Decoherence and Materials in Josephson Qubits

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NIST Boulder

NIST National Institute of Standards and Technology • Technology Administration • U.S. Department of Commerce
ARDA

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We know *experimentally* very little

- little Rabi data / low coherence
- eventually need ~99.99% fidelity

First-study of issues with Josephson qubits

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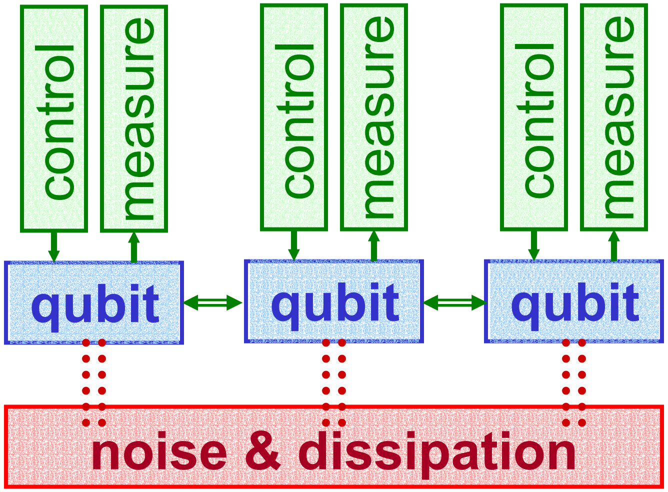
Challenge: Coupling vs. Decoherence



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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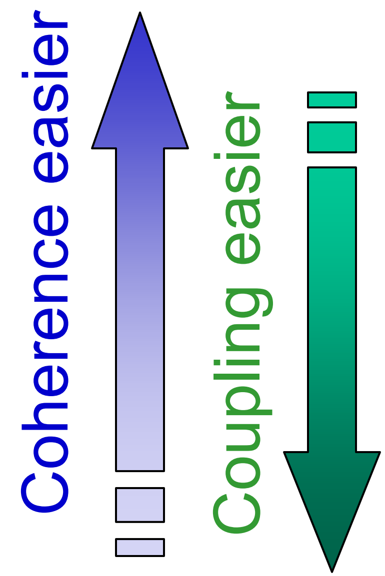
microscopic

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

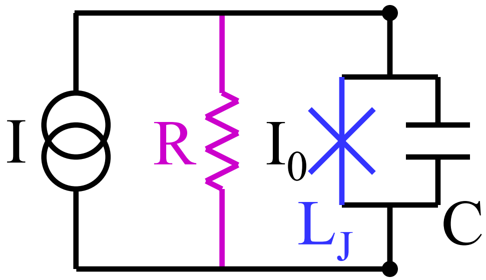


Charge
(NEC, Chalmers)
(Saclay)

Flux
(Delft)
(MIT)

Phase
(NIST, Kansas)

Qubit: Nonlinear LC resonator

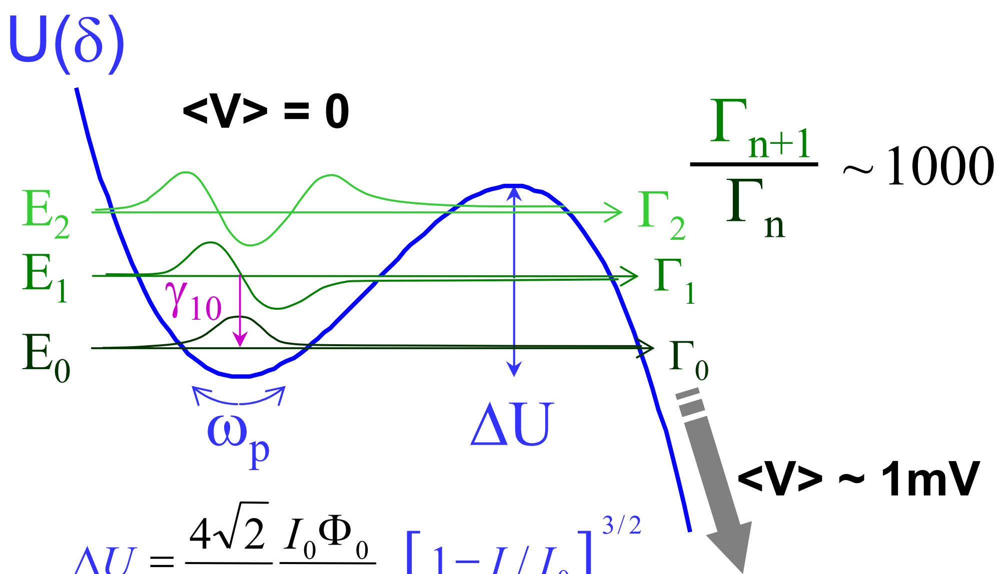


$$I = I_0 \sin\delta$$

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

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

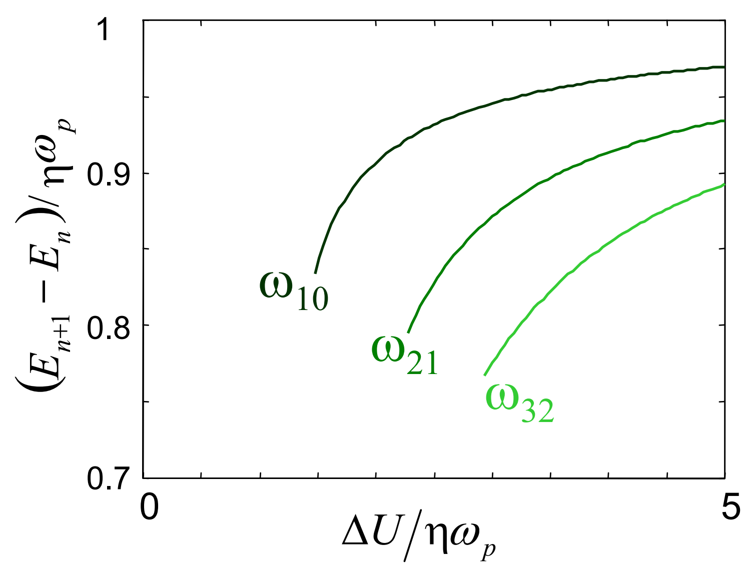
$$L_J = \Phi_0/2\pi I_0 \cos\delta$$
nonlinear inductor



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

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

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

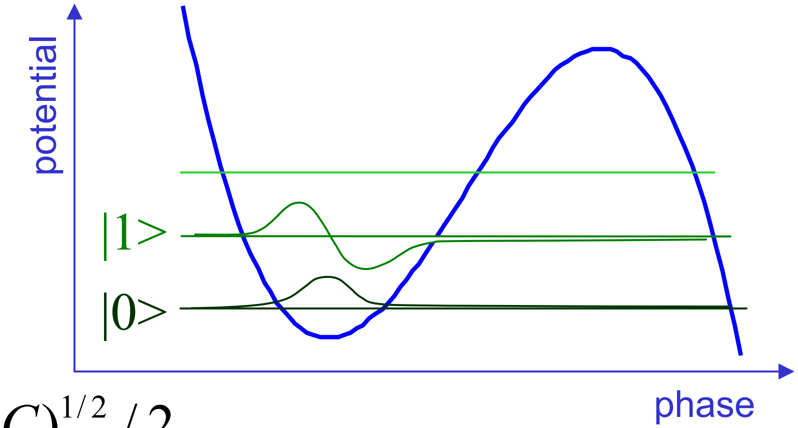


$\gamma_{10} \cong 1/RC$ Lifetime of state |1>

Josephson-Junction Qubit

- State Preparation

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



- Qubit logic with bias control

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

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

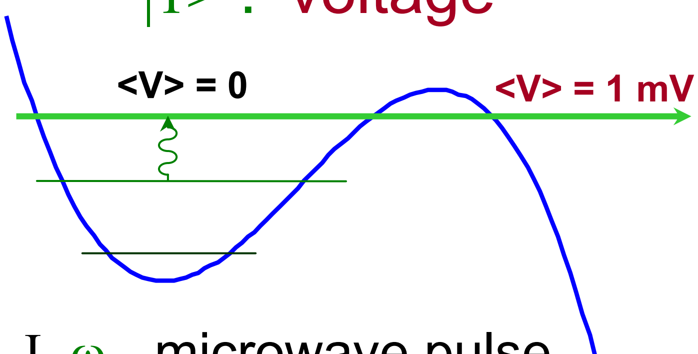
- State Measurement (Junction acts as “photomultiplier”)

  $|0\rangle$: zero voltage

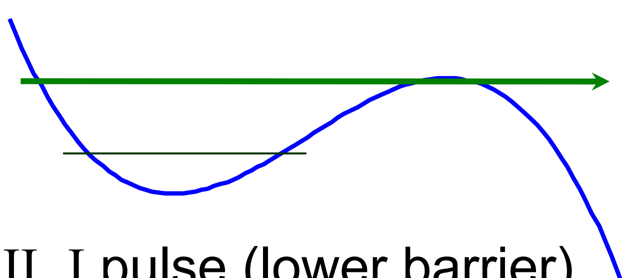
  $|1\rangle$: voltage

With $\Gamma_i/\Gamma_{i-1} \sim 1000$

Fidelity > 99% !!

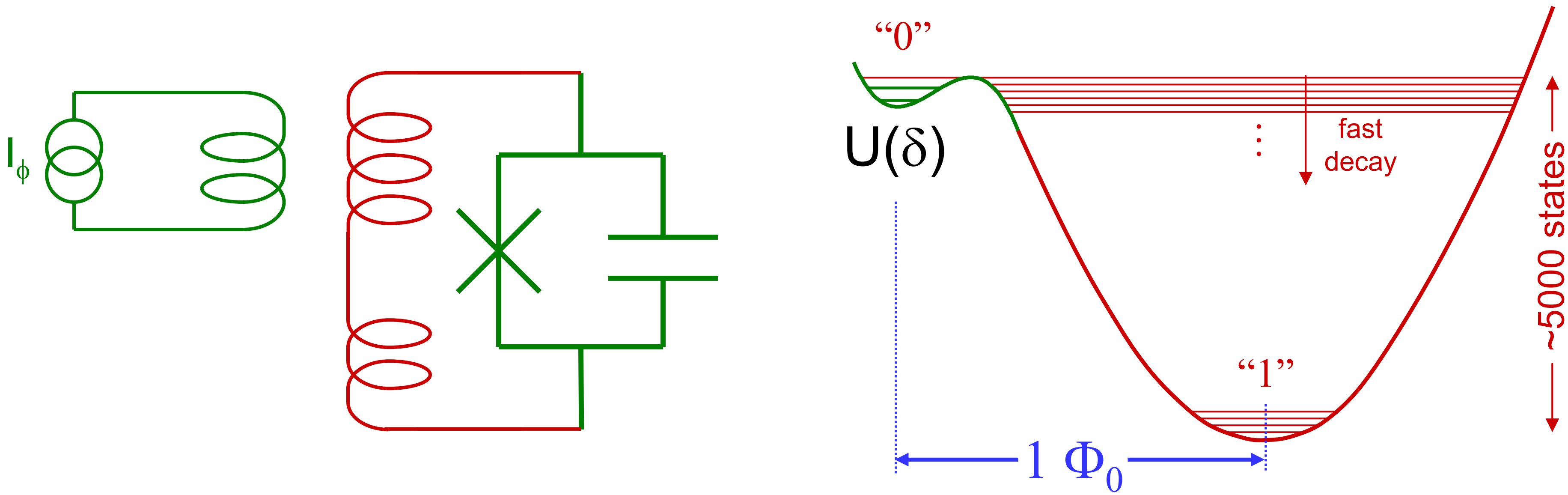


I. ω_{21} microwave pulse

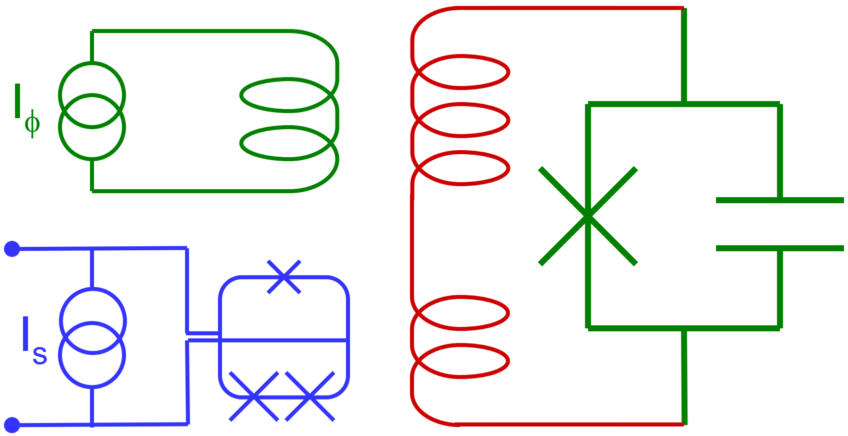


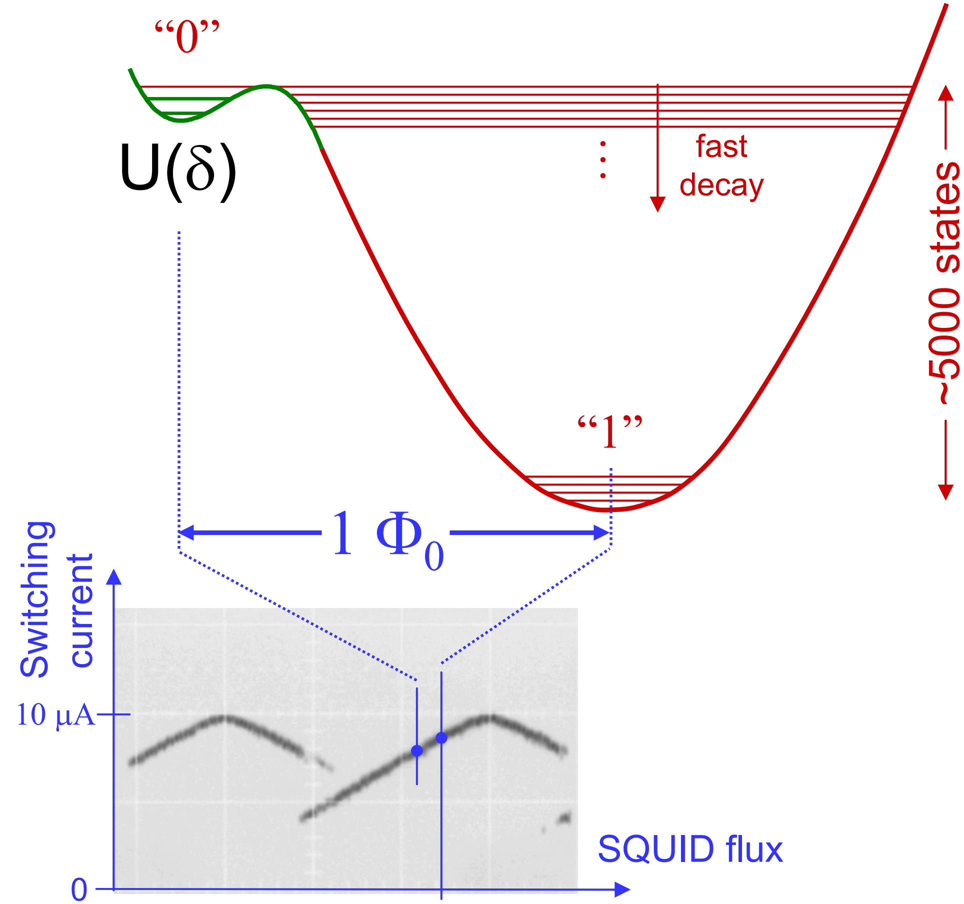
II. I pulse (lower barrier)

Qubit operation → Measurement



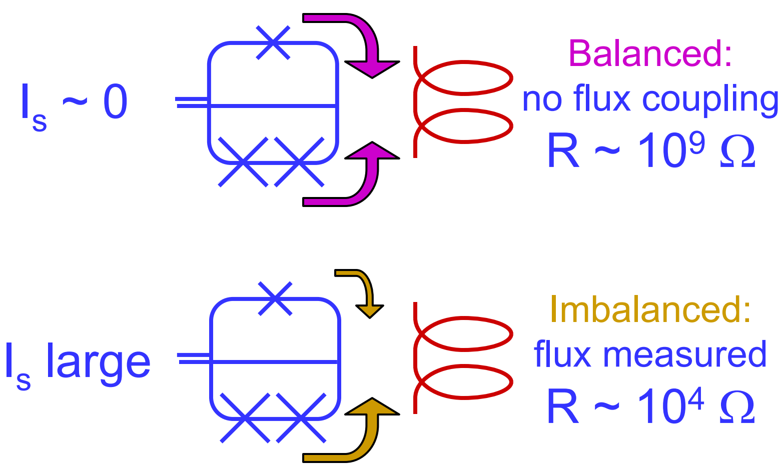
Qubit operation → Measurement → Readout

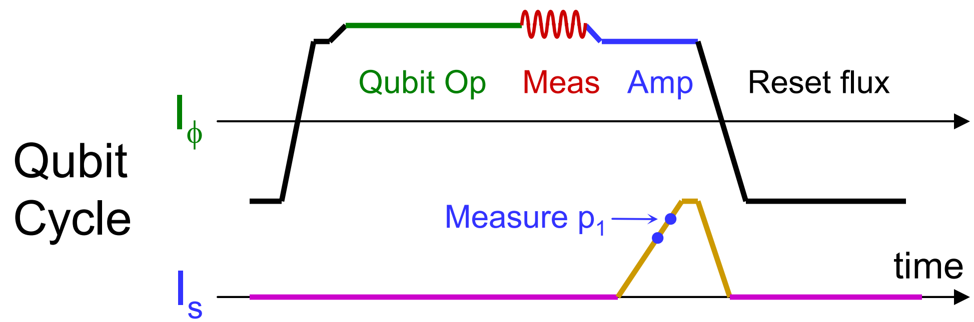




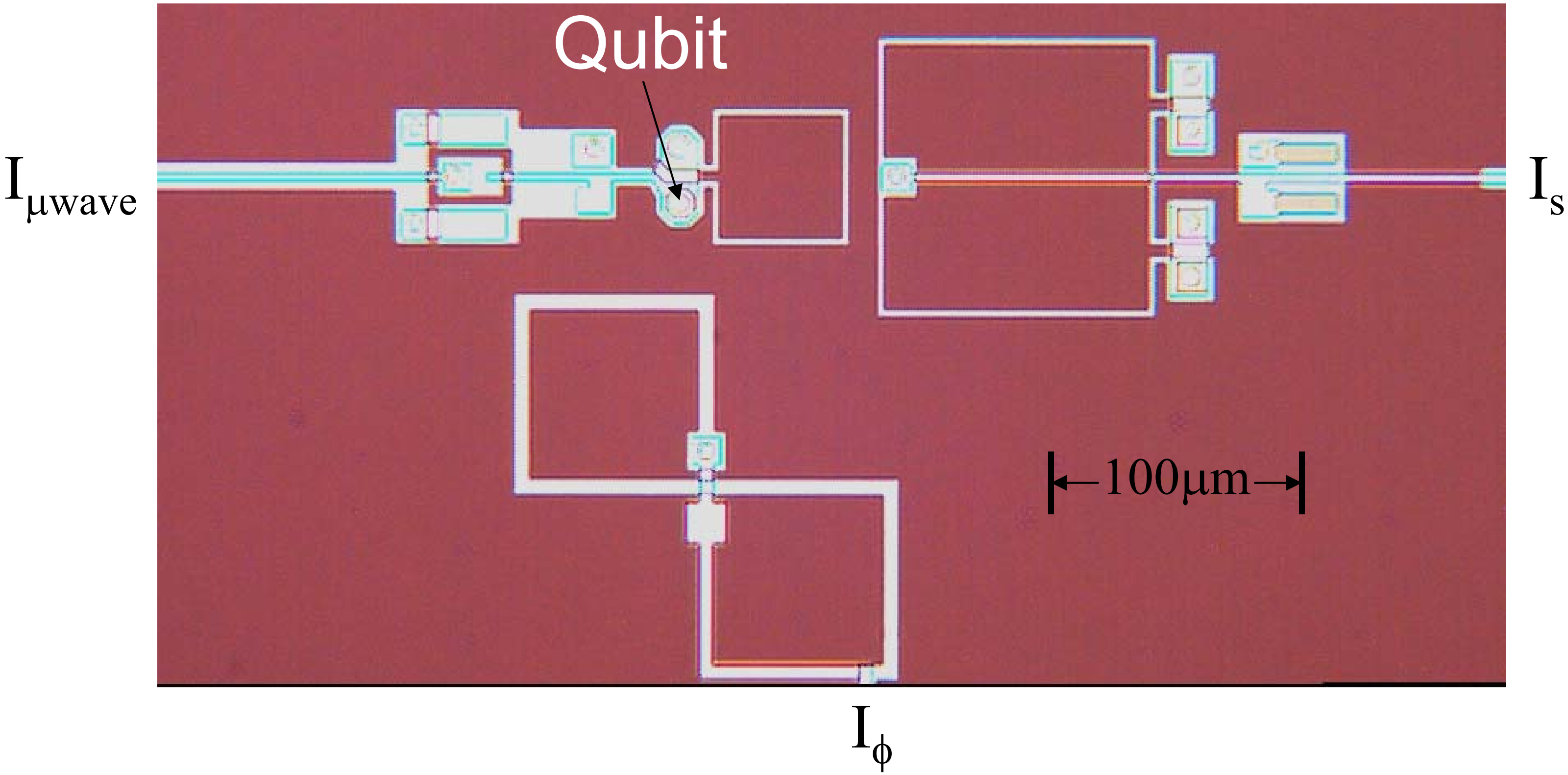
Amplifier (and its dissipation!) turned on & off with I_s

- Adjustable T_1 -

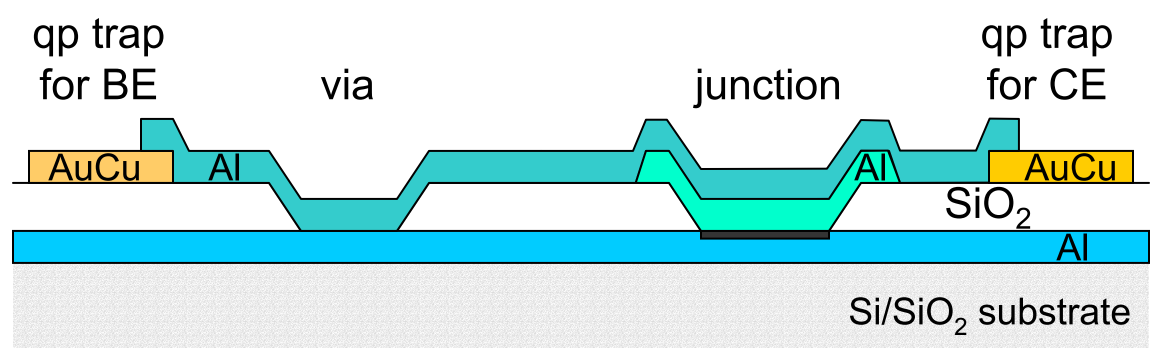




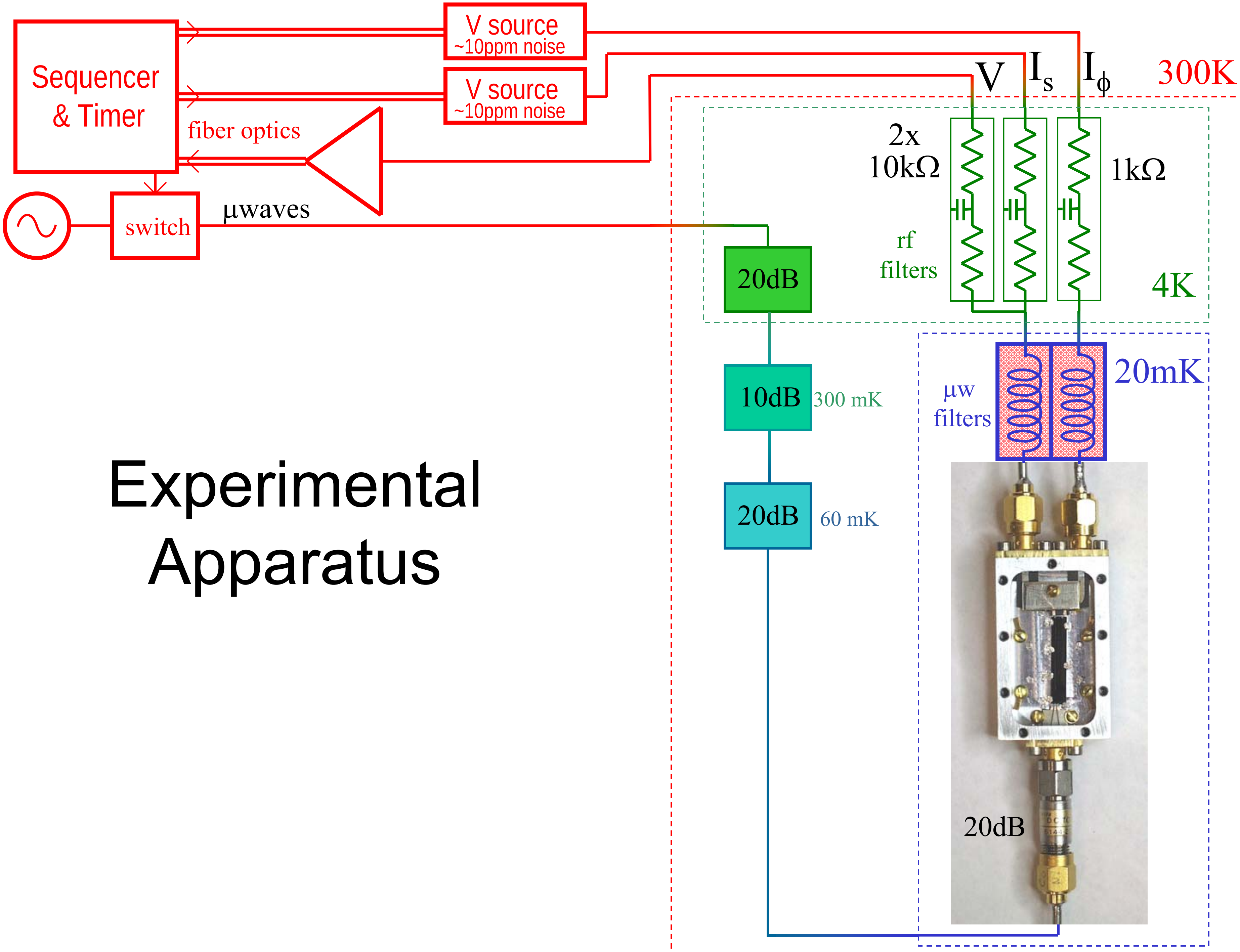
IC Fabrication



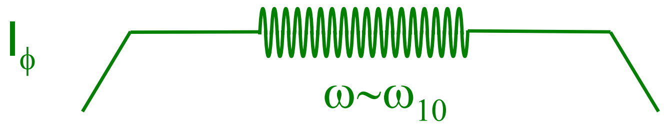
Al junction process
& optical lithography

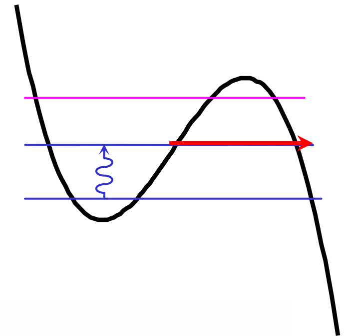


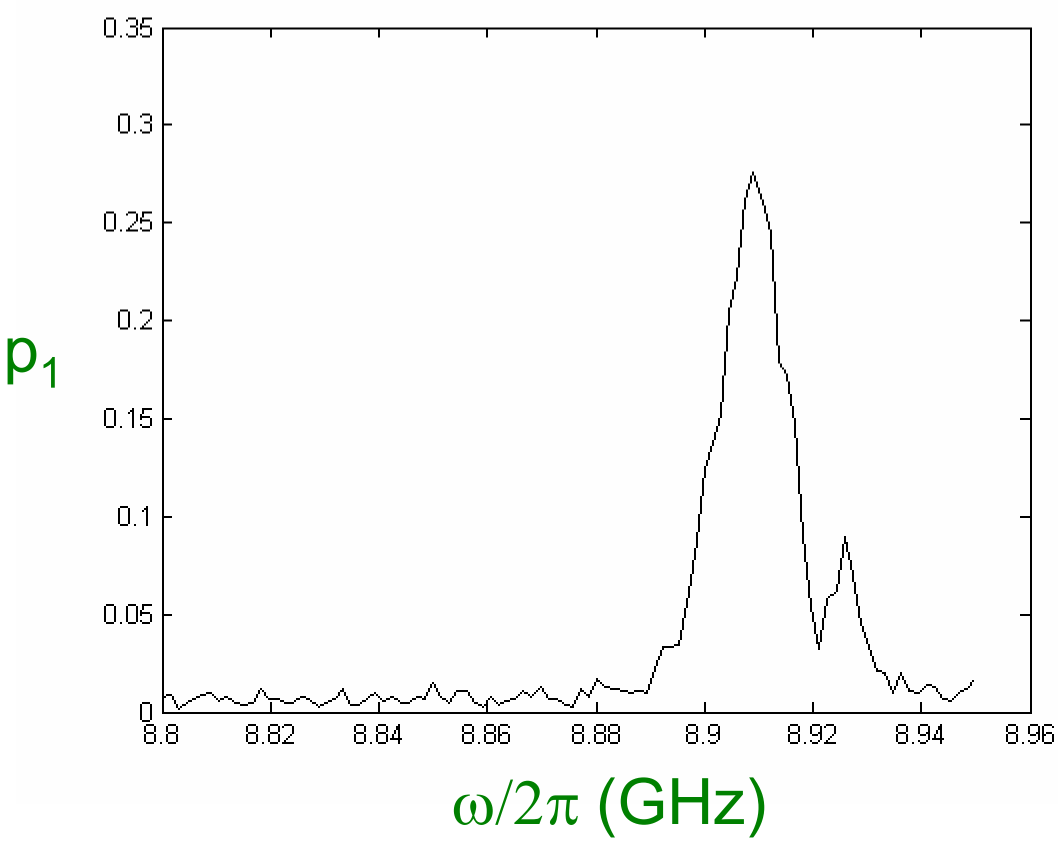
Experimental Apparatus



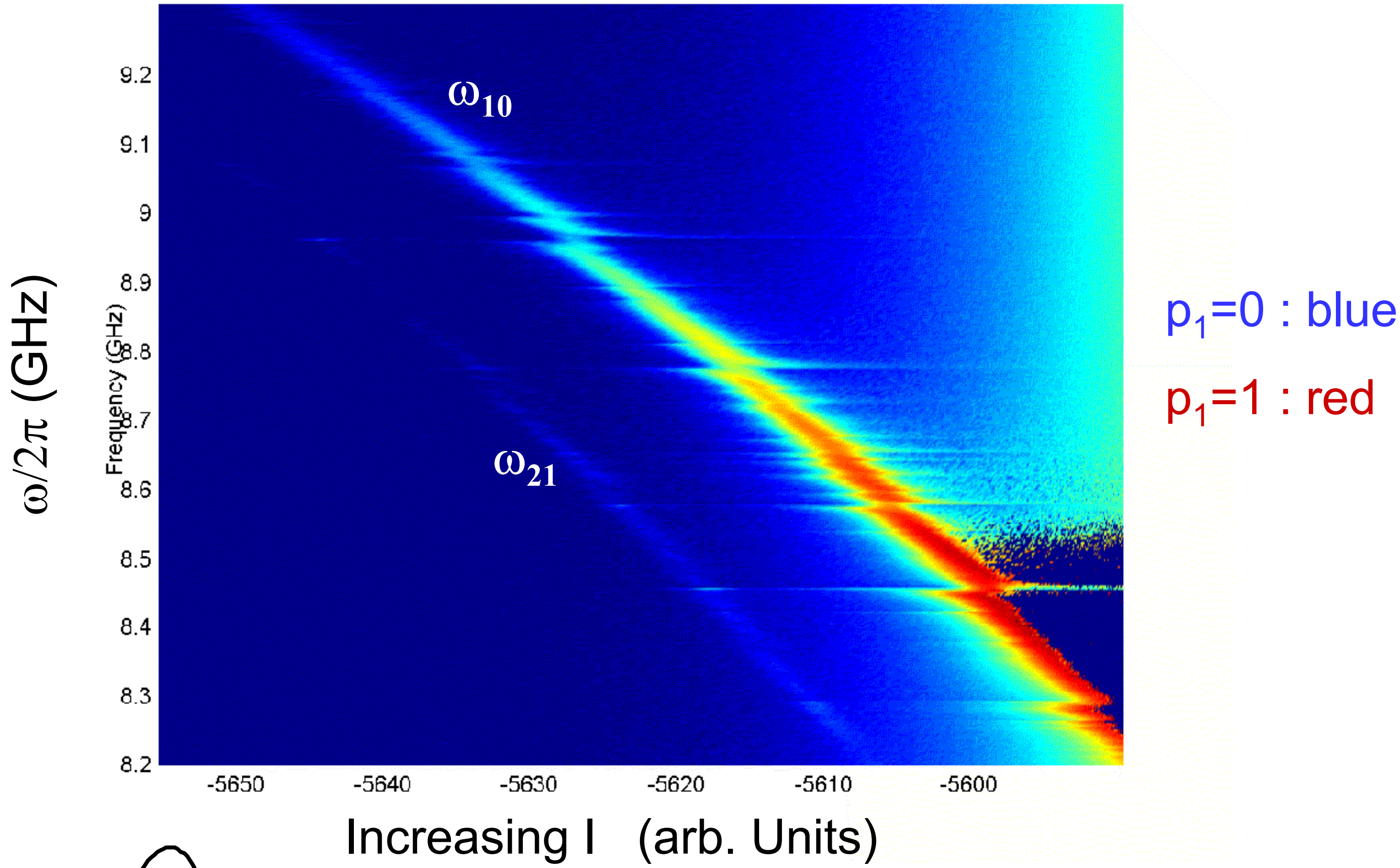
Spectroscopy

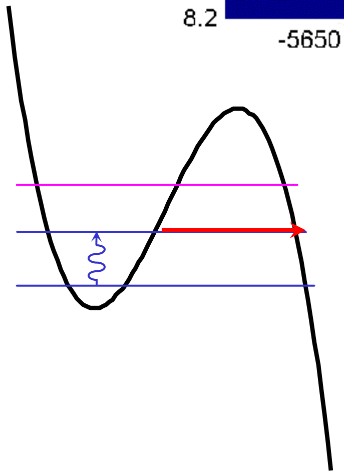


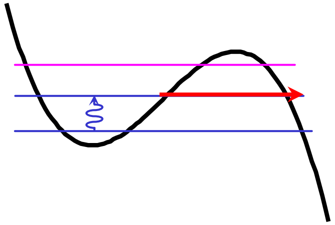




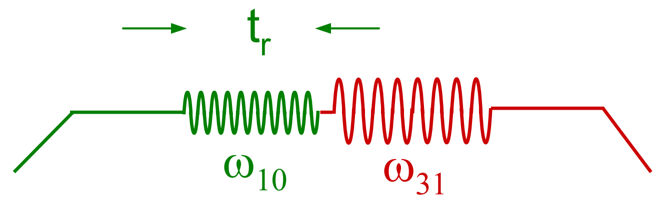
Energy Levels vs. Bias Current

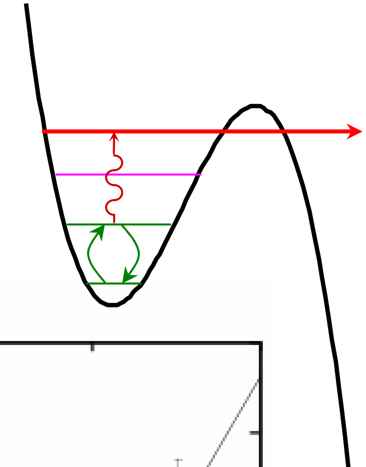


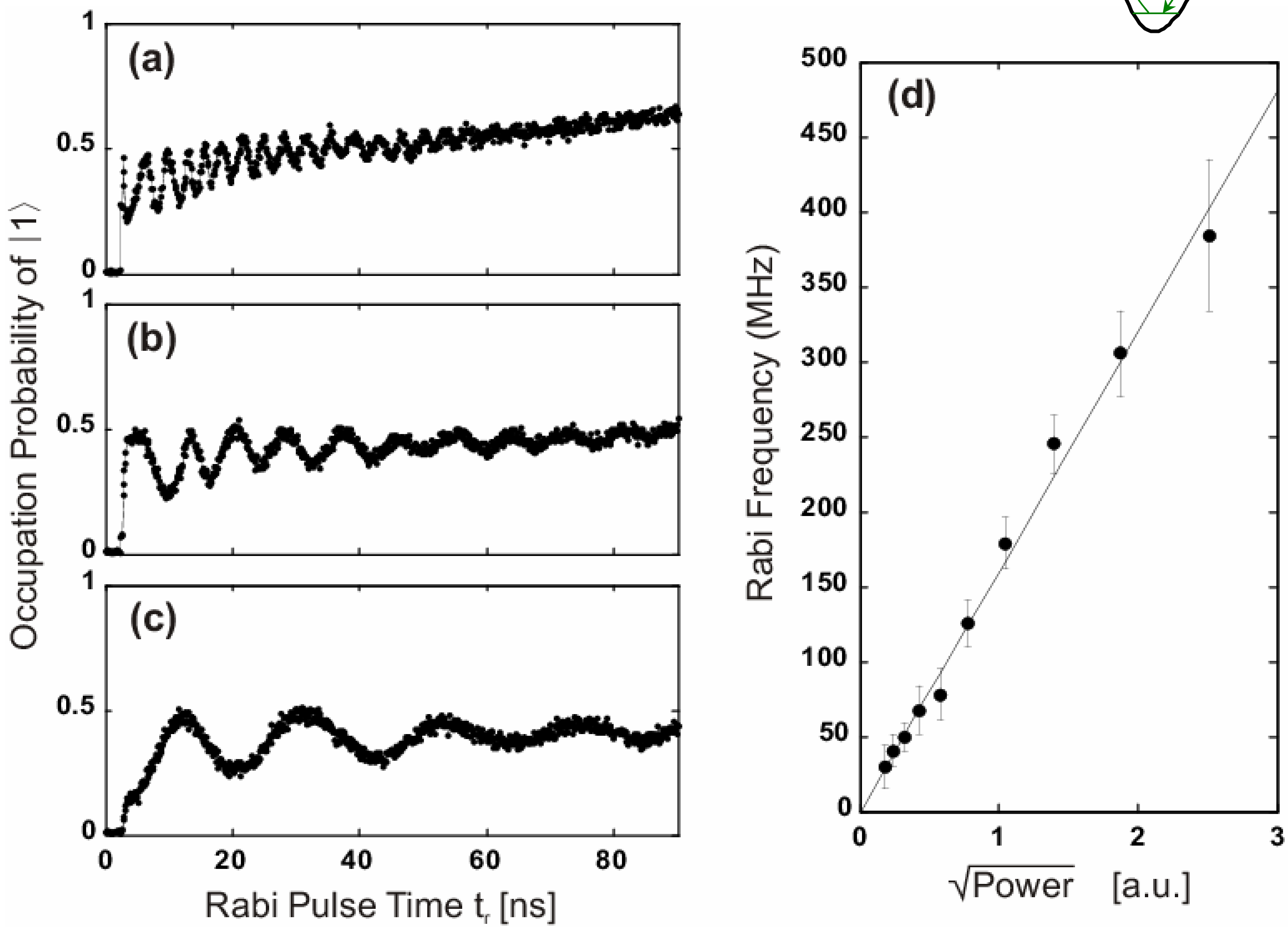




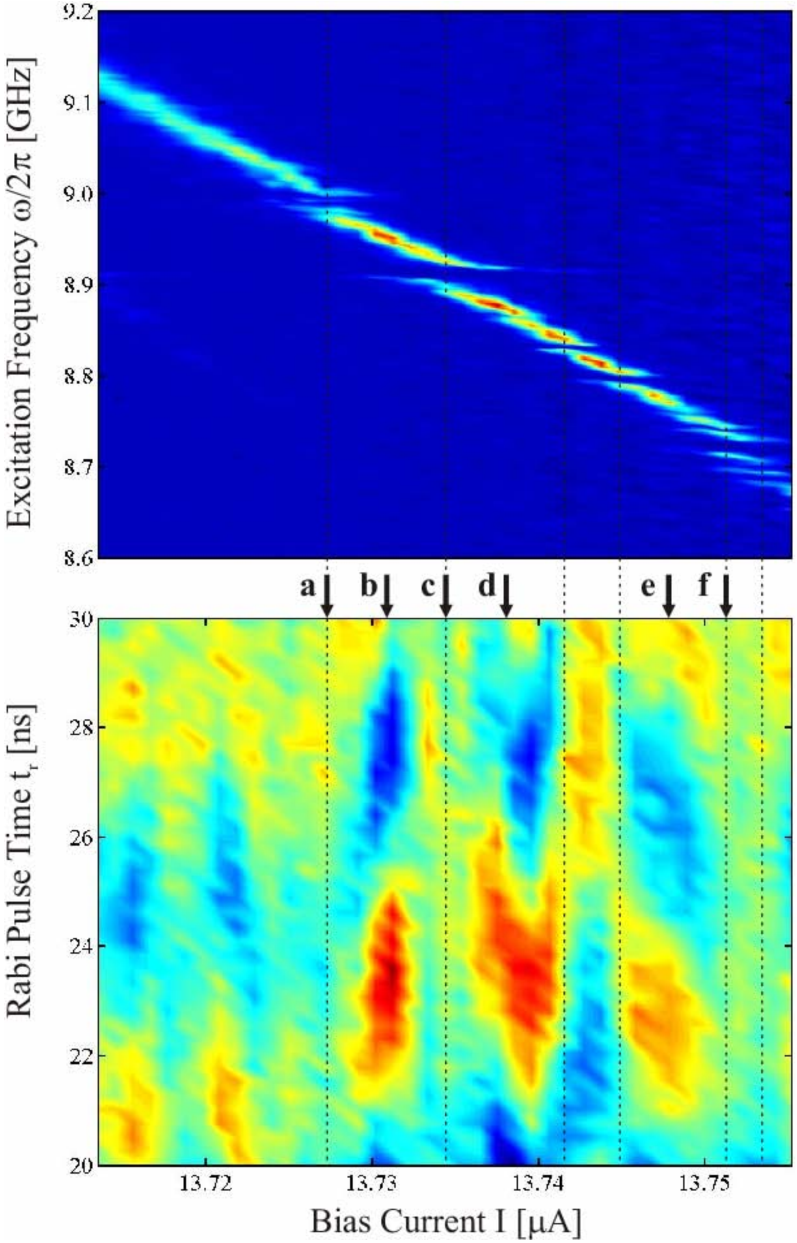
Rabi Oscillations





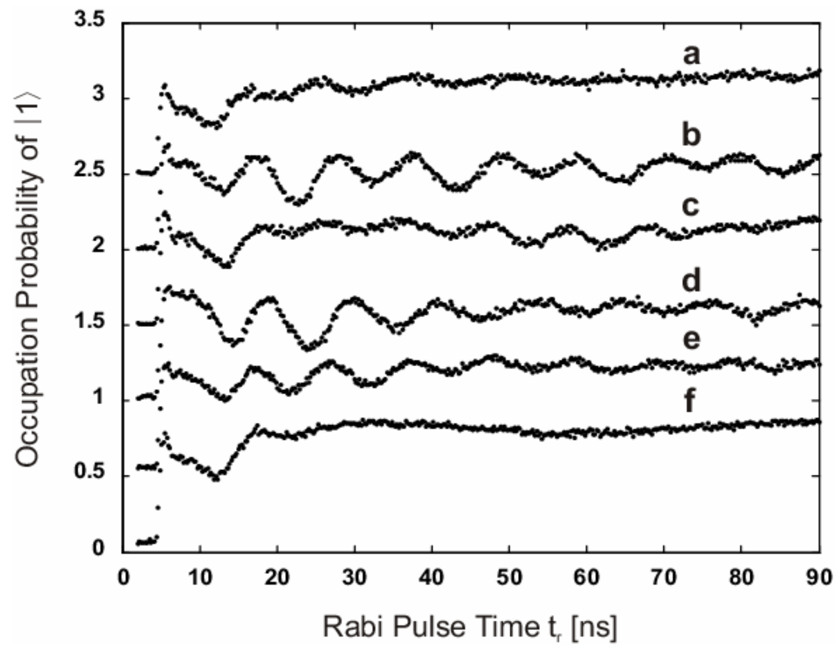


Resonances & Rabi Oscillations



p_1=0 : blue

p_1=1 : red



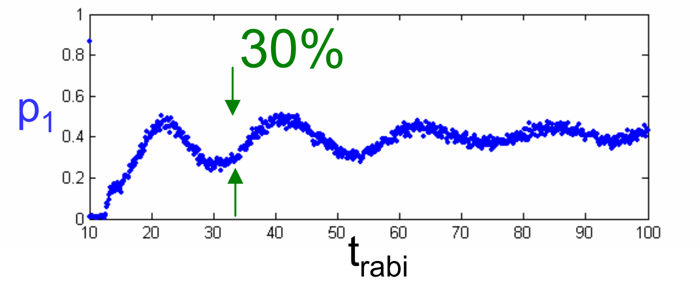
Rabi oscillations disappear at spurious resonances

Decrease in coherence amplitude, not coherence time

Amplitude Decoherence (Visibility)

- Need to report amplitude of oscillations

	barrier	coh. time	coh. ampl.
Saclay	AlOx	1 μs	(30%)
Delft	AlOx	150 ns	50%
NIST	AlOx	41 ns	30%
NIST	NbAlOx	20 ns	15%
Kansas	AlN	5 μs	1%



- All experiments have reduced amplitude

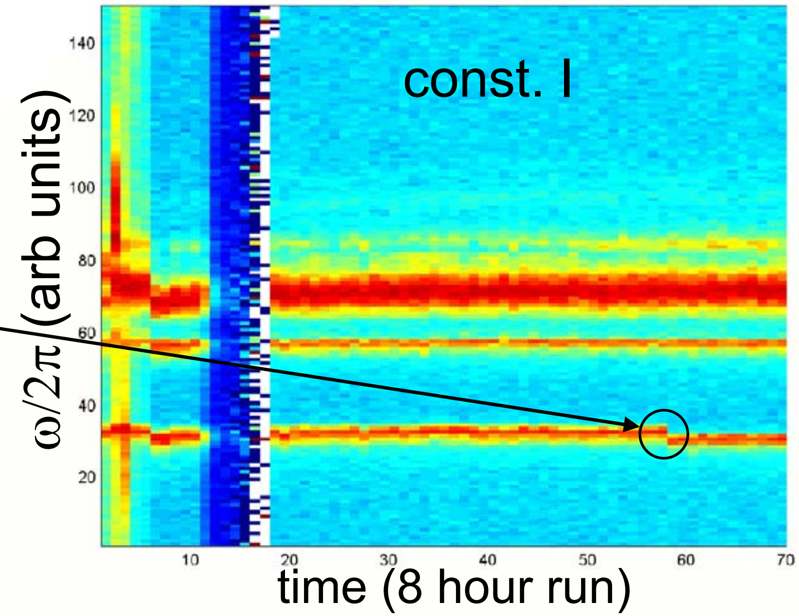
- Spurious resonances observed in Saclay, Delft experiments
  - Small junctions: fewer resonances, but greater effect

- Decoherence likely from many small resonances
  - All resonances reduce coherence amplitude
  - Expect and observe small resonances at optimal bias

- Resonances are major source of decoherence?!

What causes extra resonances?

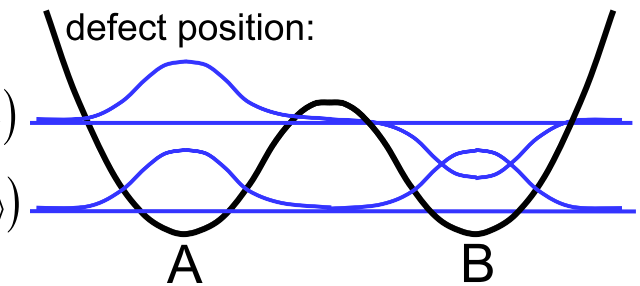
- Level-repulsion:
  Uncontrolled "Coupled qubit"
- Frequency shifts rule-out
  macroscopic EM modes
- Model as modulation of I_0
  from resonant defect motion

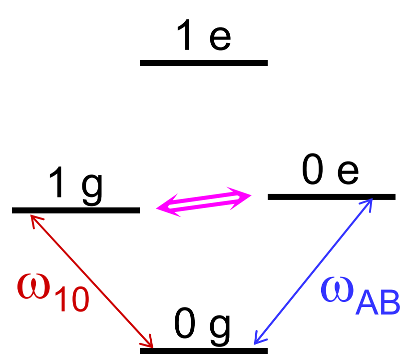


$$H_{\text{int}} = \left(-\frac{\Phi_0 I_{0A}}{2\pi}\cos\delta\right)\otimes|\Psi_A\rangle\langle\Psi_A| + \left(-\frac{\Phi_0 I_{0B}}{2\pi}\cos\delta\right)\otimes|\Psi_B\rangle\langle\Psi_B| = \frac{\Delta I_0}{2}\sqrt{\frac{\eta}{2\omega_{10}C}}\left(|0\rangle\langle 1|\otimes|e\rangle\langle g| + |1\rangle\langle 0|\otimes|g\rangle\langle e|\right)$$

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

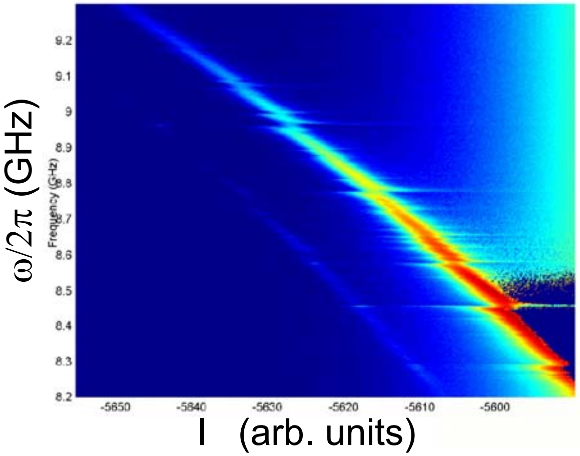
$$|g\rangle = 2^{-1/2}\left(|\Psi_A\rangle + |\Psi_B\rangle\right)$$





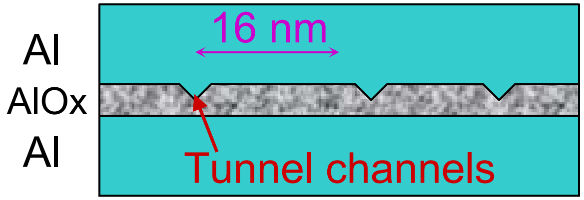
Explains energy-level repulsion

Decoherence : IV's : 1/f Noise



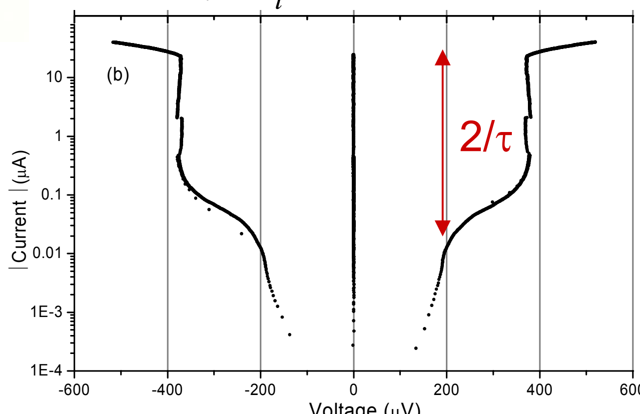
32 μm² junction

- 25 MHz splittings
- 1 resonance / 60MHz



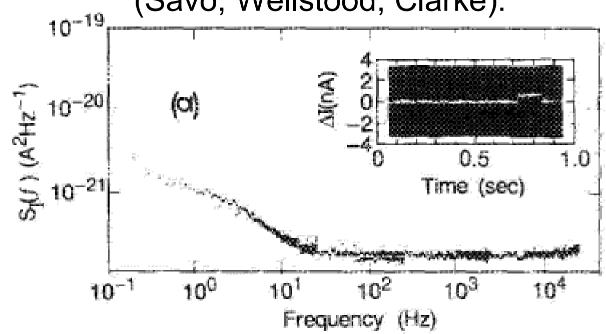
$$G_N = \frac{2e^2}{h}\sum_i \tau_i = \frac{2e^2}{h} N_{ch}\tau$$

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



- $\tau \sim 4\text{x}10^{-3}$
- 1 channel / (16nm)²

- See individual traps in sub-micron junctions (Savo, Wellstood, Clarke):



0.1 μm² junction (Van Harlingen)

- $\Delta I_0 \sim 10^{-4}\ I_0$ ($1/N_{ch} \sim 3\text{x}10^{-3}$)
- 1 trap / decade freq.

scaling to 32 μm²

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

- $\Delta I_0/I_0 \sim 8$ ppm

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

Assuming resonances & traps turn on/off channels:

Resonances and 1/f noise are same phenomenon !

Decoherence & Materials

- All oxide tunnel barriers give similar 1/f noise

(Van Harlingen et al)

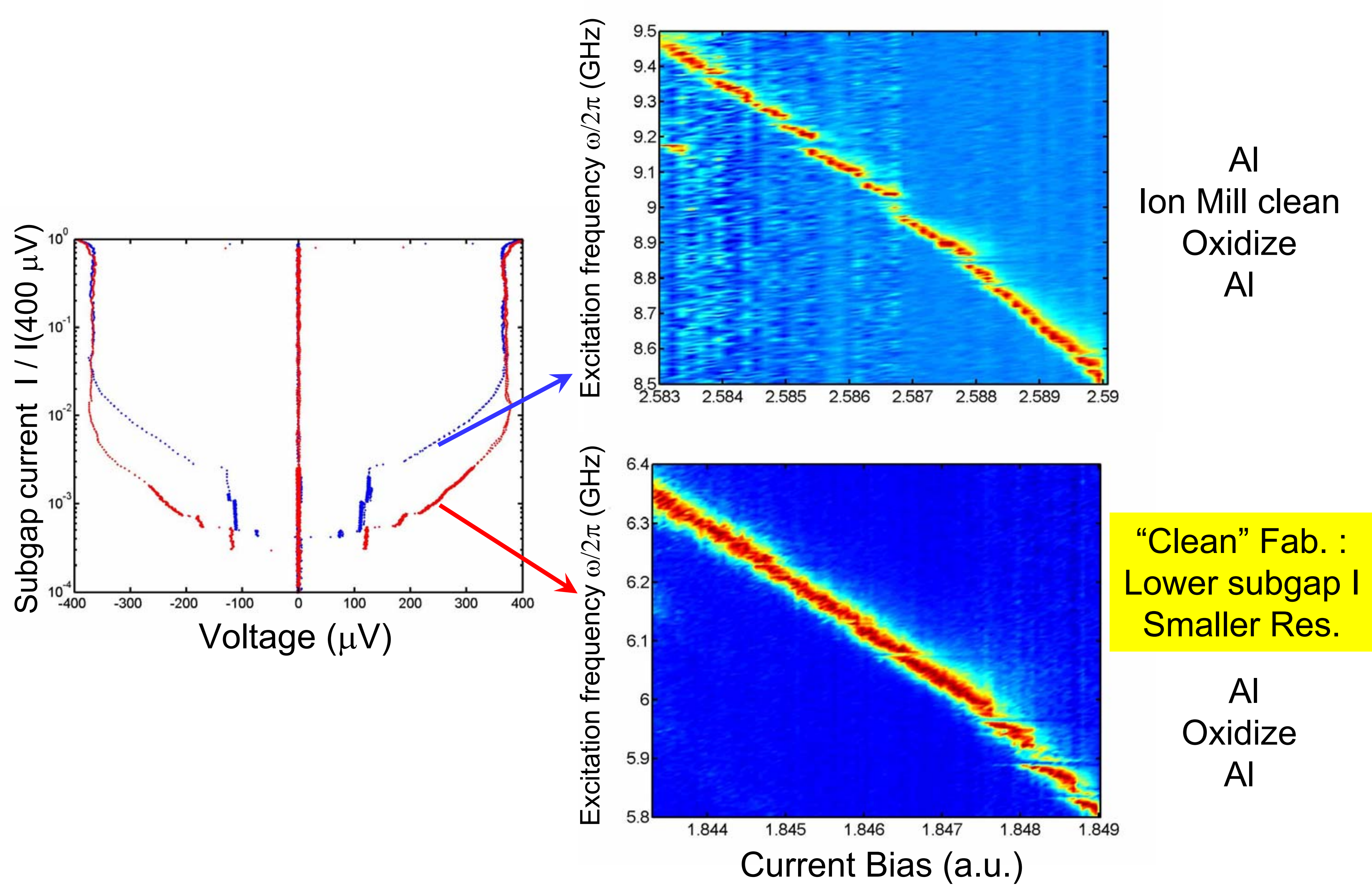
	$S_{I0}^{1/2}(1Hz)A^{1/2}/I_0$ (μm pA/Hz$^{1/2}$/μA)
Al-AlOx-Al	(~5)
Nb-AlOx-Nb	7-20
Nb-Ox-PbIn	7-20
Nb-NbOx-PbInAu	8
PbIn-Ox-Pb	15
NbN-AlN-NbN (epi)	1000

- Need Materials Research – Qubits have vastly different requirements

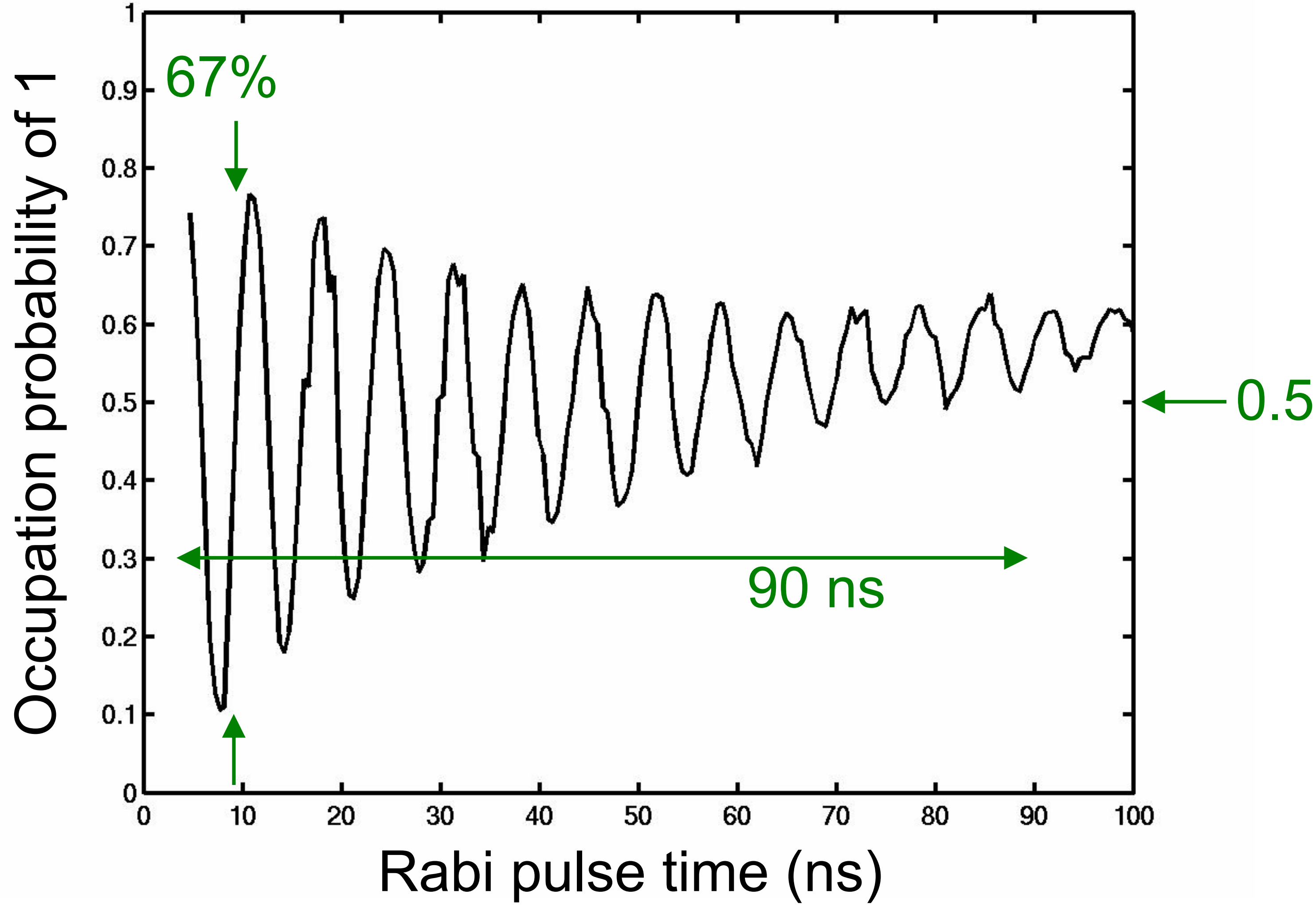
Past Research: High T_c, Q < 1 , low leakage junctions

Qubits: T_c > 1K, leakage tolerated
low fluctuations, low dielectric loss

Resonance Size Correlated with Fabrication !



Rabi Oscillations for Trilayer Junction



Materials Research

Now have model for optimization!

- New fabrication methods for current Al-AlOx-Al devices:
  - trilayer processing
  - epitaxial growth of Al ← Work by Dustin Hite
  - growth AlOx at elevated temperatures
- New substrates, junction and barrier materials:
  - Ta as a junction material
  - AlN barrier
  - Al_2O_3 crystalline barrier
- For understanding & rapid optimization, need multiple characterization tools:
  - local probe studies- conducting atomic force microscopy and scanning tunneling microscopy
  - Auger Electron Spectroscopy and LEED
  - Junction IV measurements
  - Qubit spectroscopy
  - Coherence Time (Phase qubits ideal for testing materials)

Conjecture for All Qubits:

- Josephson qubits are insensitive to defects
- Decoherence from motion of defects
- Connected to 1/f noise