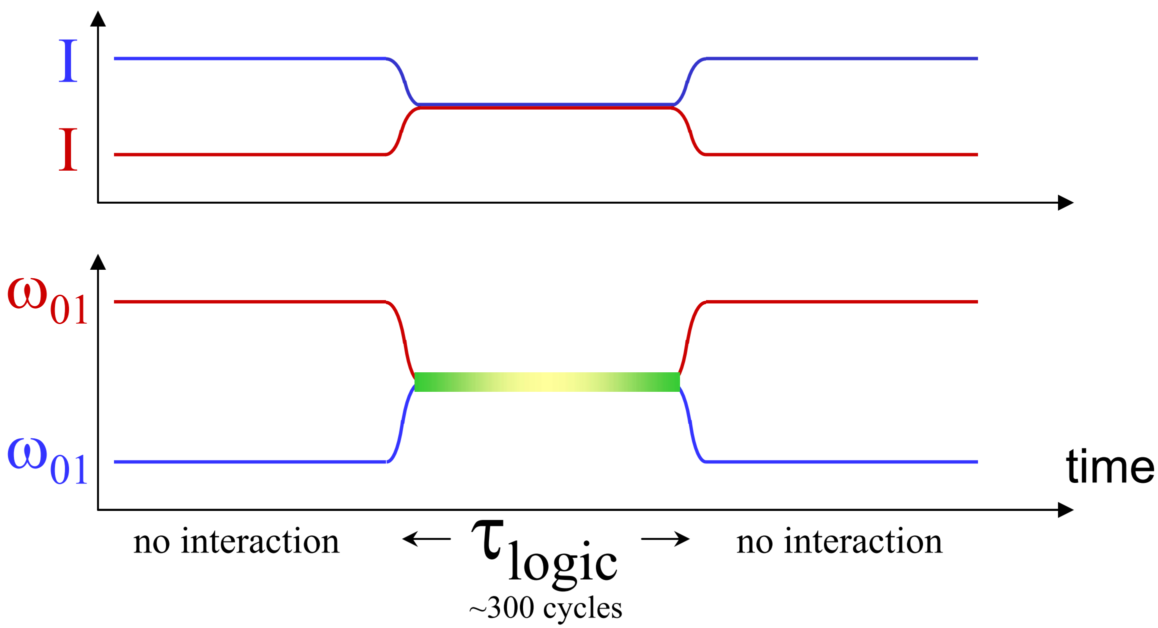
τ_{meas} ~5 ns, Fidelity ~70%

Qubit Logic with Capacitive Coupling



$$H_{\mathrm{int}} \propto C_x q_1 q_2$$
$$\propto \sigma_{y1} \sigma_{y2}$$

Turn-off interaction with single qubit operations (eg. NMR)



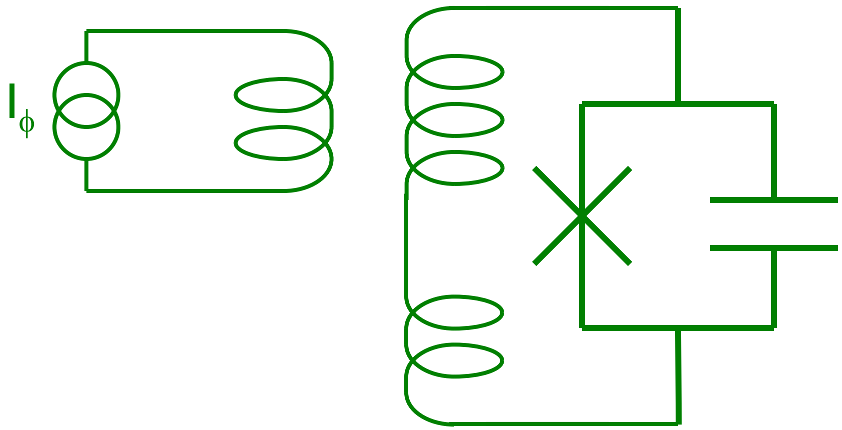
Modulate interaction by de-tuning resonance frequencies

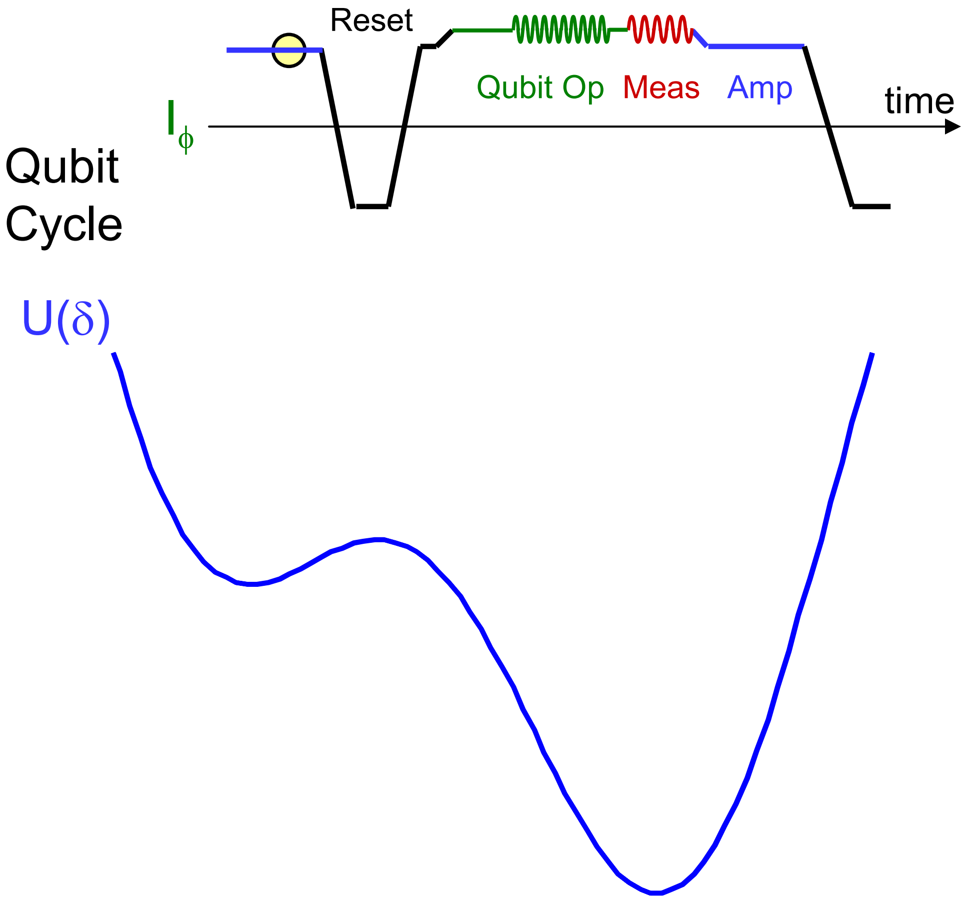
Theory (Maryland): CNOT & Phase gates

Experiment (Maryland) Level splittings

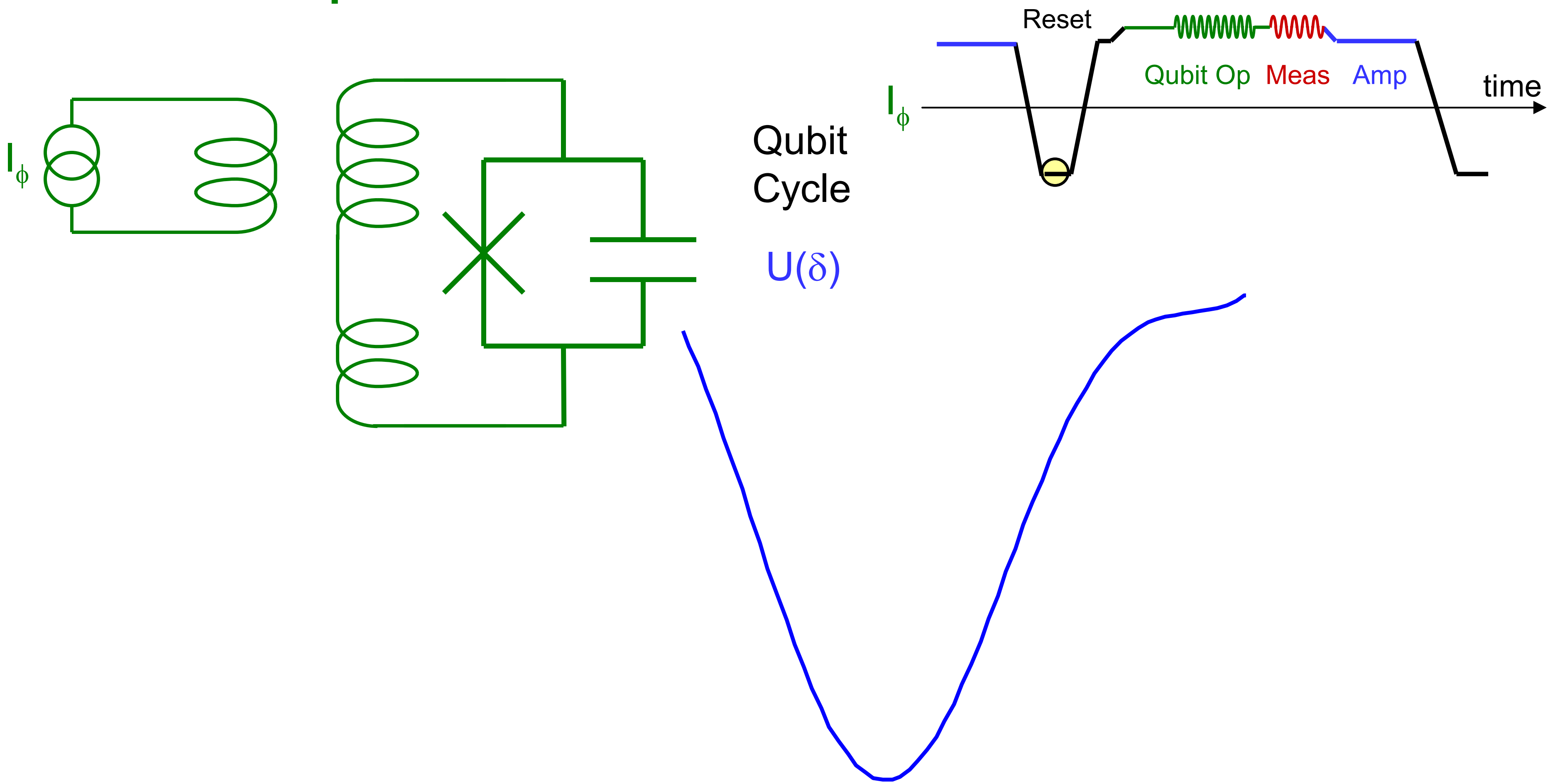
Large junctions – C_{stray} unimportant
Coupling to more qubits, lower crosstalk

Qubit operation → Measurement → Readout

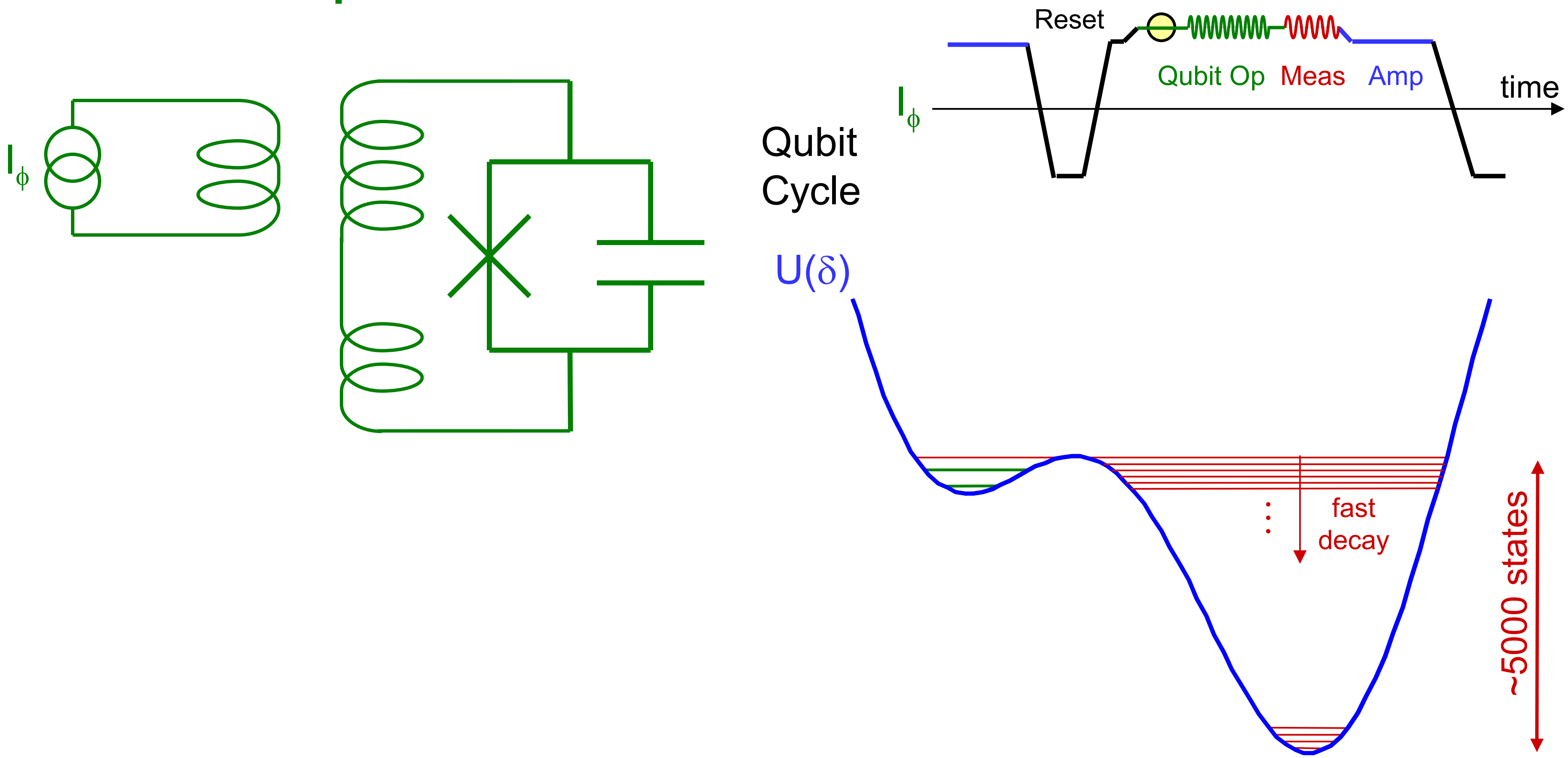




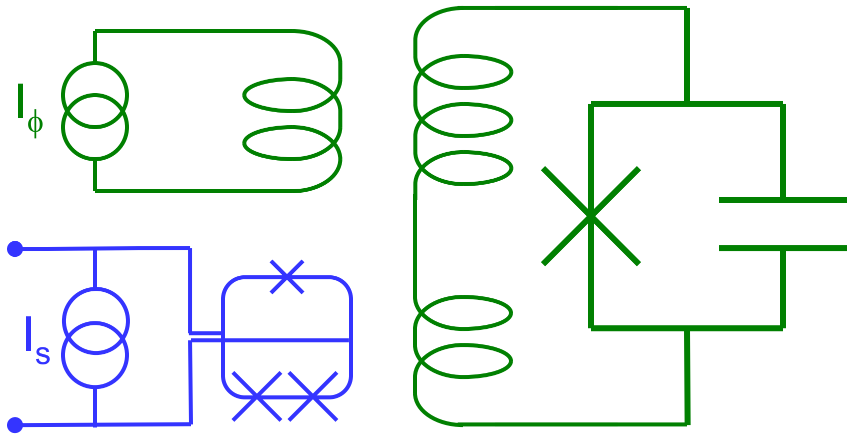
Qubit operation → Measurement → Readout

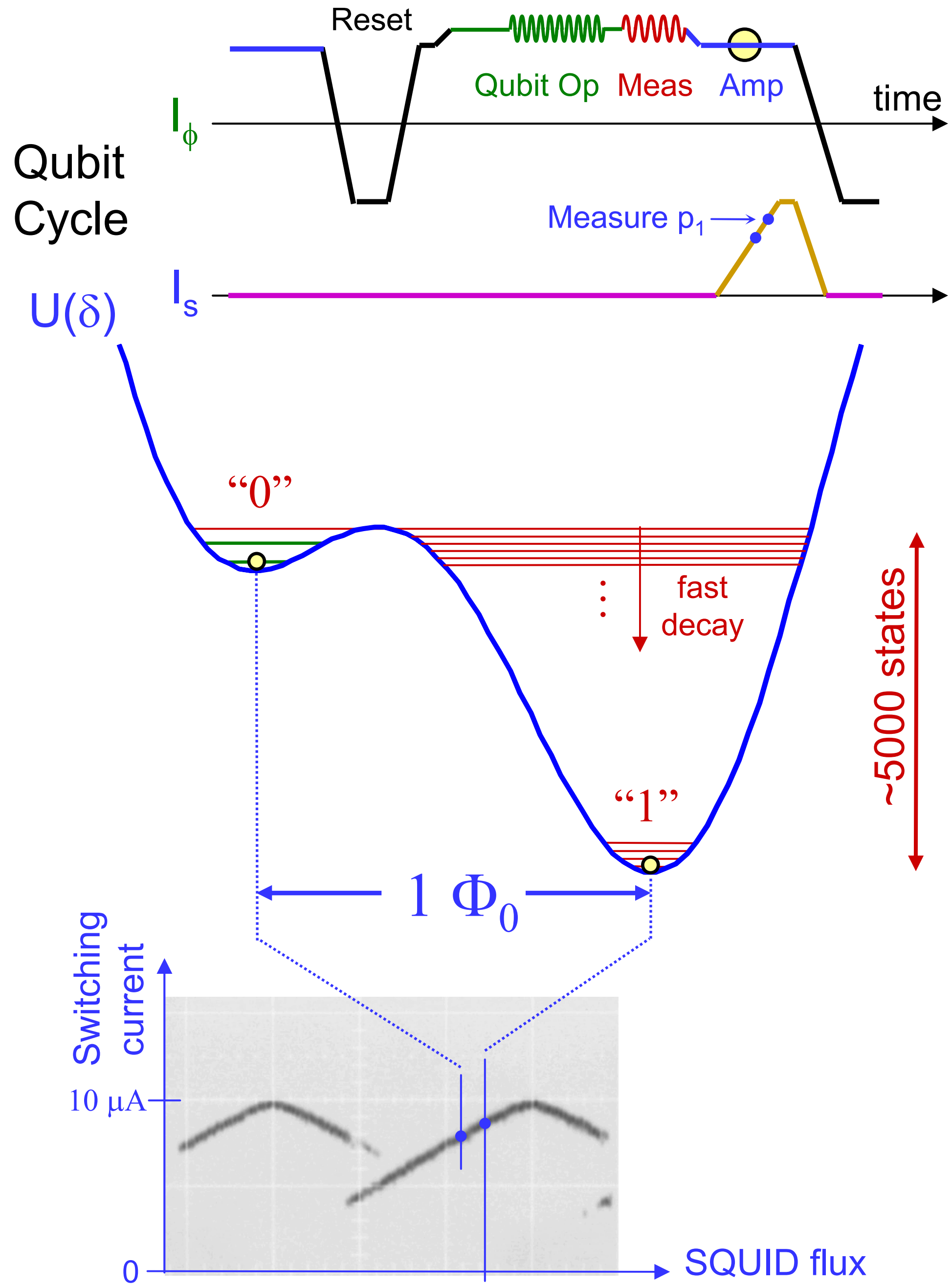


Qubit operation → Measurement → Readout

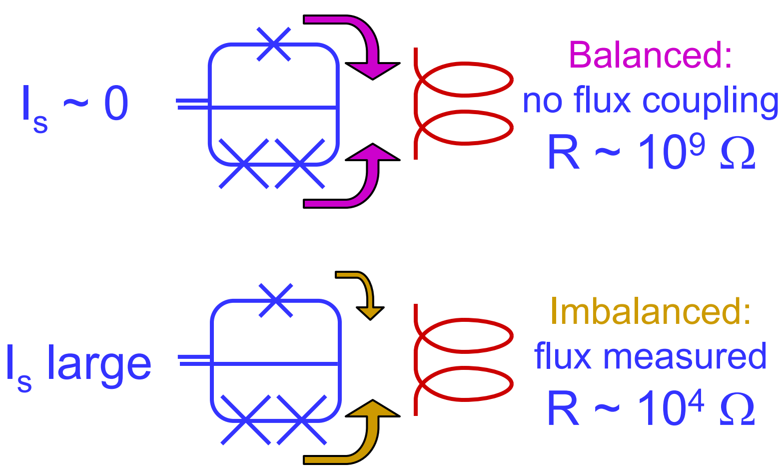


Qubit operation → Measurement → Readout

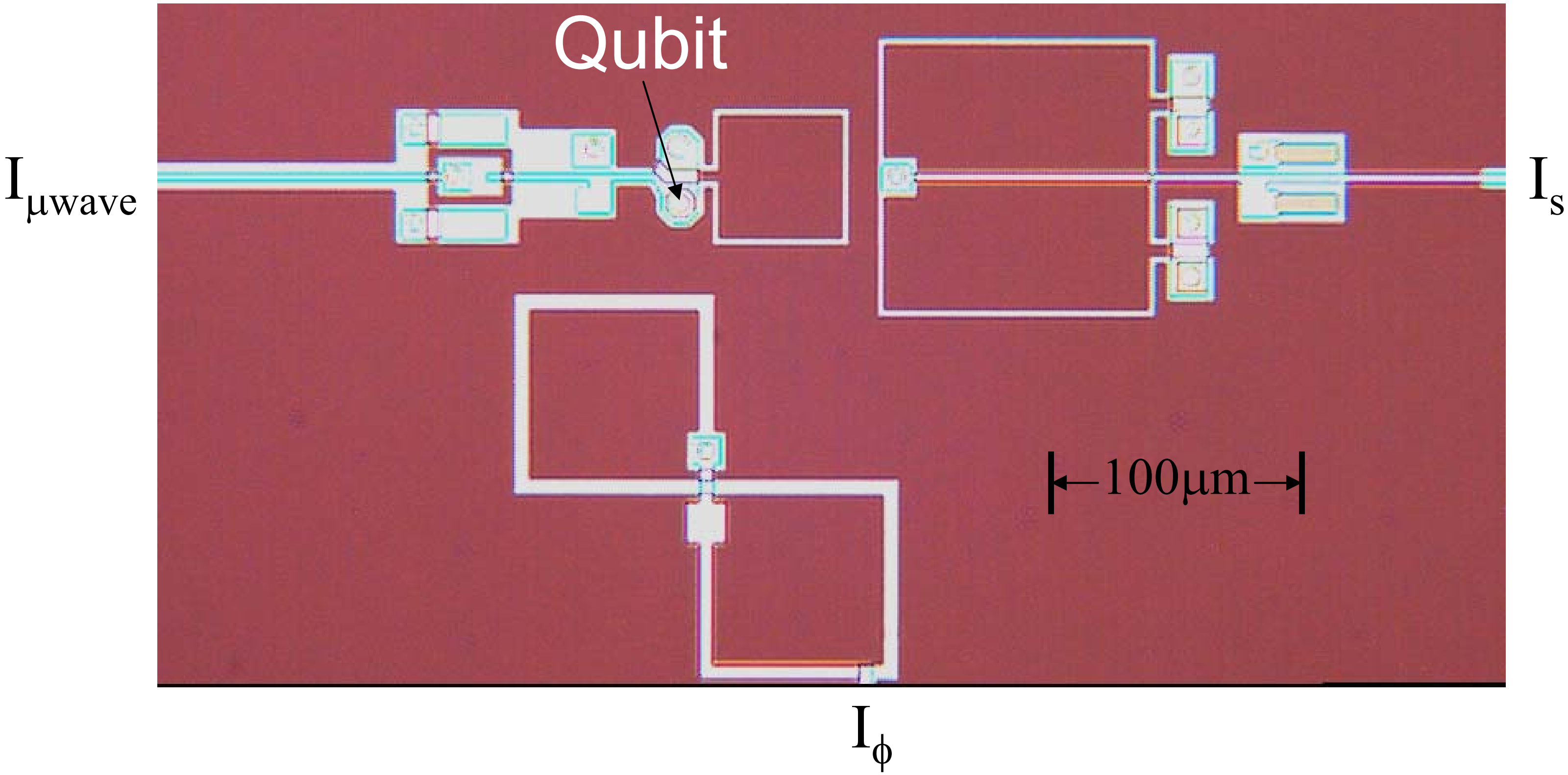




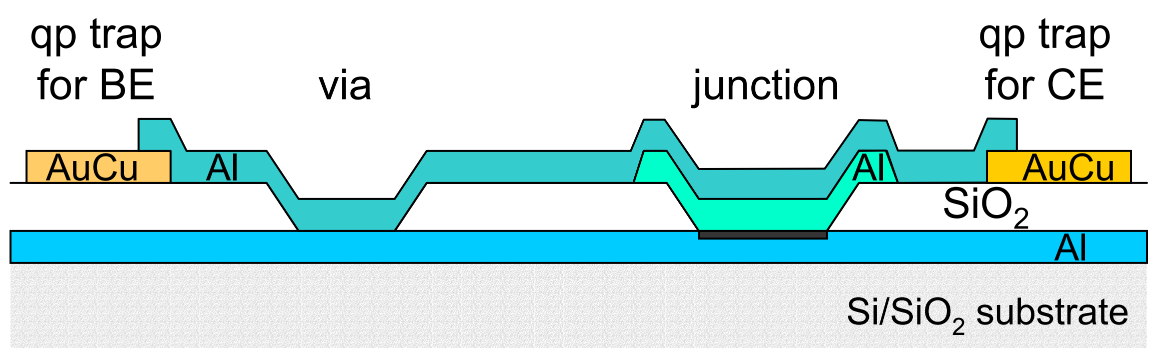
Amplifier (and its dissipation!)
turned on & off with I_s
- Adjustable T_1 -



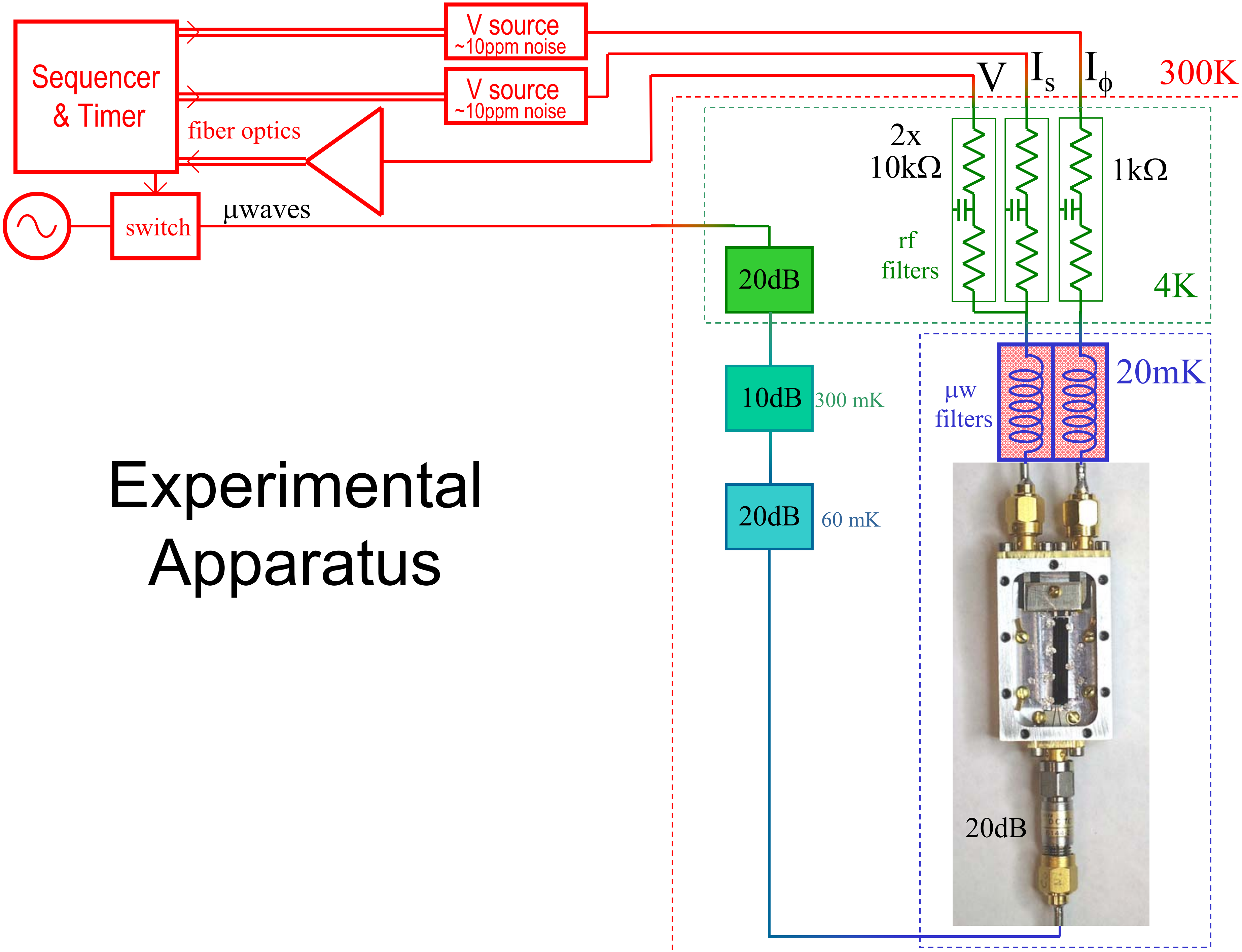
IC Fabrication



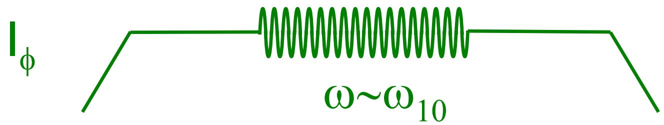
Al junction process
& optical lithography

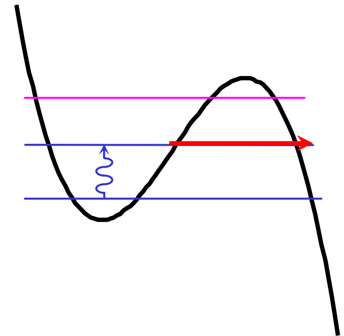


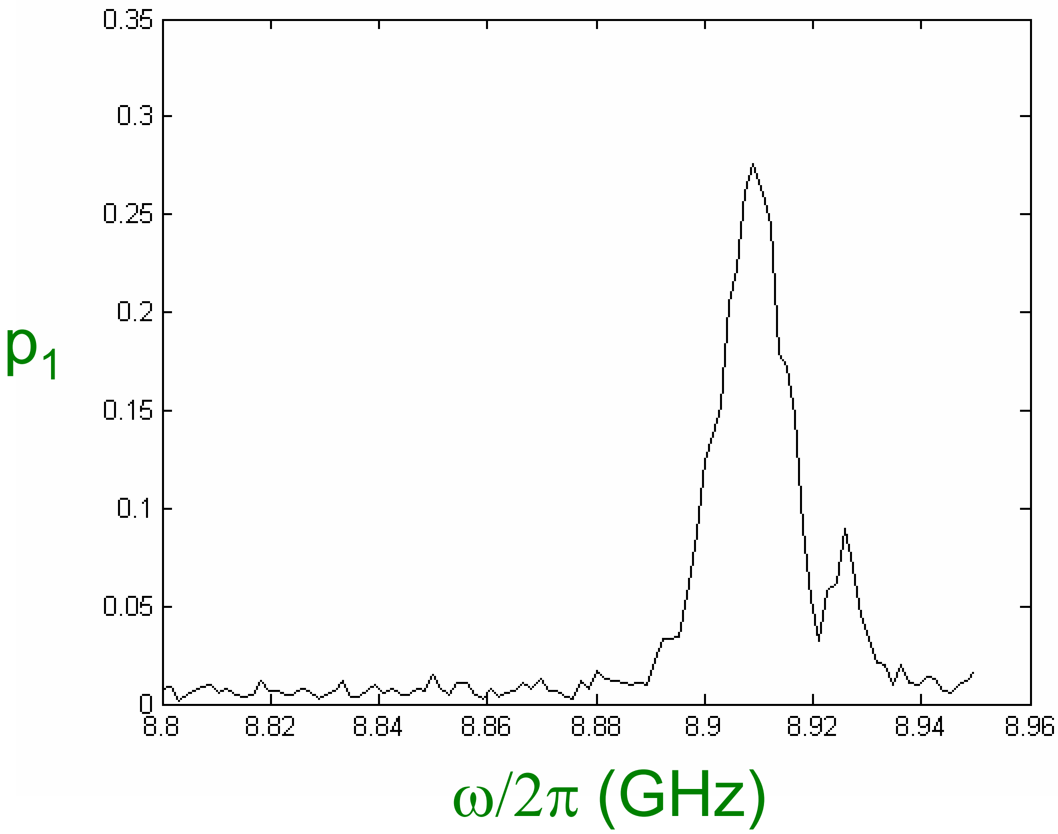
Experimental Apparatus



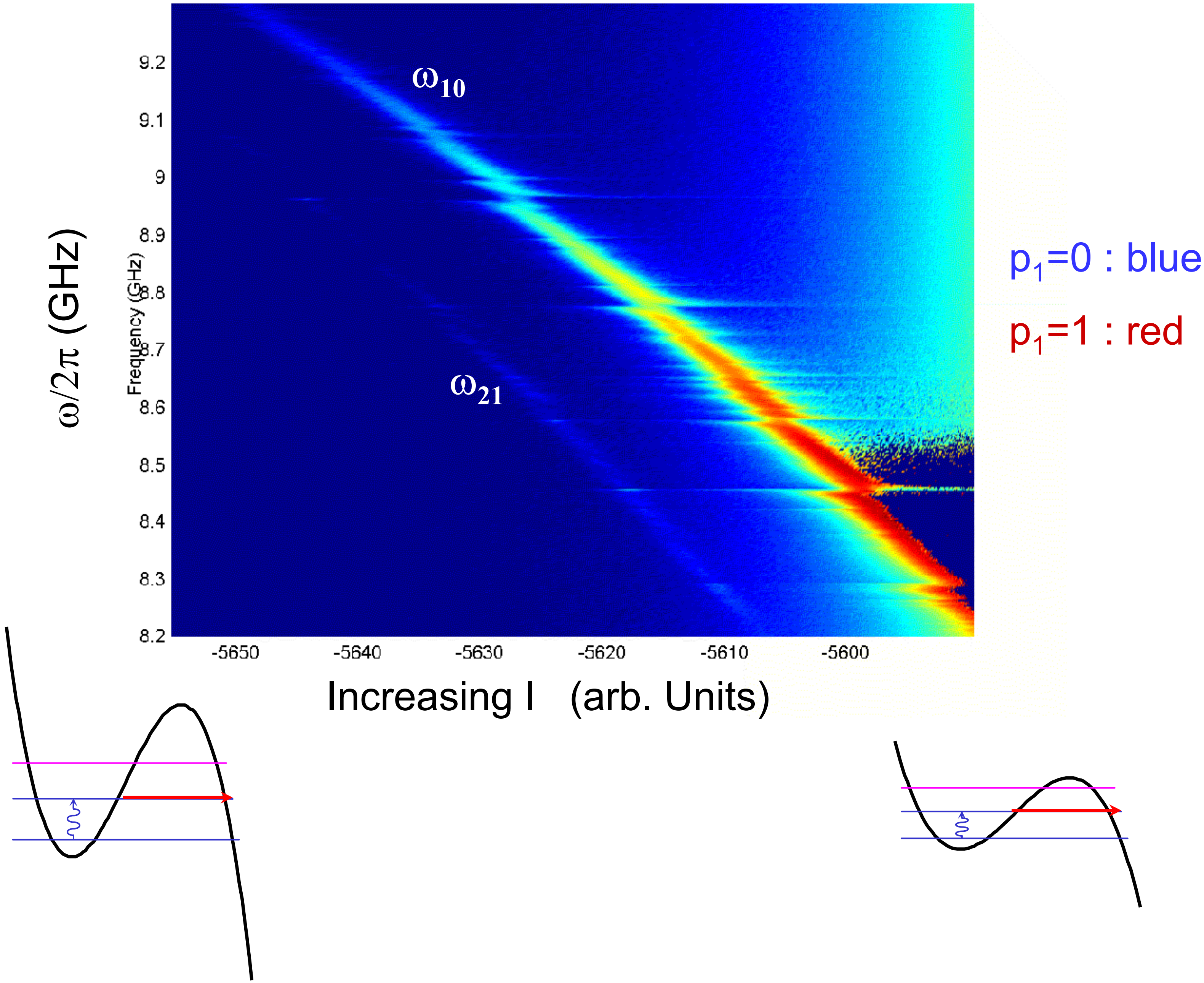
Spectroscopy



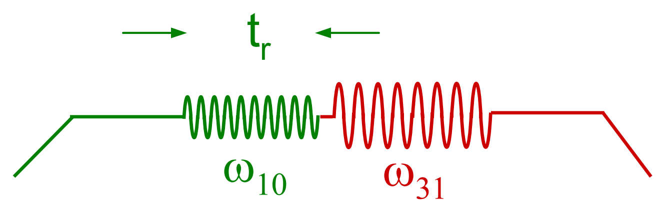


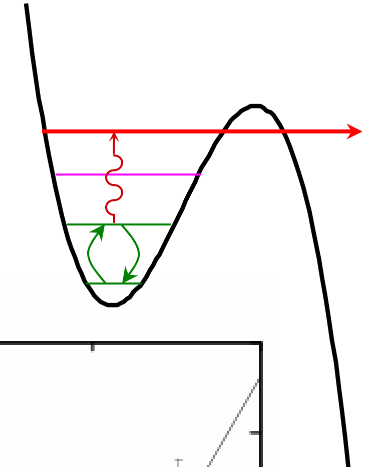


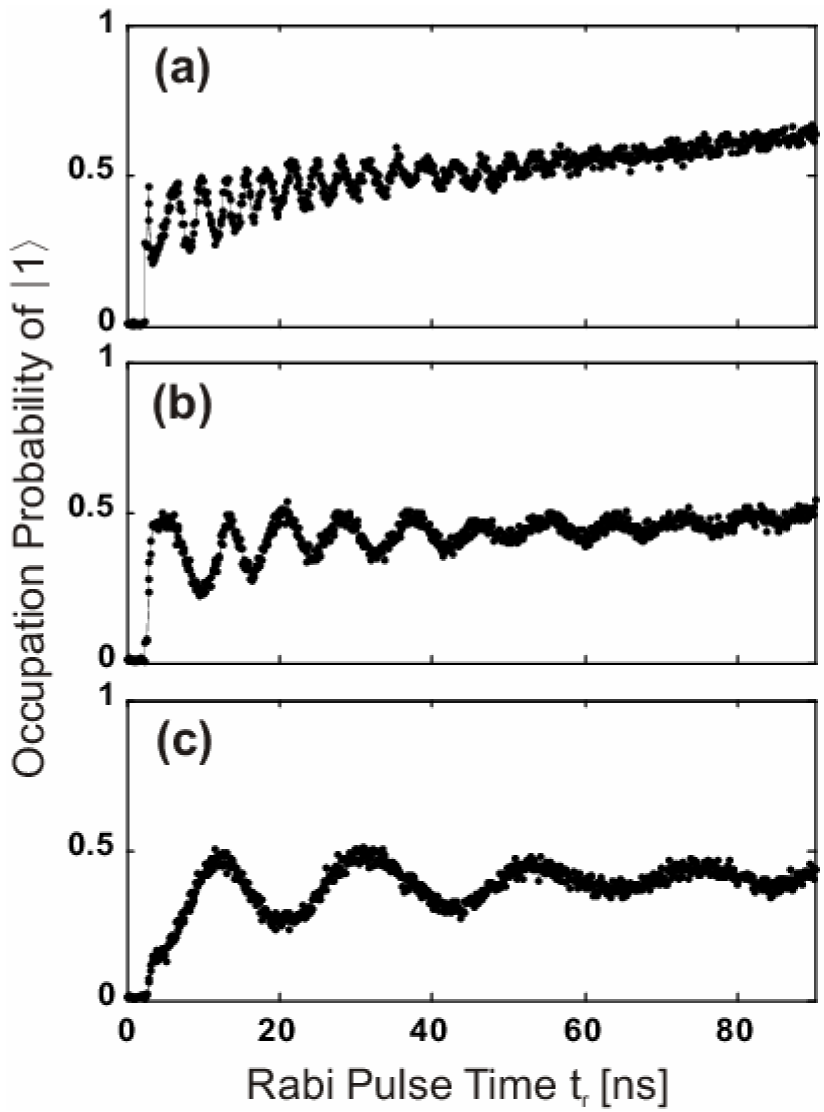
Energy Levels vs. Bias Current

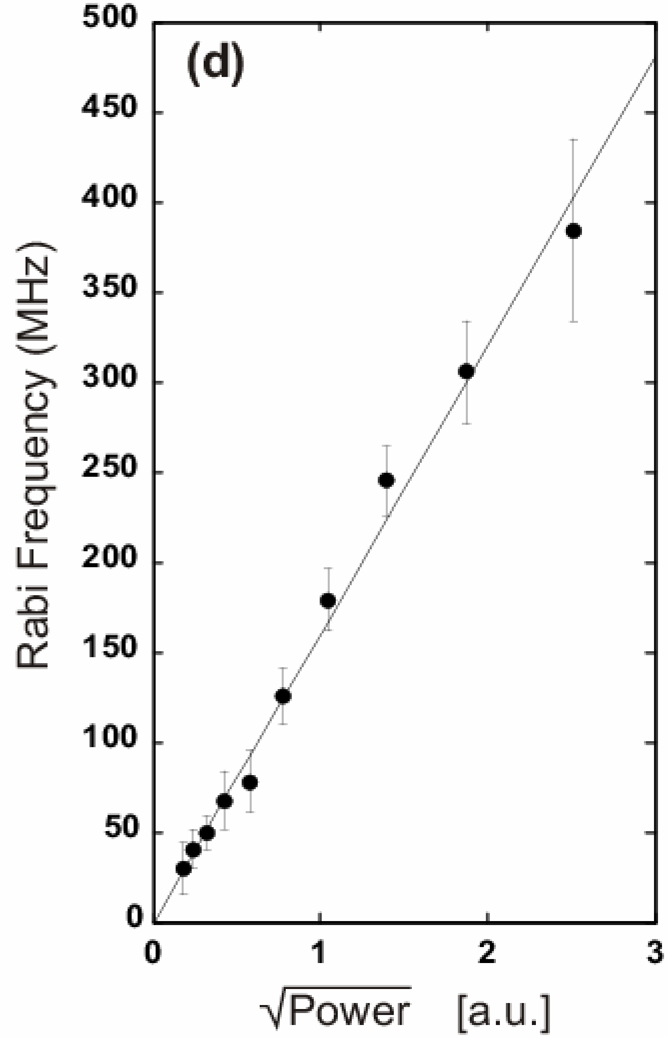


Rabi Oscillations

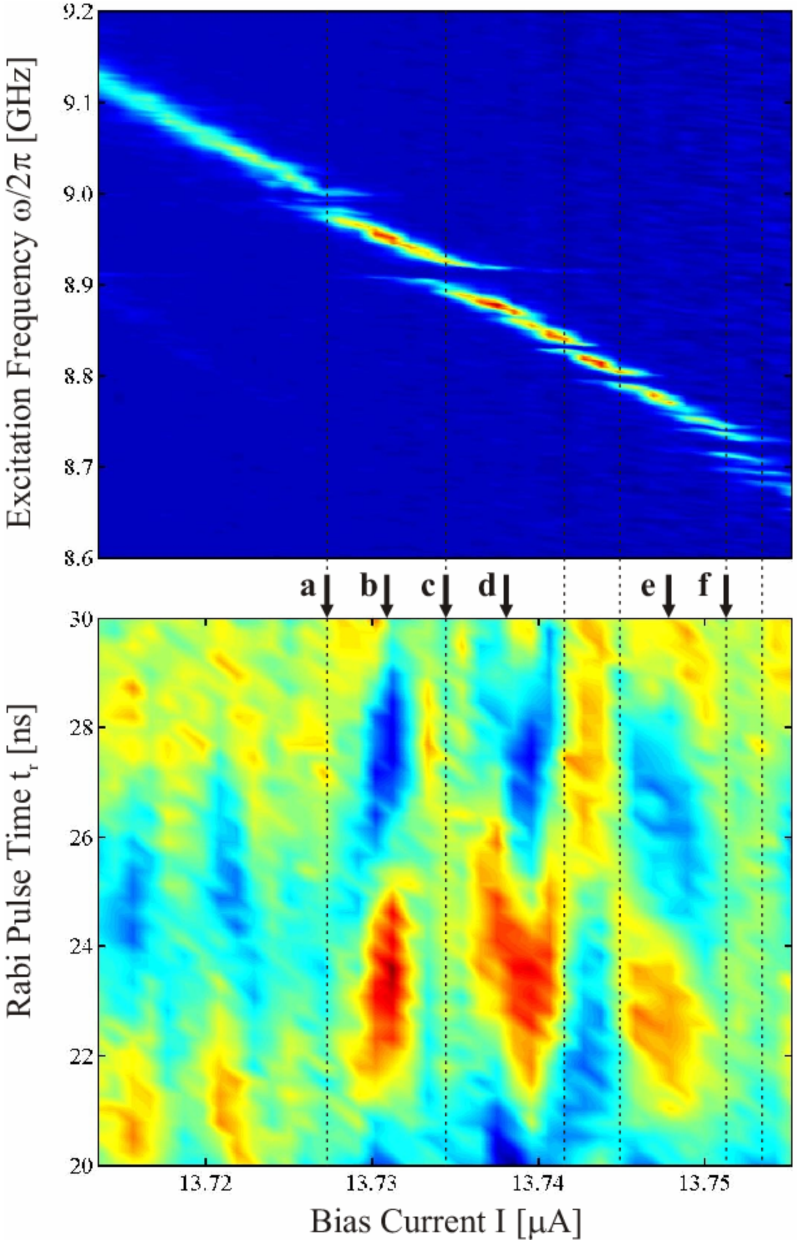






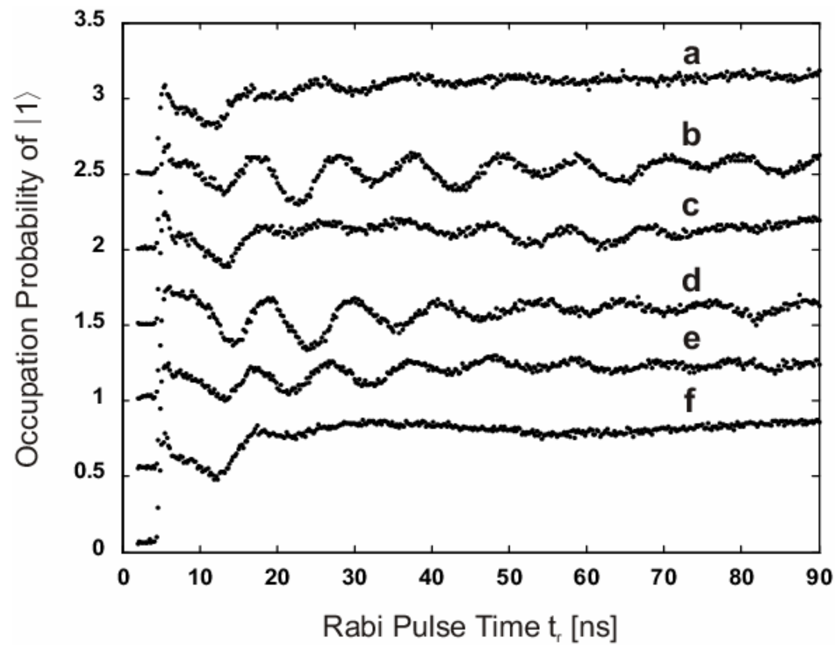


Resonances & Rabi Oscillations



$p_1=0$: blue

$p_1=1$: red

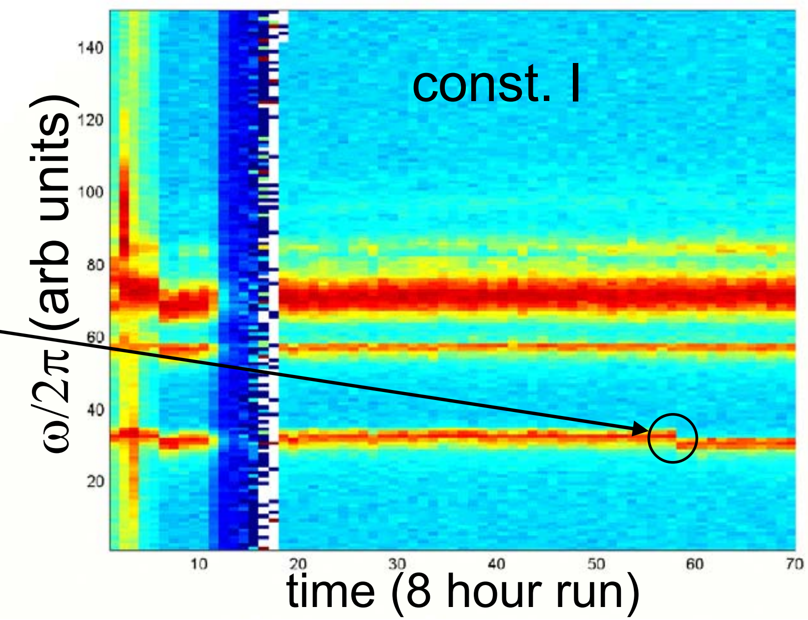


Rabi oscillations disappear at spurious resonances

Reduced coherence amplitude

What causes extra resonances?

- Resonance `fingerprint' changes at 300K (not 4K)
- Frequency shifts rule-out macroscopic EM modes
- Model as modulation of I_0 from resonant defect motion

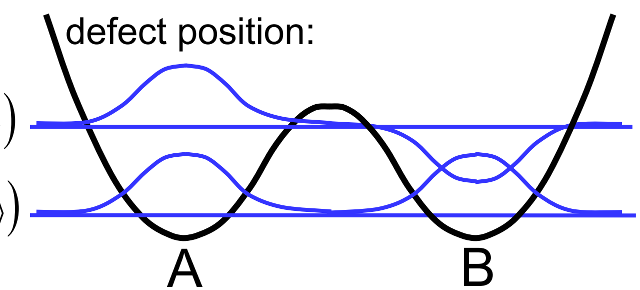


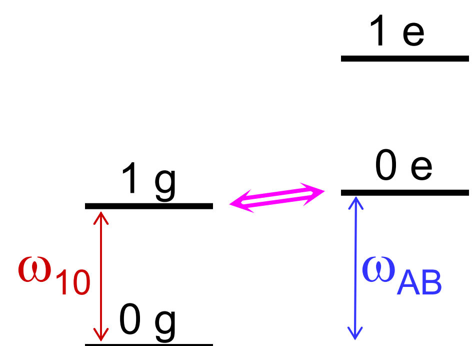
$$H_{\text{int}} = \left(-\frac{\Phi_0 I_{0A}}{2\pi} \cos\delta \right) \otimes |\Psi_A\rangle\langle\Psi_A| + \left(-\frac{\Phi_0 I_{0B}}{2\pi} \cos\delta \right) \otimes |\Psi_B\rangle\langle\Psi_B|$$

$$= \frac{\Delta I_0}{2}\sqrt{\frac{\hbar}{2\omega_{10} C}} \left(|0\rangle\langle 1| \otimes |e\rangle\langle g| + |1\rangle\langle 0| \otimes |g\rangle\langle e| \right)$$

$$|e\rangle = 2^{-1/2}\left(|\Psi_A\rangle - |\Psi_B\rangle \right)$$

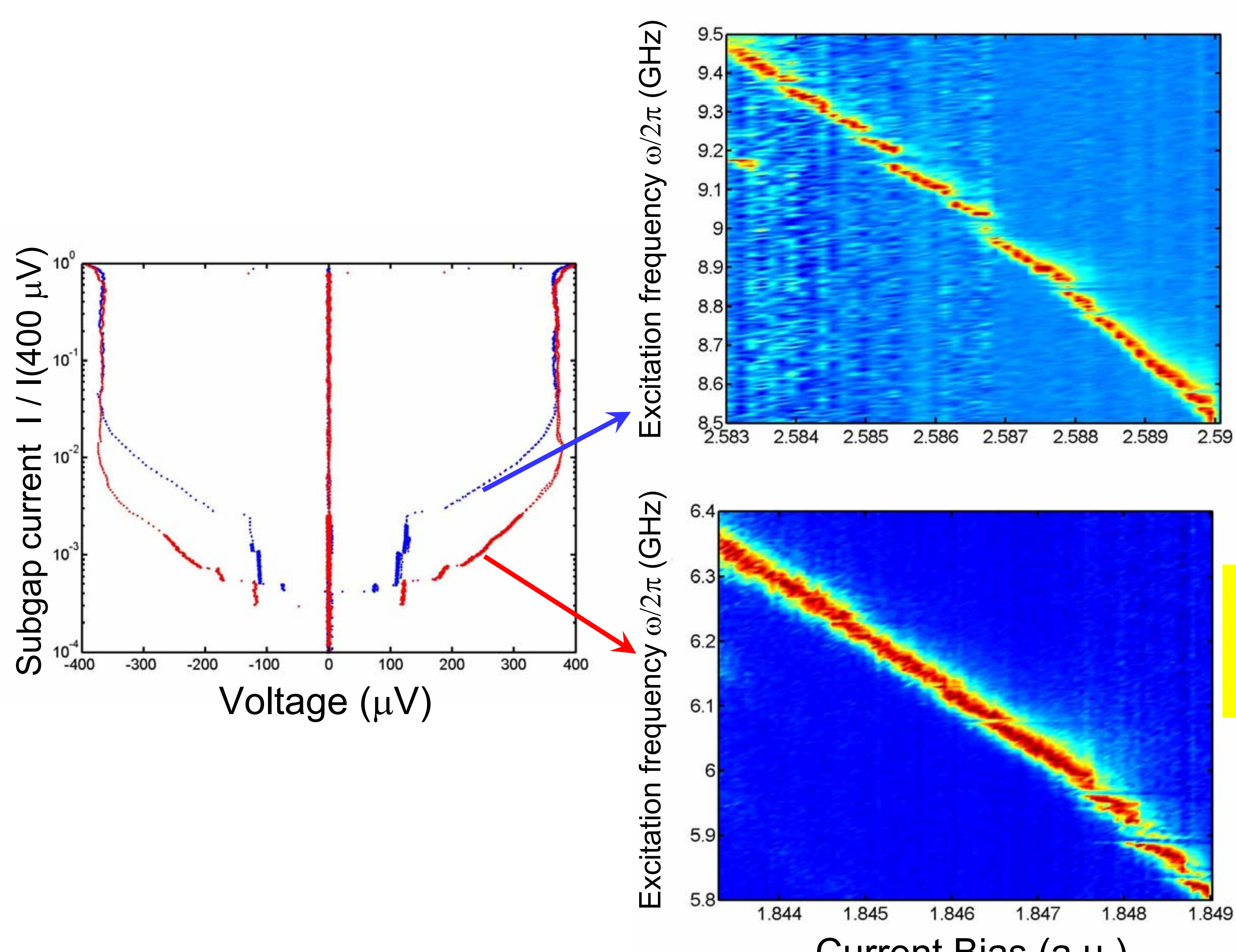
$$|g\rangle = 2^{-1/2}\left(|\Psi_A\rangle + |\Psi_B\rangle \right)$$





Explains energy-level repulsion

Resonance Size Correlated with Fabrication !

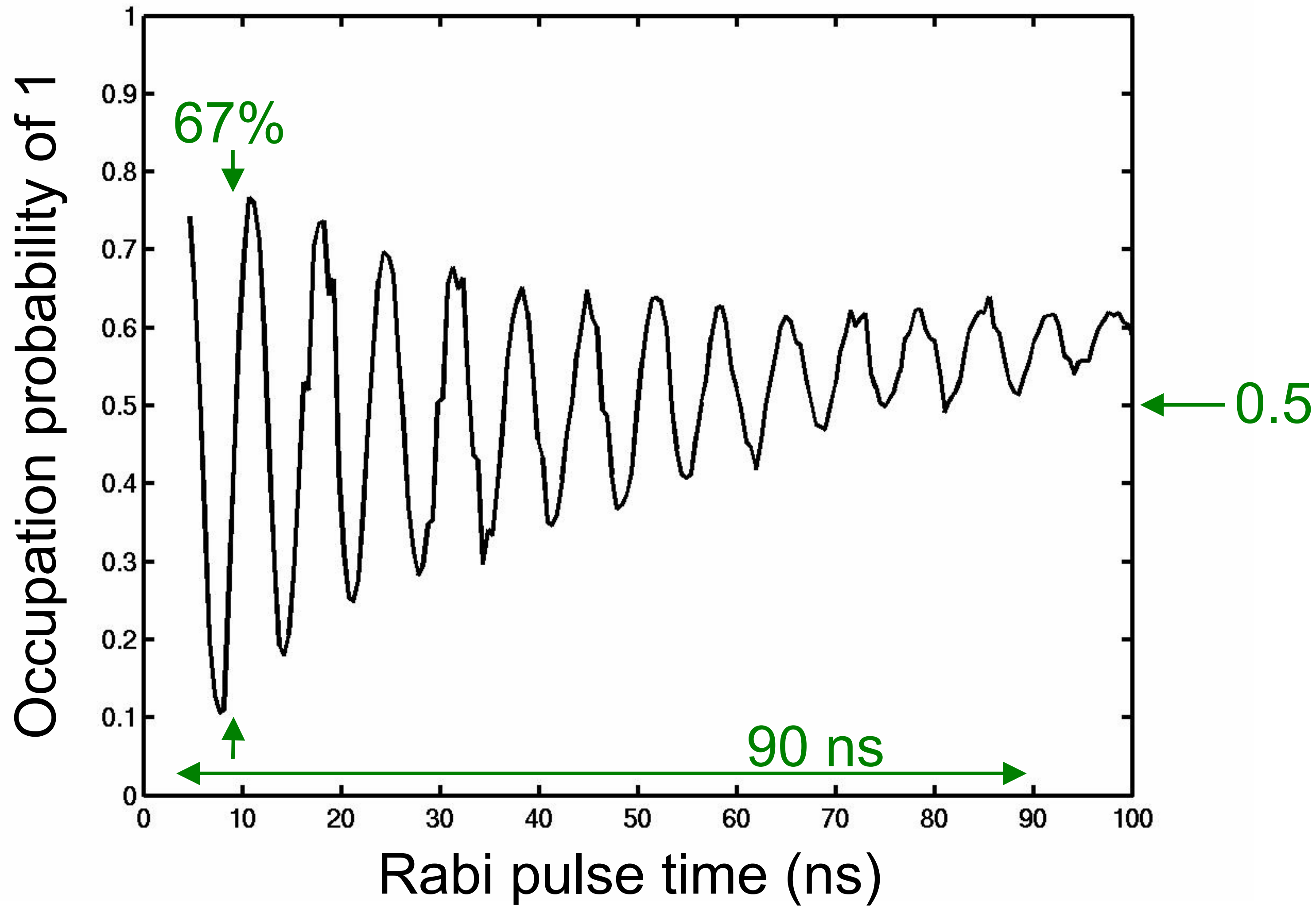


Al
Ion Mill clean
Oxidize
Al

"Clean" Fab. :
Lower subgap I
Smaller Res.

Al
Oxidize
Al

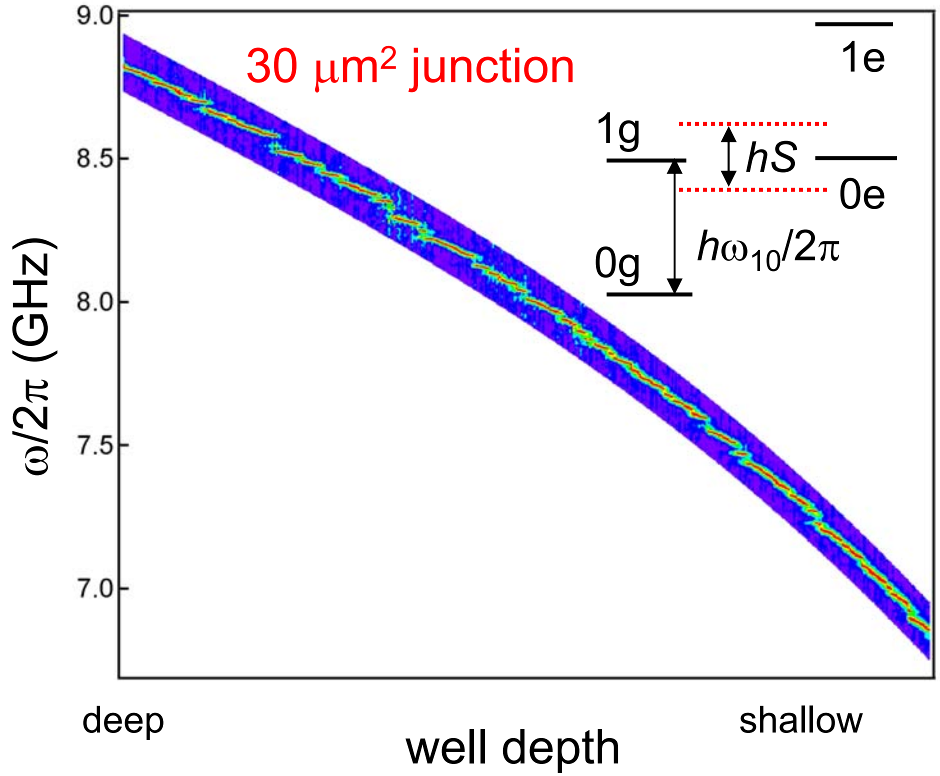
Rabi Oscillations for Trilayer Junction

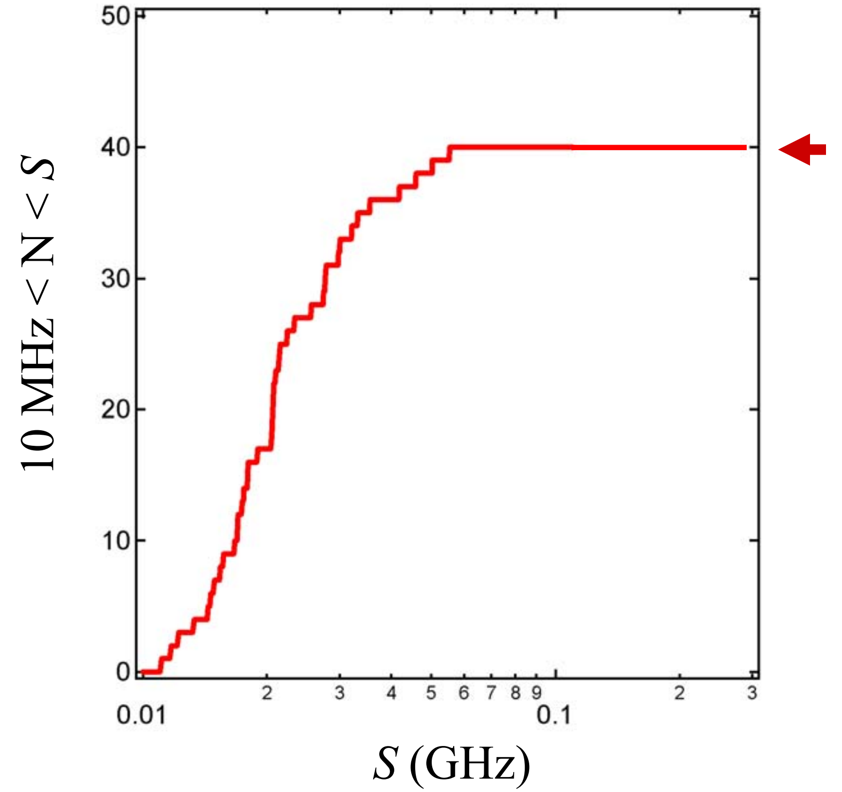


15 qubits: Typically 40-50% amplitude

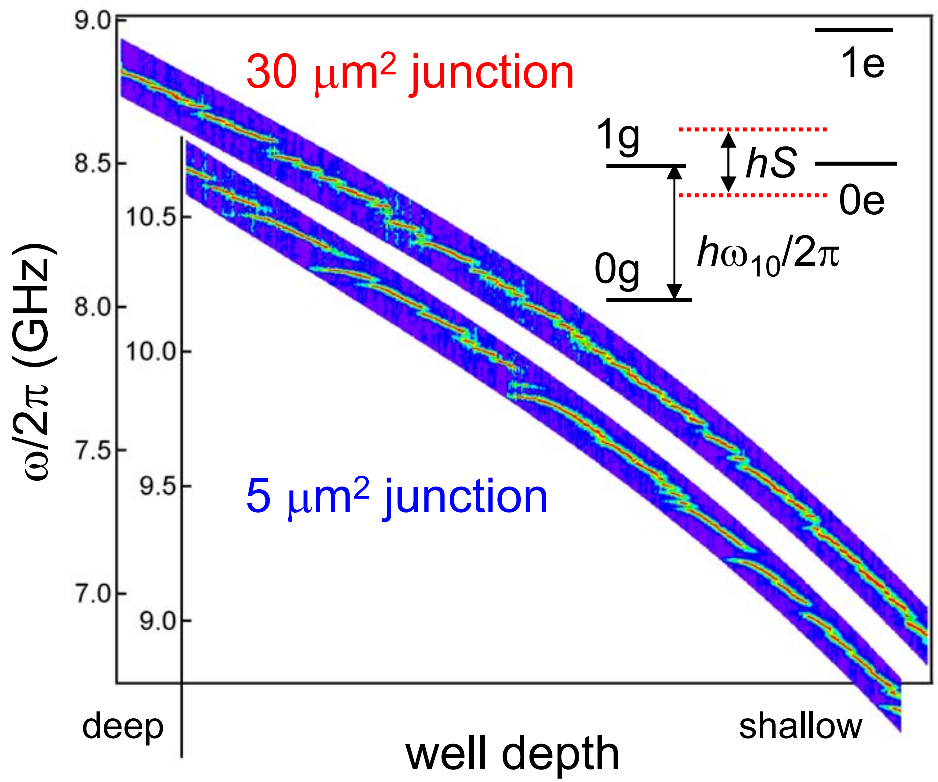
Resonator Magnitudes

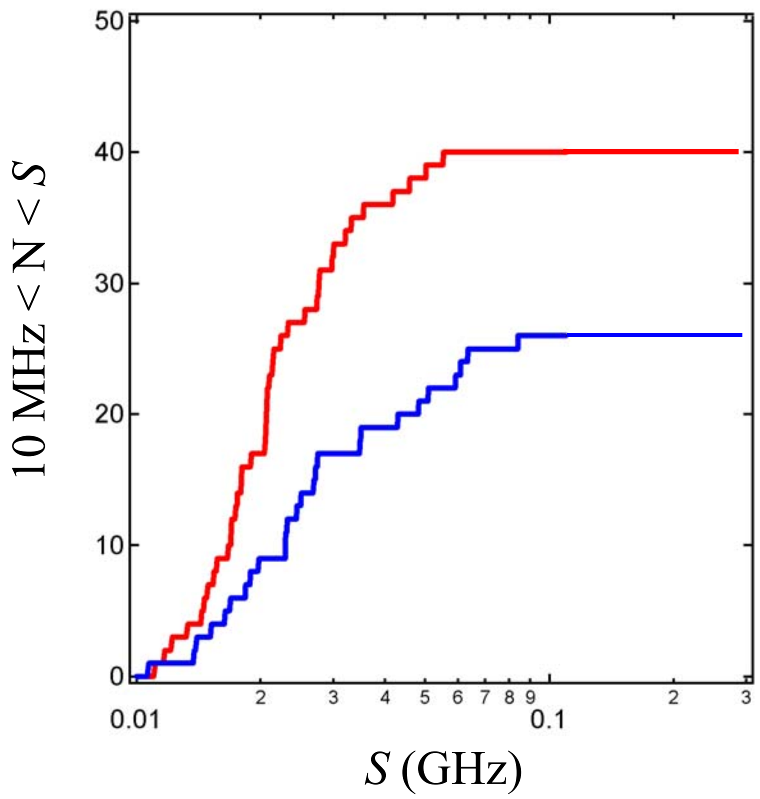
Cutoff understood from channel-conductance



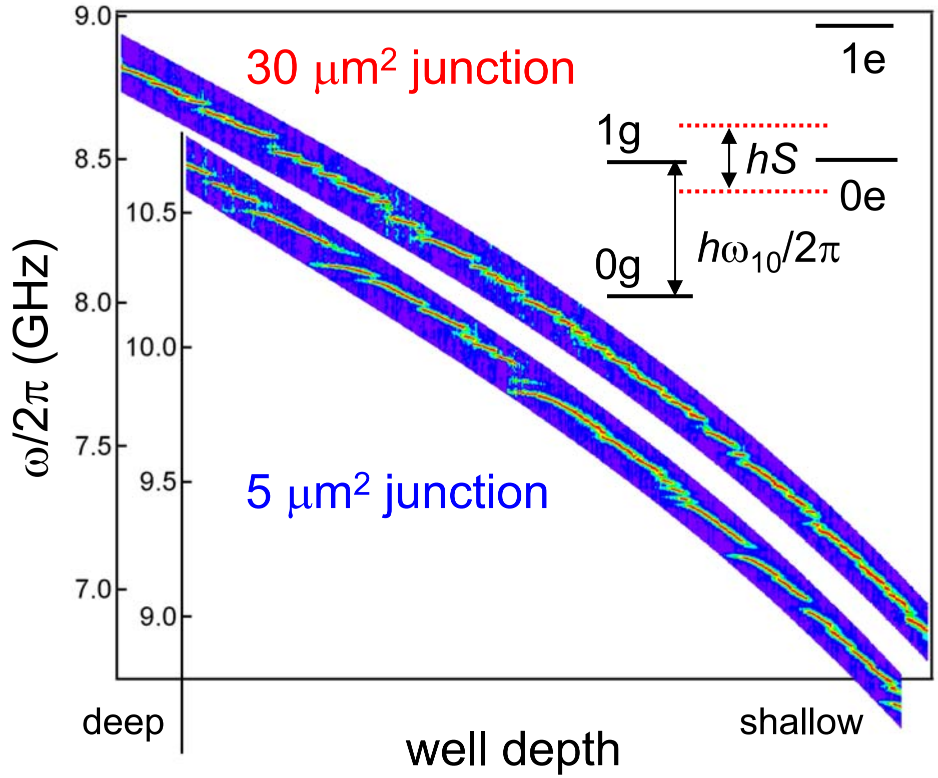


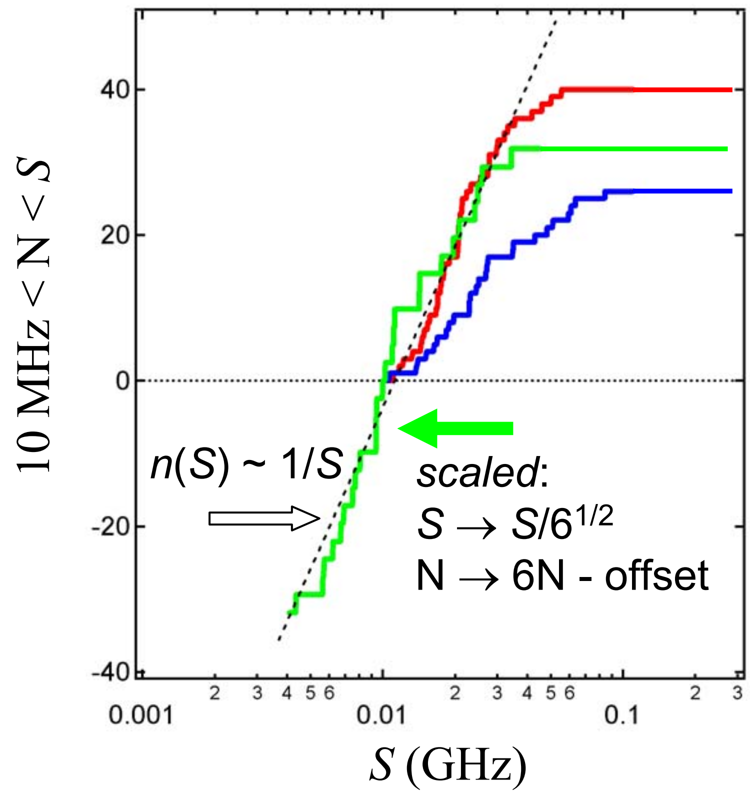
Resonator Magnitudes





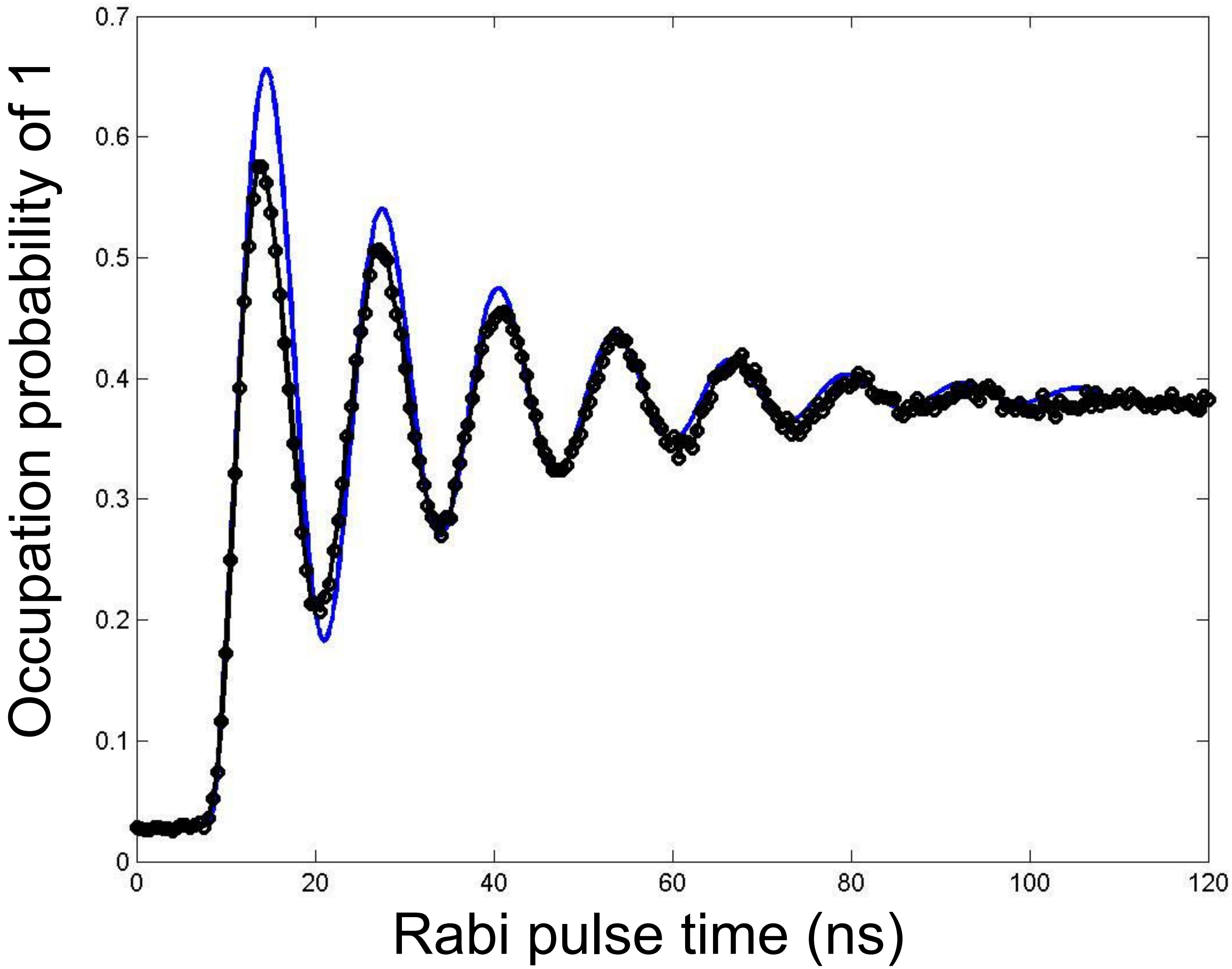
Resonator Magnitudes



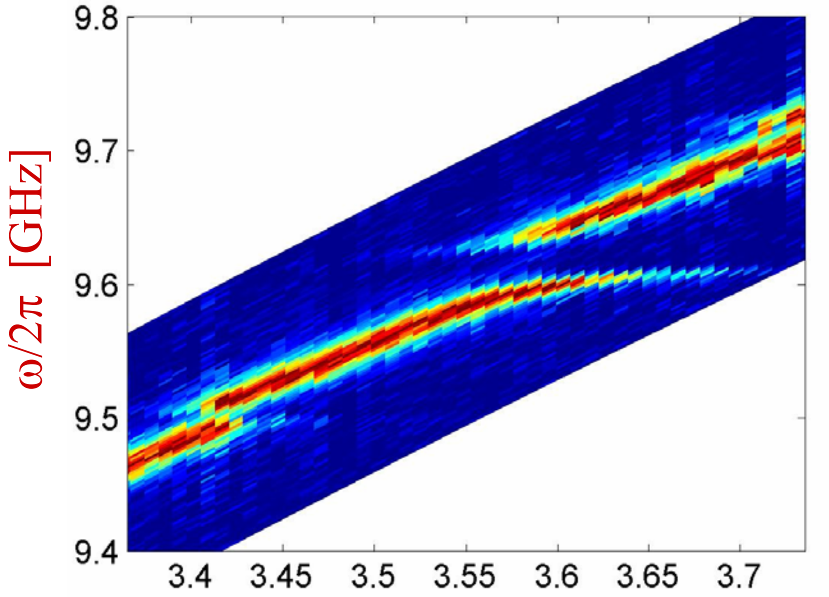


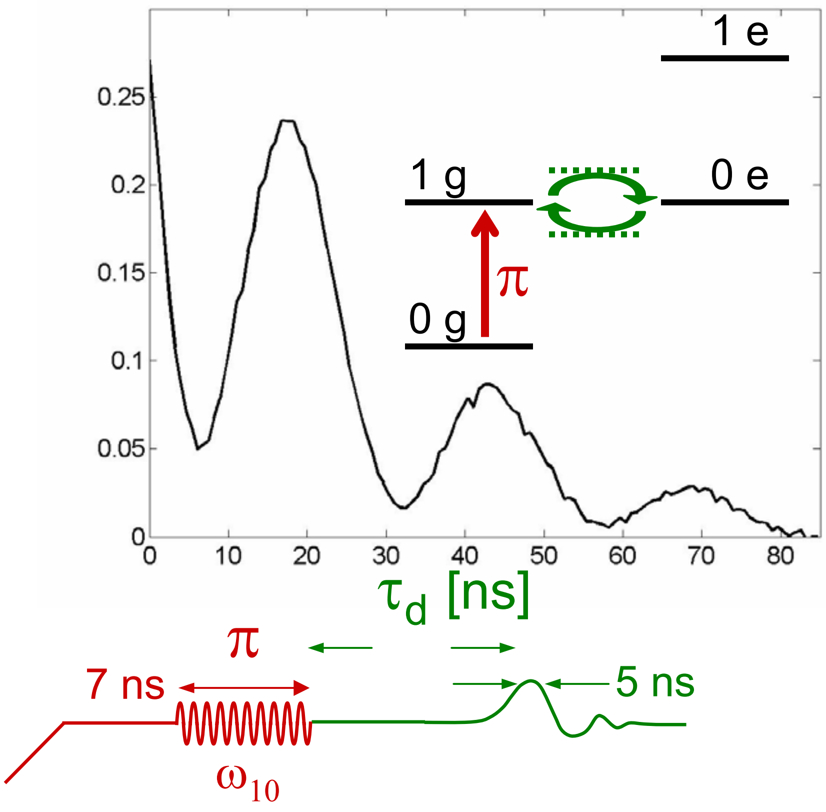
- Fewer resonators with smaller junction –
  must bias away from large resonances!
  (consistent with phase, flux qubits)
- T_1 shorter with small junction – new decoherence source

Data from yesterday (small area)

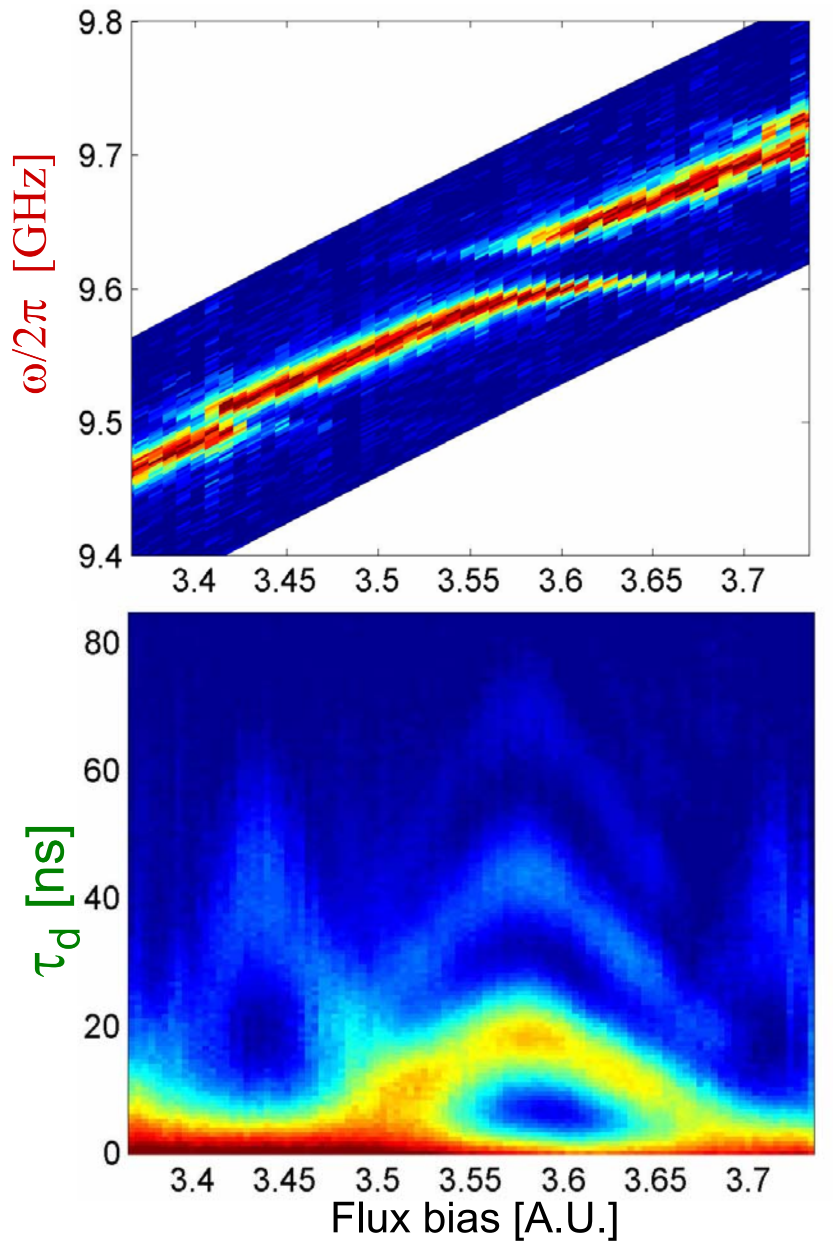


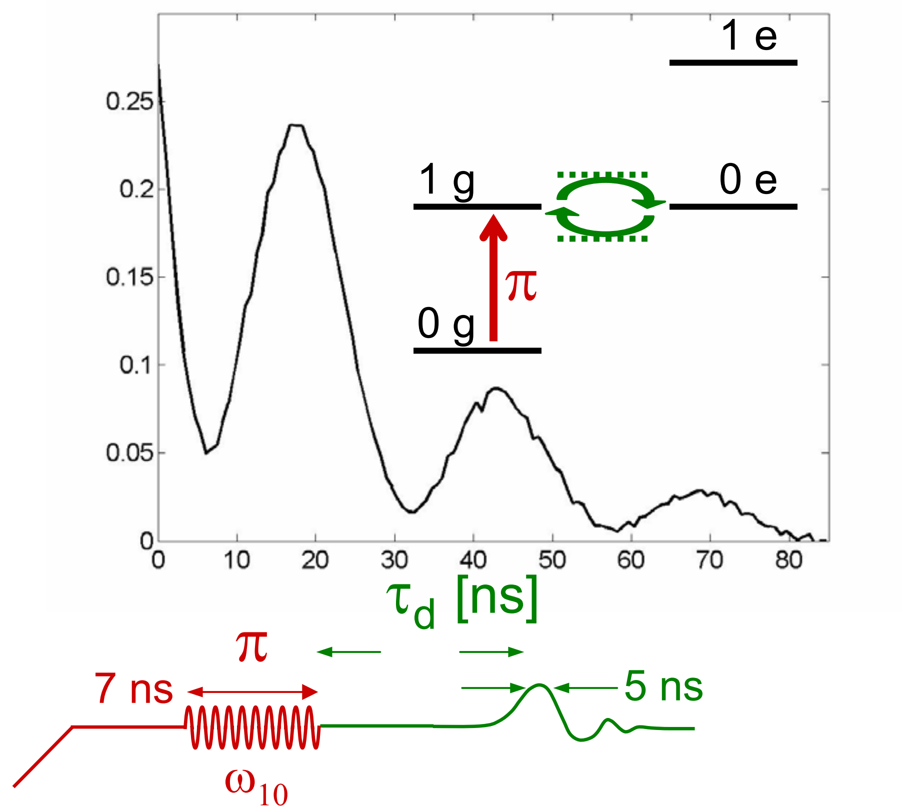
Time-Domain Measurements of Resonance





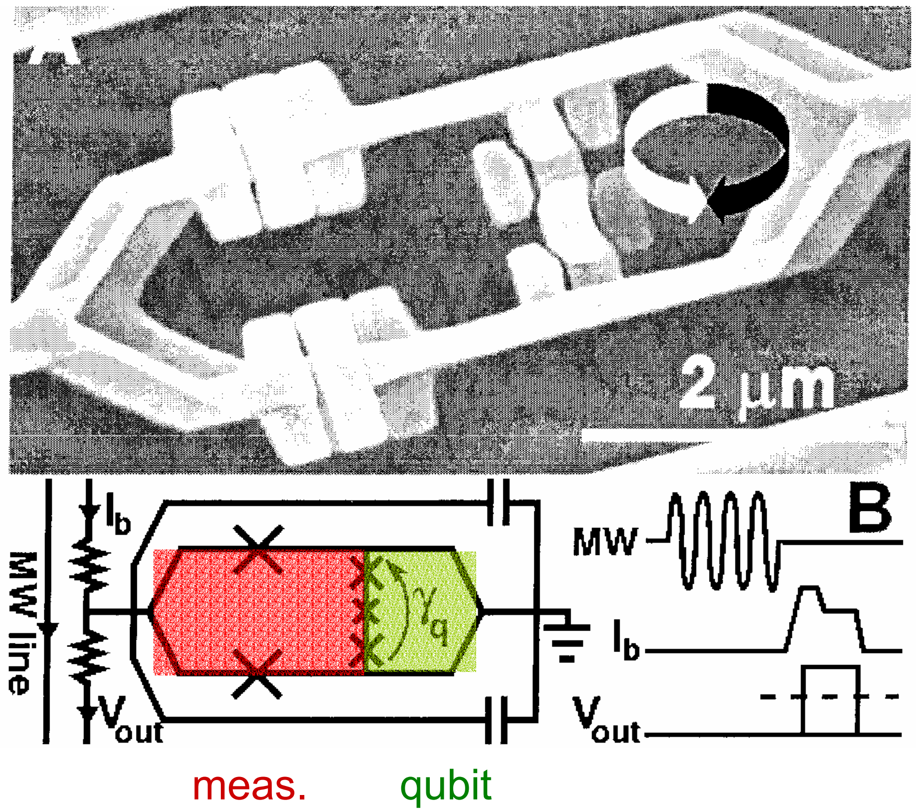
Time-Domain Measurements of Resonance

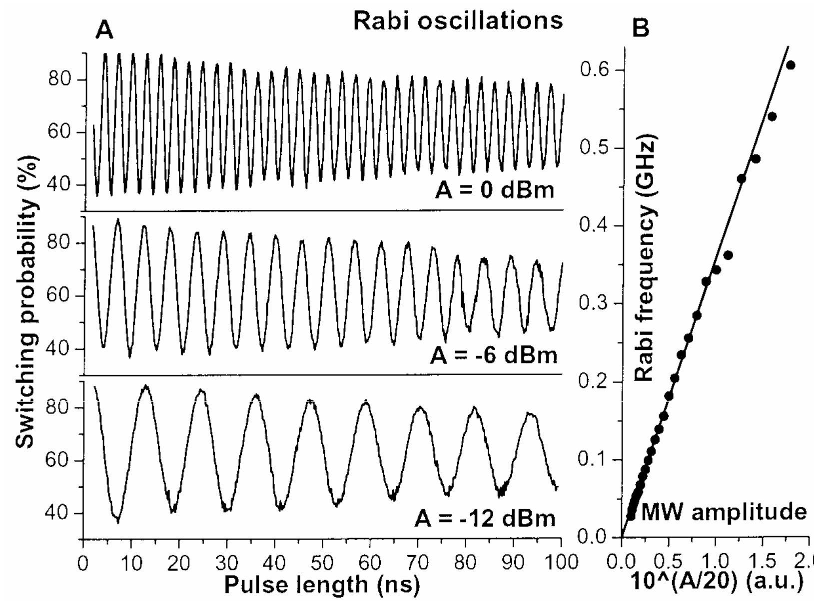


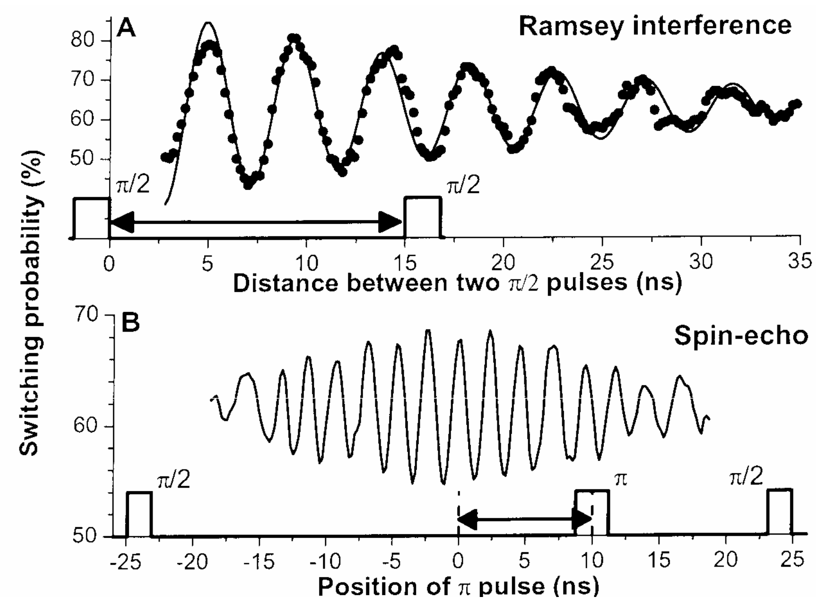


- Resonances are long-lived: cancel with spin-echo techniques?
- “Mock-up” of coupled qubit experiment measure correlation of two states

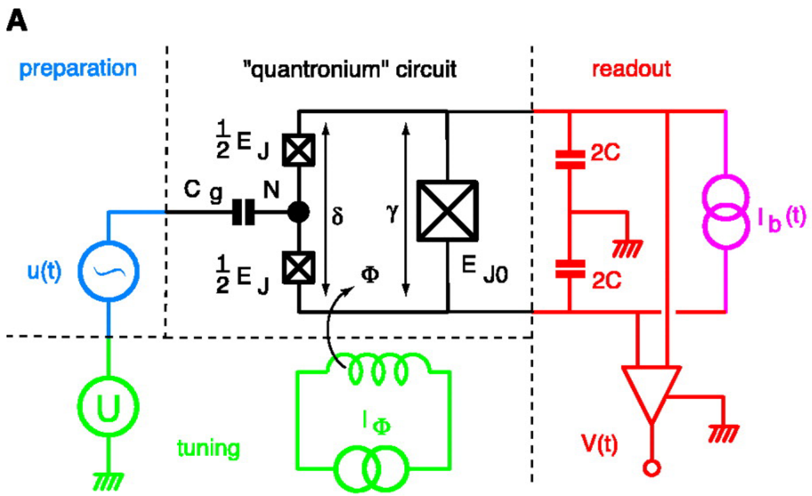
Flux Qubit (Delft)

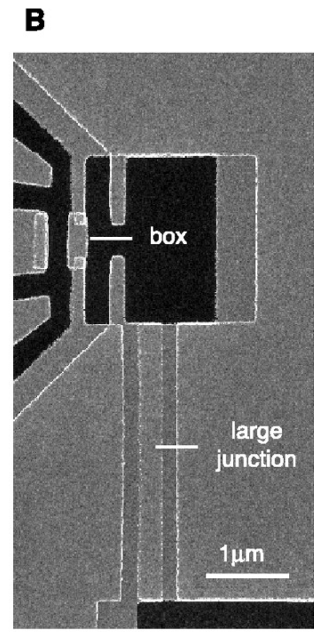


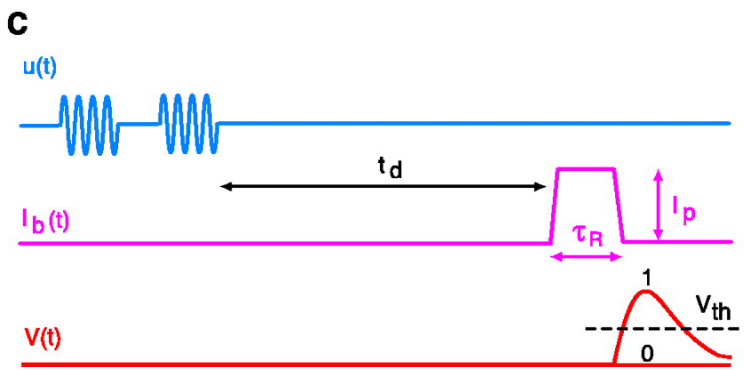


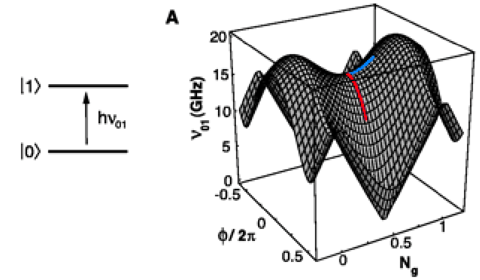


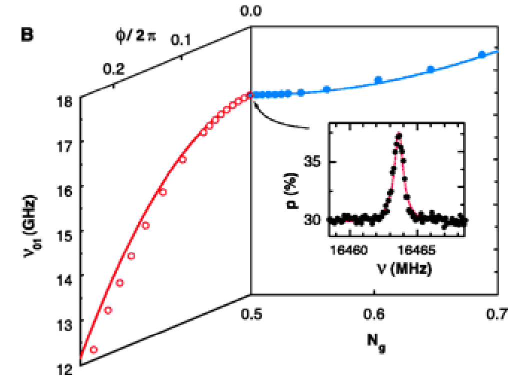
Charge Qubit (Saclay)

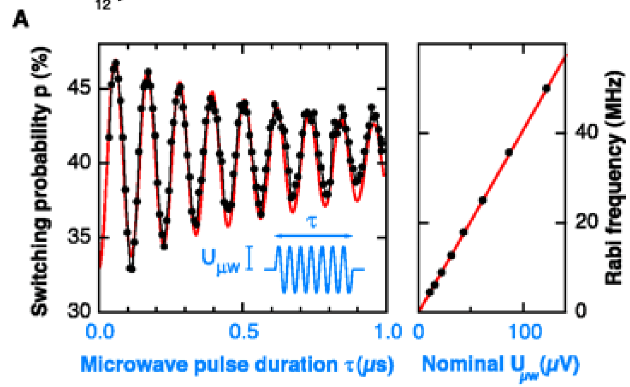


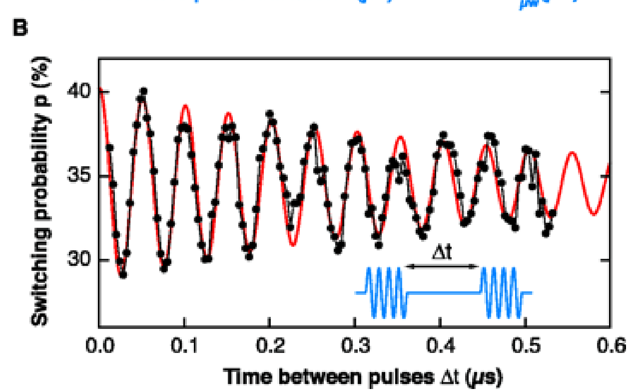












Large 1/f charge noise requires operation at degeneracy point ($d\omega/dq = 0$)

Summary & Future Work

- Understand how to design qubits
- Circuits work:
  - State preparation
  - Logic operation (Rabi oscillations)
  - State measurement
- “Mock-up” of coupled qubit experiment
- Need to eliminate spurious resonances:
  - Microscopic model
  - Understand size dependence
  - New materials - improve upon amorphous AlOx
- “Brute force” scaling to 20-100 (1000) qubits

  Room temperature sequencer and pulse generators

  DR with 100-1000 wires

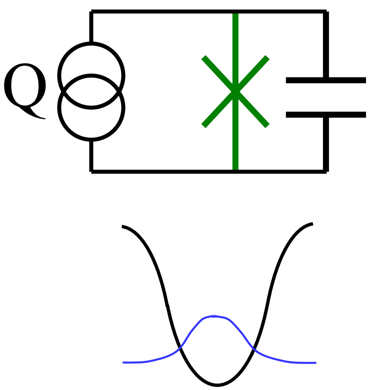
Decoherence from Fluctuations (& resonances)

(with M. Devoret)

$$\left.\begin{array}{ll} E_J = E_J^{stat} + \Delta E_J(t) & \text{med.} \\ E_C = E_C^{stat} + \Delta E_C(t) & ? \\ Q = Q^{stat} + \Delta Q(t) & \text{large} \\ L = L^{stat} + \Delta L(t) & ? \end{array}\right\} \text{Parameter Fluctuations}$$

Occurs in all qubit systems!

Charge

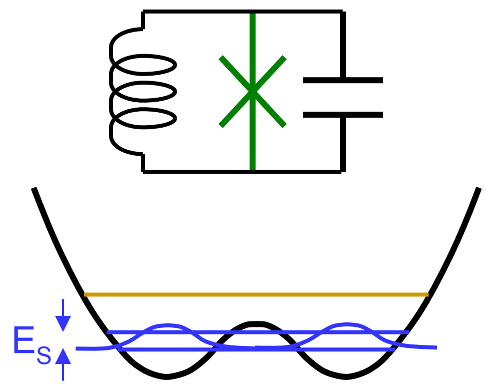


$$H \cong -\frac{E_J}{2}\sigma_z + \frac{E_C(1-Q)}{2}\sigma_x$$

Large → Low freq. I_0

≈ 0 → High freq. Q

Flux

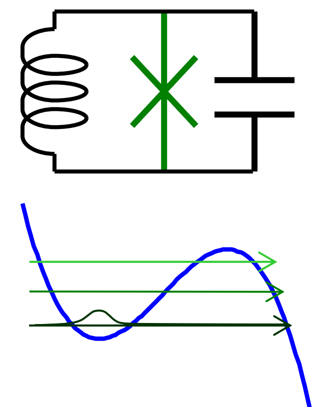


$$H \cong -\frac{E_s}{2}\sigma_z + \frac{E_\Phi\left(\frac{\Phi}{\Phi_0}-\frac{1}{2}\right)}{2}\sigma_x$$

Low freq. I_0, L, C

High freq. Φ, L, (I_0)

Phase

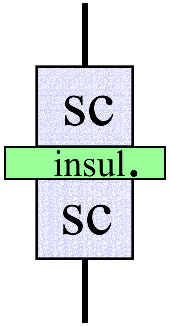


$$H \cong \hbar\omega_{10}\sigma_z + \kappa\,\Delta I\left(\sigma_x + \tfrac{1}{4}\sigma_z\right)$$

High and low freq.

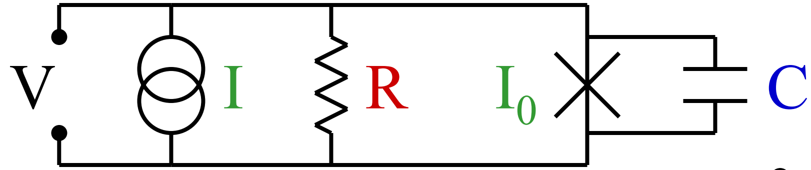
Φ, L, I_0,C

Josephson-Junction Physics



$$I_j = I_0 \sin\delta$$

$$V = (\Phi_0/2\pi)\,\dot{\delta}$$



$$I = V/R + I_0 \sin\delta + C\dot{V}$$

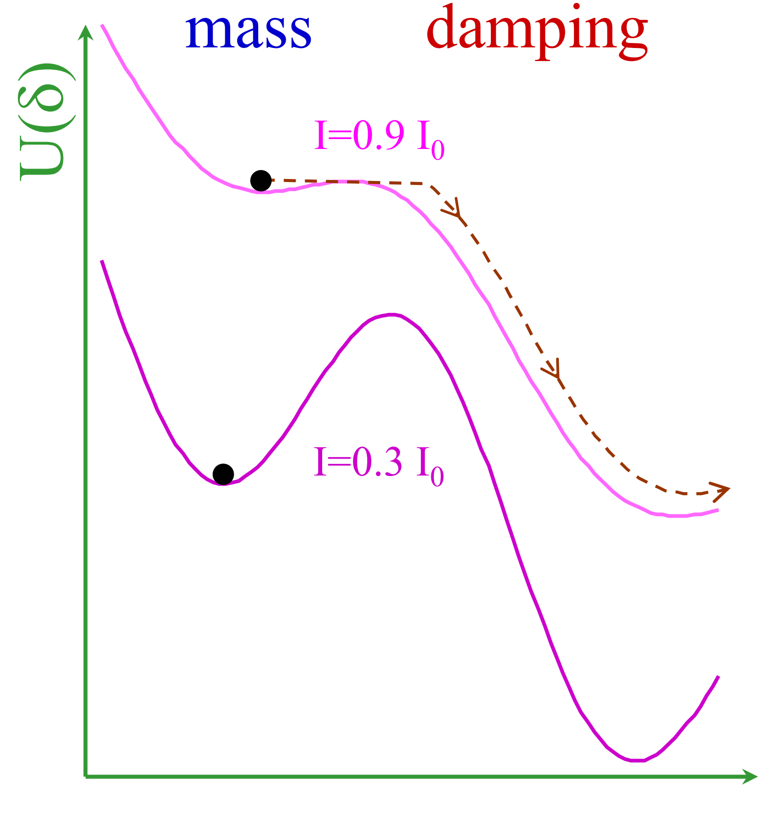
$$U = \int I_J V dt$$

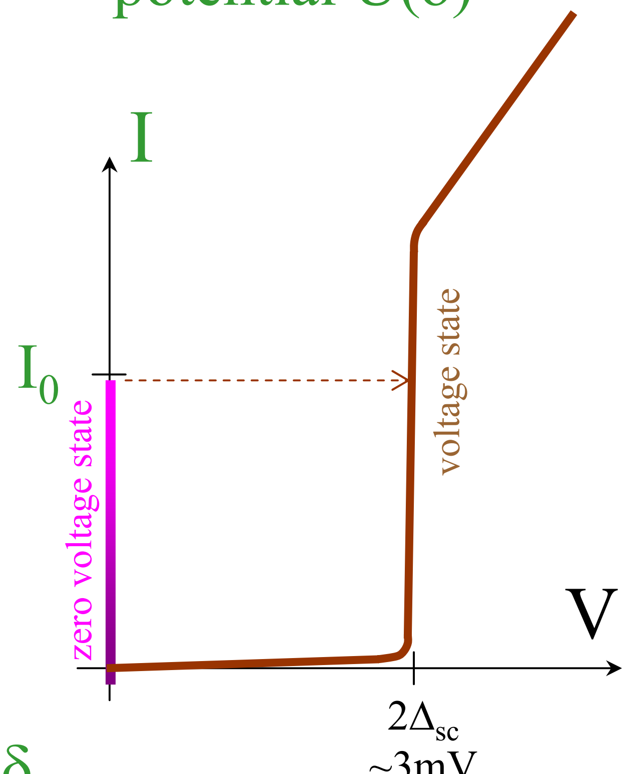
$$= \frac{I_0\Phi_0}{2\pi}\int \sin\delta \frac{d\delta}{dt} dt$$

$$= -\frac{I_0\Phi_0}{2\pi}\cos\delta$$

$$\left[C\left(\frac{\Phi_0}{2\pi}\right)^2\right]\ddot{\delta} + \left[\frac{1}{R}\left(\frac{\Phi_0}{2\pi}\right)^2\right]\dot{\delta} + \frac{\partial}{\partial\delta}\left[-I_0\frac{\Phi_0}{2\pi}\cos\delta - I\frac{\Phi_0}{2\pi}\delta\right] = 0$$

mass — damping — potential U(δ)





Qubit Taxonomy

Circuit elements:

Hamiltonian: $-\dfrac{I_0\Phi_0}{2\pi}\cos\delta$ $\quad -\dfrac{I\Phi_0}{2\pi}\delta$ $\quad \dfrac{(\Phi_0\delta)^2}{2L}$ $\quad \dfrac{e^2}{2C}q^2$

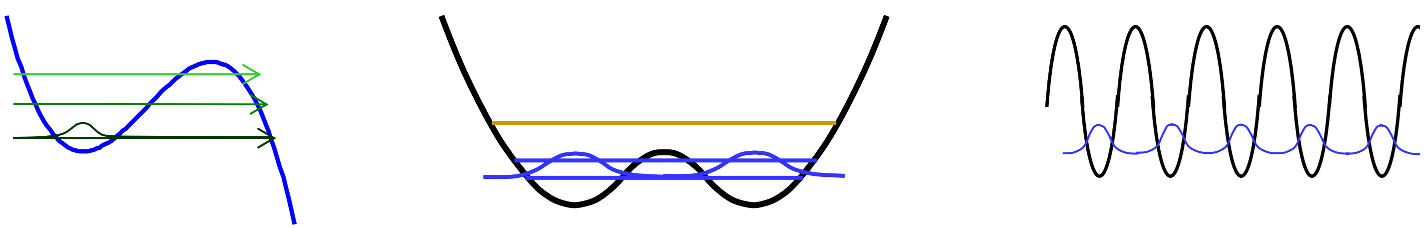
Quantum mechanics:

$$[\hat{\Phi},\hat{Q}] = i\hbar$$

$$[\hat{\delta},\hat{q}] = 2i$$

	Phase	**Flux**	**Charge**
Non-linearity	$I \rightarrow I_0$	$L \cong L_{J0}$	Bloch states in δ
$\dfrac{E_J}{E_C} = \dfrac{I_0\Phi_0/2\pi}{e^2/2C}$	10^4	10^2	1
Area (μm^2):	10-100	0.1-1	0.01

Potential & wavefunction



Engineering $Z_J=1/\omega_{10}C$	10 Ω	10^3 Ω	10^5 Ω

Effective Hamiltonian $\sigma \bullet$B

$$H = \frac{1}{2C}\hat{q}^2 + \frac{\Phi_0}{2\pi}\left[-I_0\cos\hat{\delta} - (I_{dc} + \Delta I)\hat{\delta}\right]$$

$$= \underbrace{\frac{1}{2C}\hat{q}^2 + H_{cubic}(I_{dc},\hat{\delta})}_{\text{Solve numerically}} \underbrace{- \frac{\Phi_0}{2\pi}\Delta I\hat{\delta}}_{\text{Perturbation}}$$

$$\approx \begin{pmatrix} 0 & 0 \\ 0 & \hbar\omega_{10} \end{pmatrix} + \frac{\Phi_0}{2\pi}\Delta I \begin{pmatrix} \langle 0|\hat{\delta}|0\rangle & \langle 0|\hat{\delta}|1\rangle \\ \langle 1|\hat{\delta}|0\rangle & \langle 1|\hat{\delta}|1\rangle \end{pmatrix}$$

$$= \hbar\omega_{10}\sigma_Z + \sqrt{\tfrac{\hbar}{2\omega_{10}C}}\Delta I\left(\sigma_X + \sqrt{\tfrac{\hbar\omega_{10}}{3\Delta U}}\sigma_Z\right)$$

Basis transform (rotating frame):

$$V = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\omega_{10}t} \end{pmatrix} \qquad \widetilde{H} = V^+HV - i\hbar V^+(\partial_t V)$$

$$\widetilde{H} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} + \frac{\Phi_0}{2\pi}\left(\Delta I_{dc} + I_{uwc}\cos\omega_{10}t + I_{uws}\sin\omega_{10}t\right)\begin{pmatrix} \langle 0|\hat{\delta}|0\rangle & \langle 0|\hat{\delta}|1\rangle e^{-i\omega_{10}t} \\ \langle 1|\hat{\delta}|0\rangle e^{i\omega_{10}t} & \langle 1|\hat{\delta}|1\rangle \end{pmatrix}$$

$$\approx \frac{\Phi_0}{2\pi}\left(\Delta I_{dc}\underbrace{\begin{pmatrix} \langle 0|\hat{\delta}|0\rangle & 0 \\ 0 & \langle 1|\hat{\delta}|1\rangle \end{pmatrix}}_{\sigma_z} + \frac{I_{uwc}}{2}\underbrace{\begin{pmatrix} 0 & \langle 0|\hat{\delta}|1\rangle \\ \langle 1|\hat{\delta}|0\rangle & 0 \end{pmatrix}}_{\sigma_x} + \frac{I_{uws}}{2}\underbrace{\begin{pmatrix} 0 & i\langle 0|\hat{\delta}|1\rangle \\ -i\langle 1|\hat{\delta}|0\rangle & 0 \end{pmatrix}}_{\sigma_y}\right)$$

Rotating wave approximation (neglect off resonant terms):

Decoherence & Materials

- <u>All</u> oxide tunnel barriers give similar 1/f noise

(Van Harlingen et al)	$S_{I0}^{1/2}(1\text{Hz})A^{1/2}/I_0$ (μm pA/Hz$^{1/2}$/μA)
Al-AlOx-Al	(~5)
Nb-AlOx-Nb	7-20
Nb-Ox-PbIn	7-20
Nb-NbOx-PbInAu	8
PbIn-Ox-Pb	15
NbN-AlN-NbN (epi)	1000

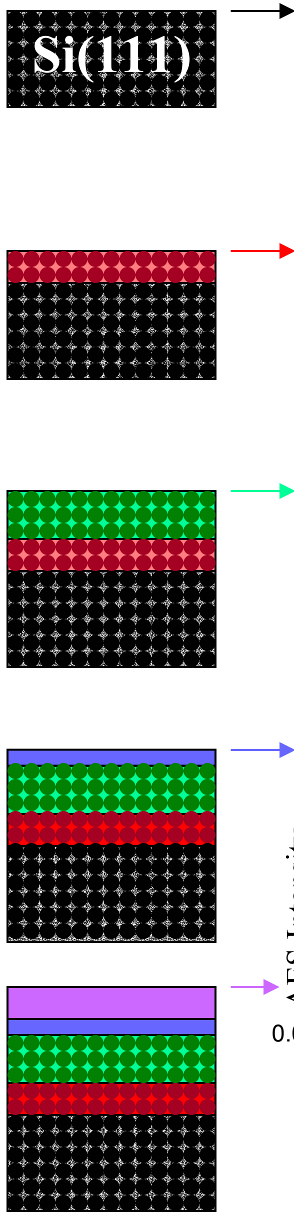
- Need Materials Research – Qubits have vastly different requirements

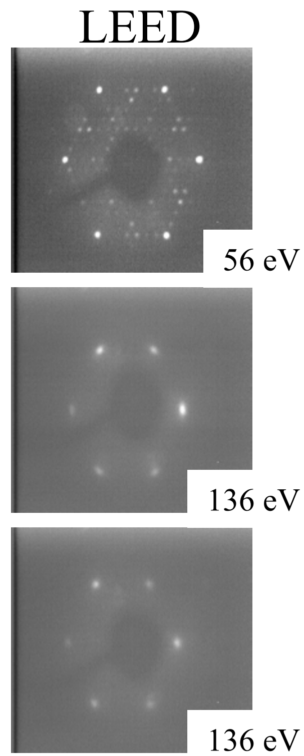
  <u>Past Research:</u> High T_c, $Q < 1$, low leakage junctions
  <u>Qubits:</u> $T_c > 1$K, leakage tolerated
  low fluctuations, low dielectric loss

- Our research directions:
  Barrier uniformity, barrier materials (AlN), epitaxial growth
  Large-area qubits are ideal test circuits

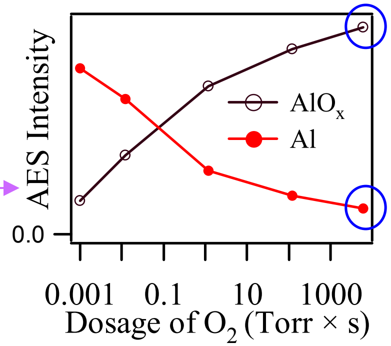
MBE Growth of Al on Si(111)

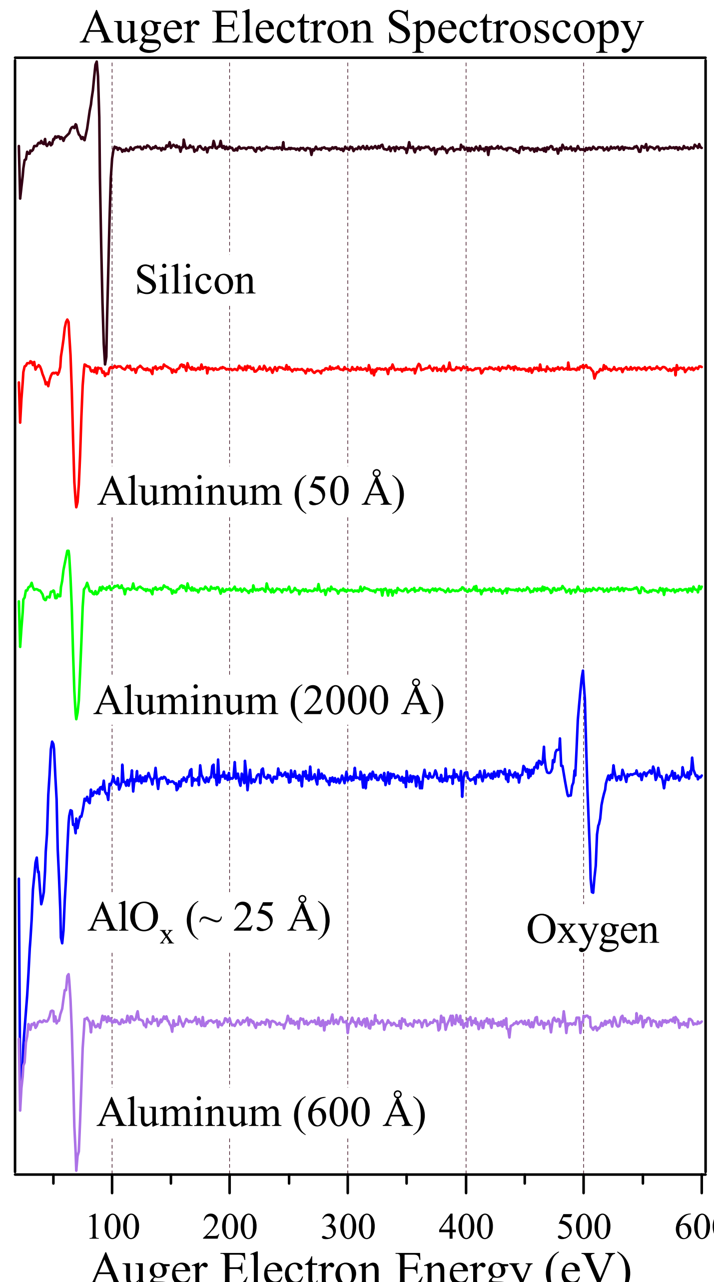
- Si(111)-(7×7)
  Flash anneal 1250°C
  Ordered
- Al seed layer 50 Å
  Evap.   100 K
  Anneal 450 K
  Ordered
- Al homo-epitaxy
  Evap.   300K
  Anneal 450 K
  Ordered
- Oxidation
  10T, 10 min, 300K
  Amorphous
- Al counter-electrode
  Amorphous



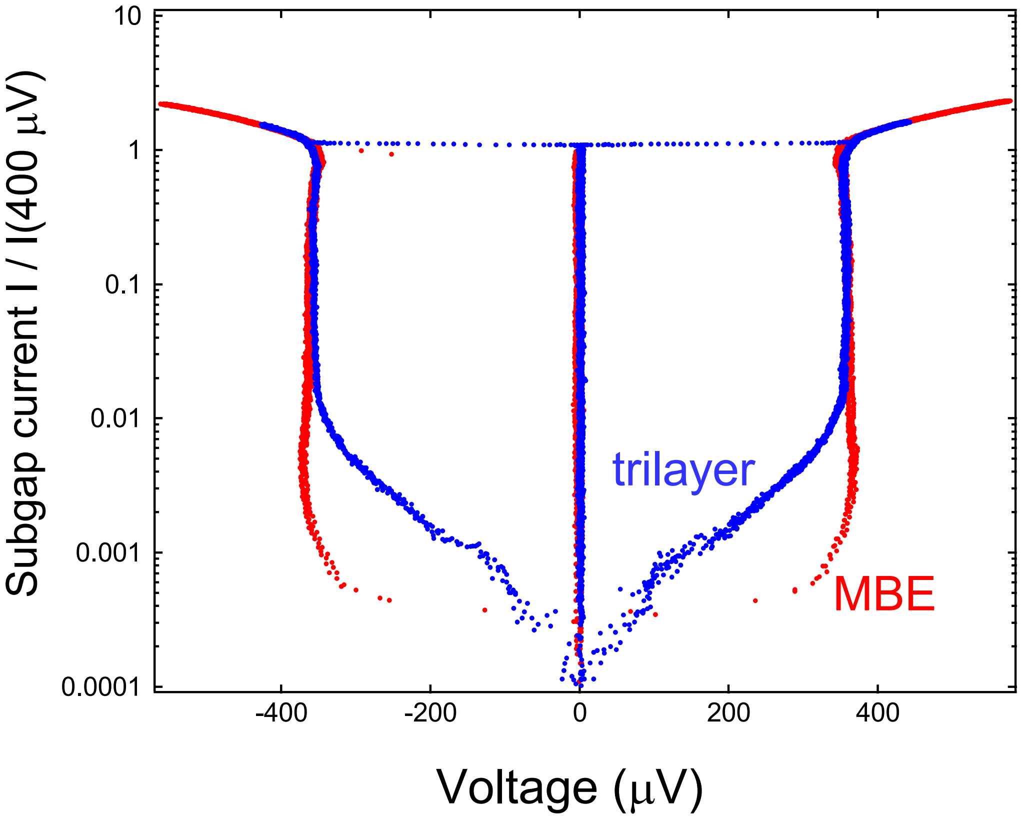


No LEED Pattern





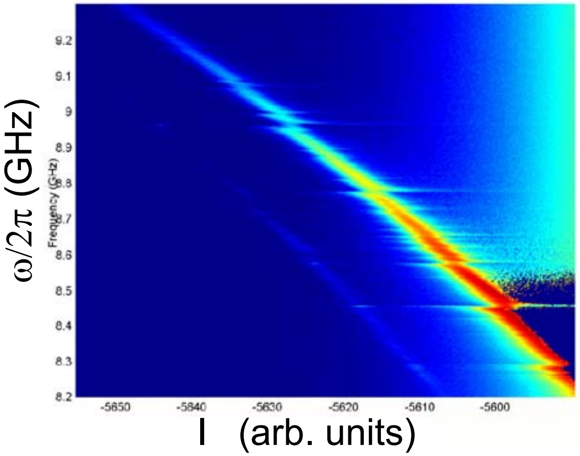
MBE Junctions – Better Quality



Why is junction yield low (30%)?

Sputtered films (10^{-10} T chamber) are more reproducible
No change in coherence (low yield, still inconclusive)

Decoherence : IV's : 1/f Noise

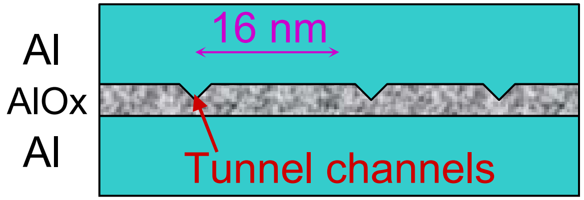


32 μm² junction

- 25 MHz splittings
- 1 resonance / 60MHz

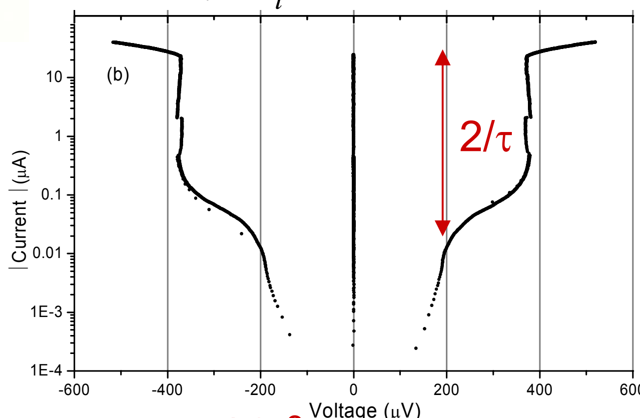
- $\Delta I_0/I_0$ ~ 65 ppm
- 5 res. / dec.-fr. - μm²

Assuming resonances & traps turn on/off channels:



$$G_N = \frac{2e^2}{h}\sum_i \tau_i = \frac{2e^2}{h} N_{ch}\tau$$

$$G_{S2} \approx \frac{2e^2}{h}\sum_i \tau_i^{\,2} \qquad (\Delta < eV < 2\Delta)$$

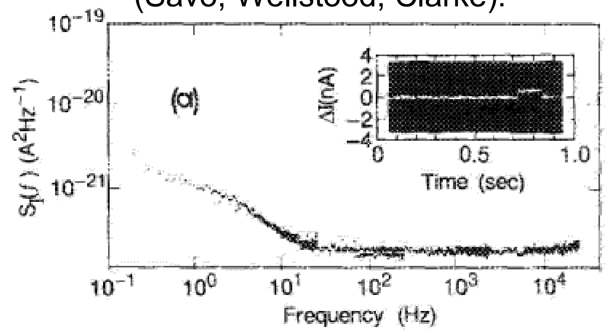


- τ ~ $4\mathrm{x}10^{-3}$
- 1 channel / (16nm)²

- $\Delta I_0/I_0$ ~ 8 ppm

- See individual traps in sub-micron junctions

(Savo, Wellstood, Clarke):



0.1 μm² junction (Van Harlingen)

- ΔI_0~10^{-4} I_0
  ($1/N_{ch}$~ $3\mathrm{x}10^{-3}$)
- 1 trap / decade freq.

scaling to 32 μm²

- $\Delta I_0/I_0$ ~ 0.3 ppm
- 10 traps / dec.-fr. - μm²

Resonances and 1/f noise are same phenomenon !