- Superconductivity

(1) Condensation into state:
notoccupied / occupied pairs of electrons
of oppos. momentum (time-reversed)

(2) All pairs have same free parameter δ

$$\psi = (u + v e^{i\delta} c_k^+ c_{-k}^+)|0\rangle$$

(4) Energy Gap Δ ($\sim 2kT_c$) For
breaking of pair $\rightarrow$ robust state

(3) S. current prop. to $\nabla\phi$; as any quantum state

Show Act's I-V

(5) For tunnel junct;

$$I \sim I_0 \sin\delta \qquad (I_0 \propto A;\ \text{thickn barrier})$$

(A s. current, I with V=0)

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

Later equation like Faraday's law

$$V = \dot{\Phi}\ ;\ \text{so}\ \tilde{\Phi} = \left(\frac{\hbar}{2e}\delta\right)$$

Can manip δ with B Field (Flux).

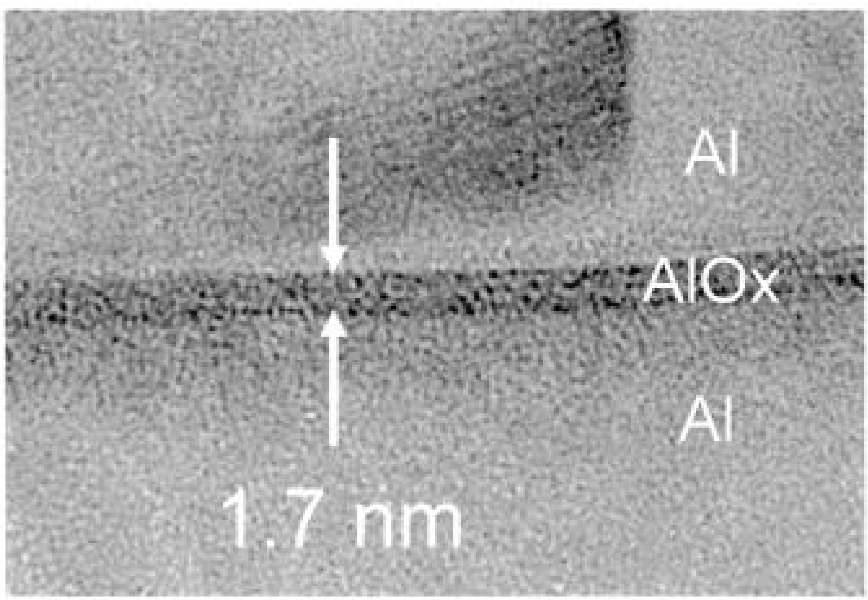
(6) In a loop, δ is 2π periodic, so
see Device behavior periodic in Field; with applied Flux

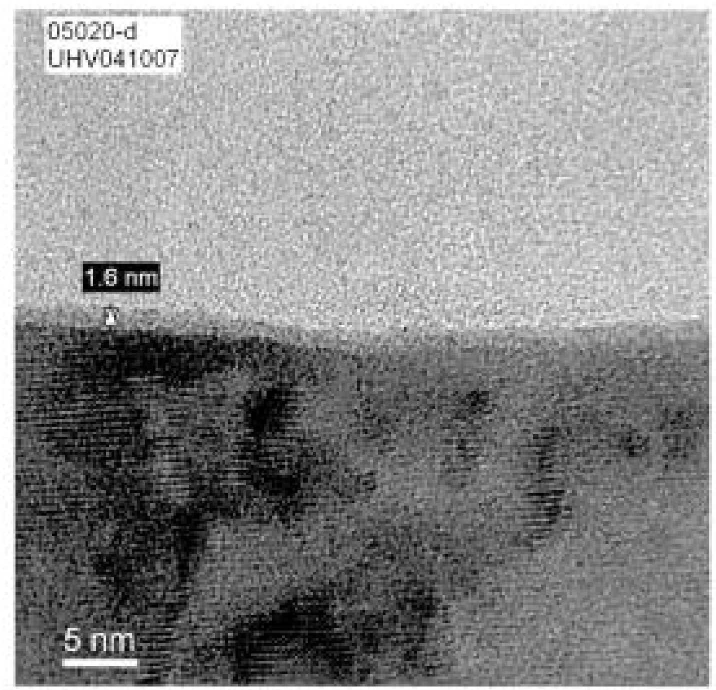
$$\vec{B}\cdot\vec{A} = n(\Phi_0 = h/2e)$$

In tunnel junct. See S Current;
No I of $V < 2\Delta$ because for e's to
tunnel, need to break CP's into 2e's $\rightarrow$ 2Δ of E min.

TOPS 35500

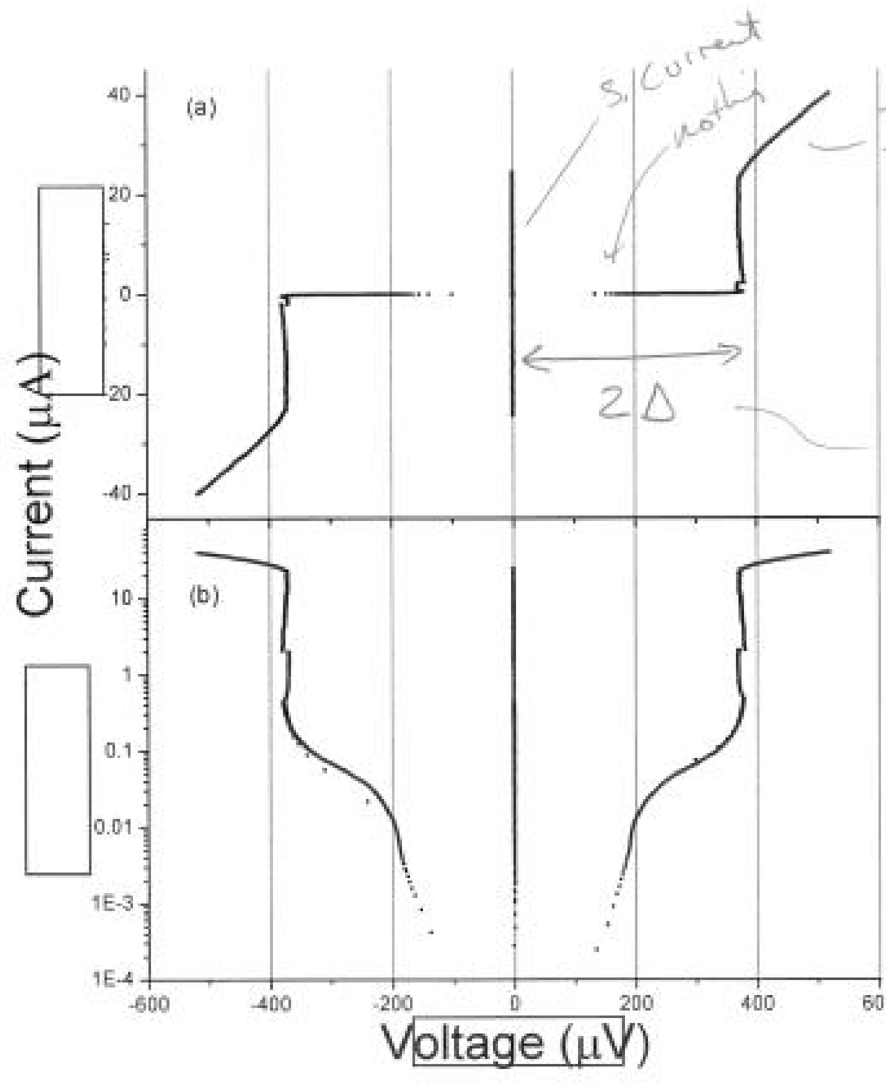
Tunnel Junctions





Al
Al_2O_3
Re

Tunnel Junctions



– I rise; |V| > 2Δ

Dist prop to T_c

Al/AlOx/AL:
Good quality junctions

Low sub-gap
leakage

($\sim 10^{-3}$ at 2Δ rise)

Additional Discussion

(1) Understand phase parameter in S.C.

(BCS_Λ explicit Focus of δ)
"spin model"

(2) Josephson Effect

<u>Proper</u> 2nd order calculation of effect.

→ Understand where comes from (Not in textbooks)

→ Why S.C. has <u>No</u> resistance
→ An actual calculation!

(3) <u>Exact</u> Calc. of Josephson Effect
(Arbitrary coupling) via Andreev Bound states.

- S.C. Gap protects from Dissipation
- Understand subgap current

All with simple (as possible) Mathematics.
(Learn in 1st year of Grad. School).

understanding of the junction physics is thus needed so that nonideal behavior can be more readily identified, understood, and eliminated. Although we will not discuss specific imperfections of junctions in this paper, we want to describe a clear and precise model of the Josephson junction that can give an intuitive understanding of the Josephson effect. This is especially needed since textbooks do not typically derive the Josephson effect from a microscopic viewpoint. As standard calculations use only perturbation theory, we will also need to introduce an exact description of the Josephson effect via the mesoscopic theory of quasiparticle bound-states.

The outline of the paper is as follows. We first describe in Sec. 2 the nonlinear Josephson inductance. In Sec. 3 we discuss the three types of qubit circuits, and show how these circuits use this nonlinearity in unique manners. We then give a brief derivation of the BCS theory in Sec. 4, highlighting the appearance of the macroscopic phase parameter. The Josephson equations are derived in Sec. 5 using standard first and second order perturbation theory that describe quasiparticle and Cooper-pair tunneling. An exact calculation of the Josephson effect then follows in Sec. 6 using the quasiparticle bound-state theory. Section 7 expands upon this theory and describes quasiparticle excitations as transitions from the ground to excited bound states from nonadiabatic changes in the bias. Although quasiparticle current is typically calculated only for a constant DC voltage, the advantage to this approach is seen in Sec. 8, where we qualitatively describe quasiparticle tunneling with AC voltage excitations, as appropriate for the qubit state. This section describes how the Josephson qubit is typically insensitive to quasiparticle damping, even to the extent that a phase qubit can be constructed from microbridge junctions.

2 The Nonlinear Josephson Inductance

A Josephson tunnel junction is formed by separating two superconducting electrodes with an insulator thin enough so that electrons can quantum-mechanically tunnel through the barrier, as illustrated in Fig. 1. The Josephson effect describes the supercurrent I_J that flows through the junction according to the classical equations

(2) I-V relations, will derive later.

$$I_J = I_0 \sin\delta \tag{2.1a}$$

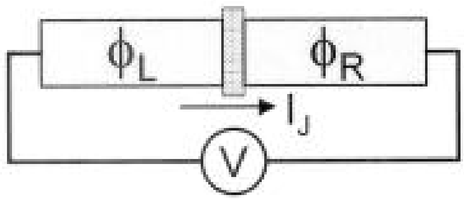
$$V = \frac{\Phi_0}{2\pi}\frac{d\delta}{dt}, \tag{2.1b}$$

where $\Phi_0 = h/2e$ is the superconducting flux quantum, I_0 is the critical-current parameter of the junction, and $\delta = \phi_L - \phi_R$ and V are respectively the superconducting phase difference and voltage across the junction. The

This like Φ; $\delta = 2\pi\,\Phi/\Phi_0$

NO

$I = \frac{\Phi_0}{L}$



① thin oxide barrier

Fig. 1. Schematic diagram of a Josephson junction connected to a bias voltage V. The Josephson current is given by $I_J = I_0 \sin\delta$, where $\delta = \phi_L - \phi_R$ is the difference in the superconducting phase across the junction.

dynamical behavior of these two equations can be understood by first differentiating Eq. 2.1a and replacing $d\delta/dt$ with V according to Eq. 2.1b

$$\frac{dI_J}{dt} = I_0 \cos\delta \, \frac{2\pi}{\Phi_0} V \ . \tag{2.2}$$

"Differential Inductance"

With dI_J/dt proportional to V, this equation describes an inductor. By defining a Josephson inductance L_J according to the conventional definition $V = L_J dI_J/dt$, one finds

$$L_J = \frac{\Phi_0}{2\pi I_0 \cos\delta} \ . \tag{2.3a}$$

Non linear L_J with $\cos\delta$ ($\delta \to \pi/2$ @ $I \to I_0$)

The $1/\cos\delta$ term reveals that this inductance is nonlinear. It becomes large as $\delta \to \pi/2$, and is negative for $\pi/2 < \delta < 3\pi/2$. The inductance at zero bias is $L_{J0} = \Phi_0/2\pi I_0$.

An inductance describes an energy-conserving circuit element. The energy stored in the junction is given by

Energy stored in L_J

$$U_J = \int I_J V \, dt \tag{2.4a}$$

$$= \int I_0 \sin\delta \, \frac{\Phi_0}{2\pi} \frac{d\delta}{dt} dt \tag{2.4b}$$

$$= \frac{I_0 \Phi_0}{2\pi} \int \sin\delta \, d\delta \tag{2.4c}$$

$$= -\frac{I_0 \Phi_0}{2\pi} \cos\delta \ . \tag{2.4d}$$

This calculation of energy can be generalized for other nondissipative circuit elements. For example, a similar calculation for a current bias gives $U_{\mathrm{bias}} = -(I\Phi_0/2\pi)\delta$. Conversely, if a circuit element has an energy $U(\delta)$, then the current-phase relationship of the element, analogous to Eq. 2.1a, is

$$I_J(\delta) = \frac{2\pi}{\Phi_0} \frac{\partial U(\delta)}{\partial \delta} \ . \tag{2.5}$$

↓ Useful relations used later

A generalized Josephson inductance can be also be found from the second derivative of U ,

$$\frac{1}{L_J} = \left(\frac{2\pi}{\Phi_0}\right)^2 \frac{\partial^2 U(\delta)}{\partial \delta^2} \ . \tag{2.6}$$

The classical and quantum behavior of a particular circuit is described by a Hamiltonian, which of course depends on the exact circuit configuration. The procedure for writing down a Hamiltonian for an arbitrary circuit has been described in detail in a prior publication [11]. The general form of the Hamiltonian for the Josephson effect is $H_J = U_J$.

3 Phase, Flux, and Charge Qubits

A Josephson qubit can be understood as a nonlinear resonator formed from the Josephson inductance and its junction capacitance. nonlinearity is crucial because the system has many energy levels, but the operating space of the qubit must be restricted to only the two lowest states. The system is effectively a two-state system [12] only if the frequency ω_{10} that drives transitions between the qubit states $0 \longleftrightarrow 1$ is different from the frequency ω_{21} for transitions $1 \longleftrightarrow 2$.

We review here three different ways that these nonlinear resonators can be made, and which are named as phase, flux, or charge qubits.

The circuit for the phase-qubit circuit is drawn in Fig. 2(a). Its Hamiltonian is

$$H = \frac{1}{2C}\widehat{Q}^2 - \frac{I_0\Phi_0}{2\pi}\cos\widehat{\delta} - \frac{I\Phi_0}{2\pi}\widehat{\delta} \ , \tag{3.1}$$

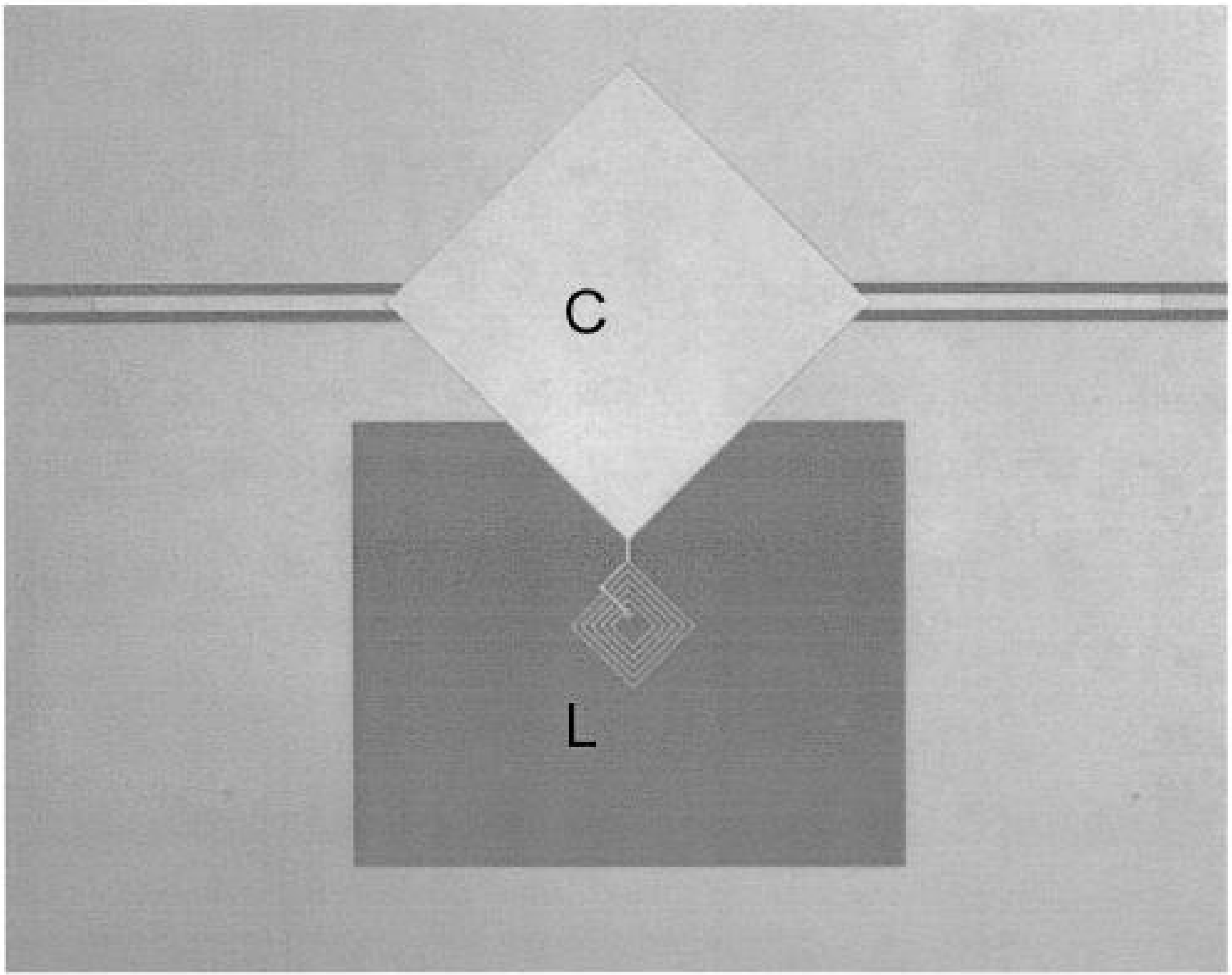
where C is the capacitance of the tunnel junction. A similar circuit is drawn for the flux-qubit circuit in Fig. 2(b), and its Hamiltonian is

$$H = \frac{1}{2C}\widehat{Q}^2 - \frac{I_0\Phi_0}{2\pi}\cos\widehat{\delta} + \frac{1}{2L}(\Phi - \frac{\Phi_0}{2\pi}\widehat{\delta})^2 \ . \tag{3.2}$$

The charge qubit has a Hamiltonian similar to that in Eq. 3.1, and is described elsewhere in this publication. Here we have explicitly used notation appropriate for a quantum description, with operators charge $\widehat{Q}$ and phase difference $\widehat{\delta}$ that obey a commutation relationship $[\widehat{\delta}, \widehat{Q}] = 2ei$. Note that the phase and flux qubit Hamiltonians are equivalent for $L \to \infty$ and $I = \Phi/L$, which corresponds to a current bias created from an inductor with infinite impedance.

The commutation relationship between $\widehat{\delta}$ and $\widehat{Q}$ imply that these quantities must be described by a wavefunction. The characteristic widths of this wavefunction are controlled by the energy scales of the system, the charging energy of the junction $E_C = e^2/2C$ and the Josephson energy $E_J = I_0\Phi_0/2\pi$. When the energy of the junction dominates, $E_J \gg E_C$,

LC Microwave Resonator

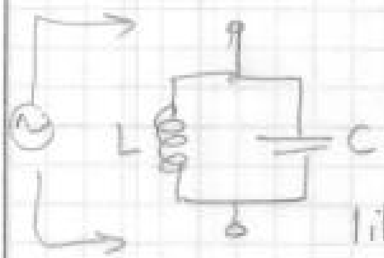


Circuit Atoms

- Most all qubits formed by considering 2 states ($|0\rangle + |1\rangle$ labeled) of more complex "atom"

$$\boxed{\omega_{res} = \frac{1}{\sqrt{LC}} \; ; \; Z_{res} = \omega_r L = \sqrt{\frac{L}{C}}}$$

- To understand Josephson, first look at LC osc. More useful class. descrip.



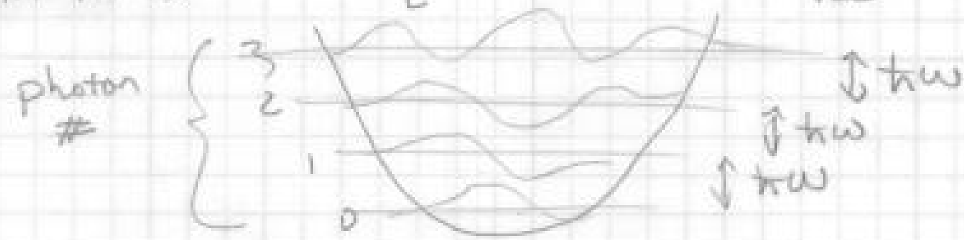
$$H = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L} \qquad [\hat{Q}, \hat{\Phi}] = i\hbar$$

$$\text{like}\left[H_{HO} = \frac{\hat{p}^2}{2m} + \frac{1}{2}k\hat{x}^2 \qquad [\hat{x}, \hat{p}] = i\hbar \right]$$

- Solve in standard way for Harm. Osc. $\left(\begin{matrix} \hat{p} \to \hat{Q} ; m \to C \\ \hat{x} \to \hat{\Phi} ; k \to \frac{1}{L} \end{matrix} \right)$

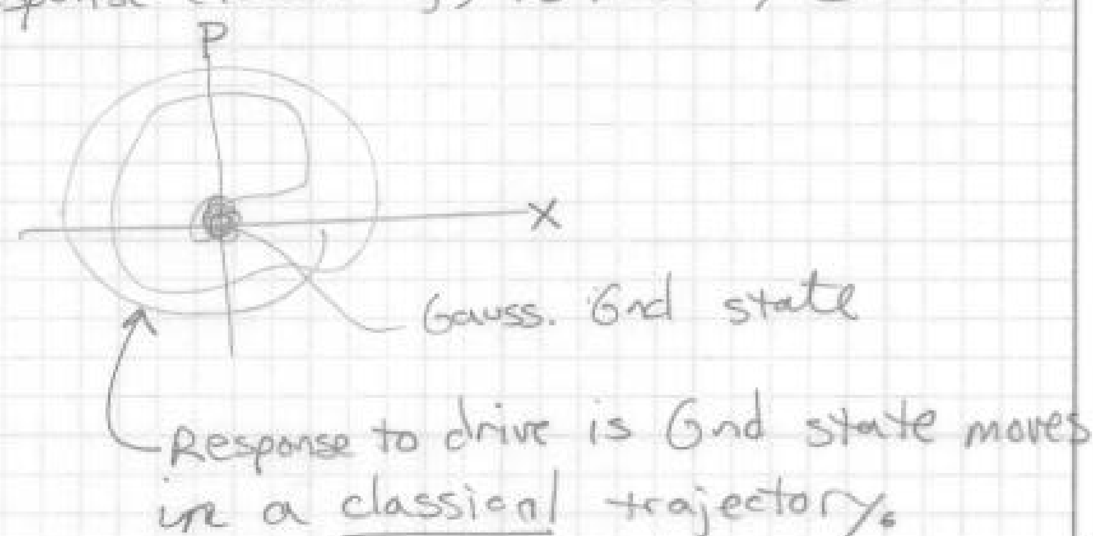
$a^+|n\rangle = \sqrt{n+1}\,|n+1\rangle$ $\qquad H = \left(a^+a + \frac{1}{2}\right)\hbar\omega$

$a|n\rangle = \sqrt{n}\,|n-1\rangle$ $\qquad \hookrightarrow \frac{1}{\sqrt{LC}}$; osc freq

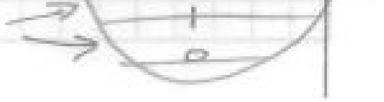


- Problem(s) for qubit
  (1) All energy level sep's same, can't define $|0\rangle$ $|1\rangle$ and keep in that subspace.

  (2) Response (to driving) is linear / classical



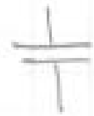
- Need Non-linearity for Qubit states



Circuit H / energies

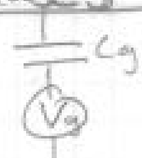
(1) (Paper by Devoret describes mathem. to determ. H, depends on wiring).

(2) Not spend time, but can understand basic energy terms:

(3) C  $\rightarrow \frac{Q^2}{2C}$

L  $\rightarrow \frac{\Phi^2}{2L}$

(4) biases:



$$\frac{(Q - C_g V_g)^2}{2C}$$

offset to charge (new equilib. value)

$$\frac{(\Phi - \Phi_b)^2}{2L}$$

(5) J-Junction

 $E = -E_J \cos\delta$ in δ-space

$E_J = \left(\frac{I_0 \Phi_0}{2\pi}\right)$ Josephson energy

(6) J-eqt Far. Law

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

$$\left[\frac{\cancel{\hbar}}{\cancel{2e}}\hat{\delta}, e\hat{q}\right] = i\cancel{\hbar}$$

$$[\hat{\delta}, \hat{q}] = 2i \quad \text{dim'less units}$$

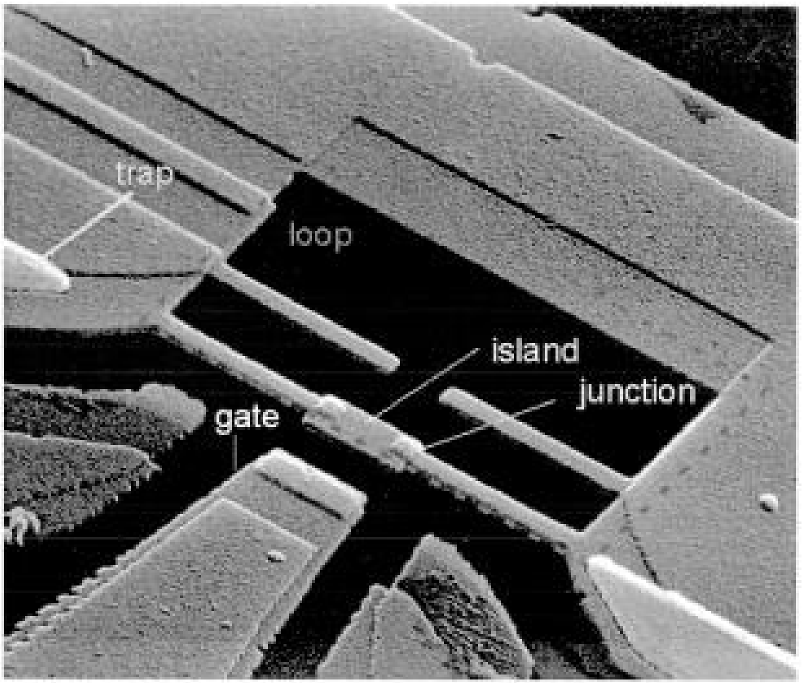
$\hat{q}$ = FT $\hat{\delta}$ potential; $\frac{e^{i\hat{\delta}} + e^{-i\hat{\delta}}}{2}$; chg. $\hat{q}$ by 2

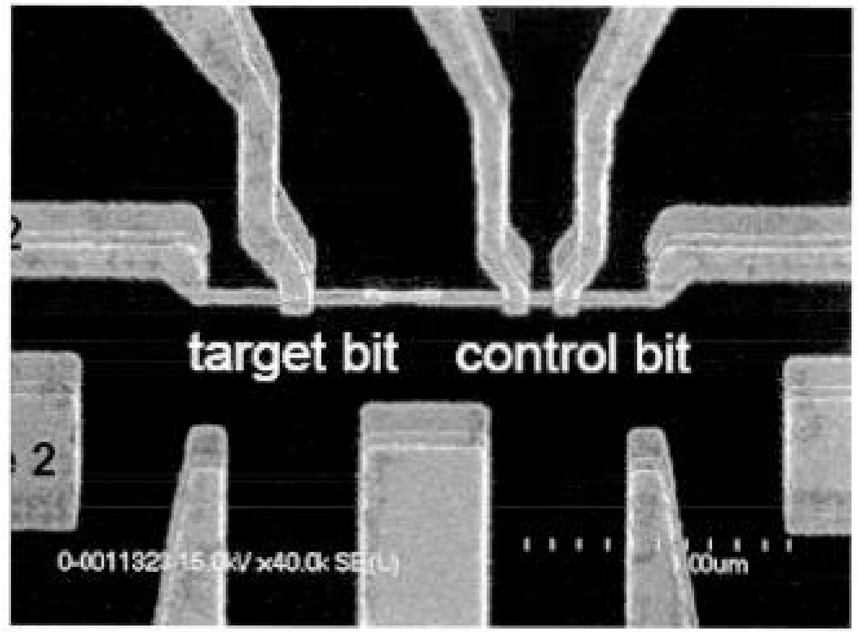
$\boxed{\text{As expect, J-effect is transf 1 pair}}$ $E = -\frac{E_J}{2}\left[|\hat{q}\rangle\langle\hat{q}+2| + |q+2\rangle\langle q|\right]$ $\hat{q}$-space

chg. by 1 CoP.

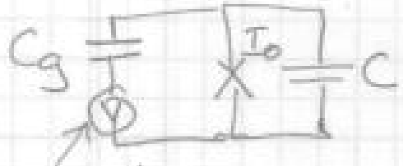
Charge Qubit

Made by evap Al thr a shadow mask stencil made from e-beam resist.





Charge Qubit



Junct: Josephson I_0 + Cap. C

V is control parameter

C energy

Josephson (CP-transfer) Energy

$$H = \frac{e^2}{2(C+C_g)}\left(\hat{q} - \frac{C_g V}{e}\right)^2 - \frac{I_0 \Phi_0}{2\pi}\cos\hat{\delta}$$

$$= E_c\left(\hat{q} - q_b\right)^2 - \frac{E_J}{2}\boxed{\left[|\hat{q}\rangle\langle\hat{q}+2| + |\hat{q}+2\rangle\langle\hat{q}|\right]}$$

To solve:

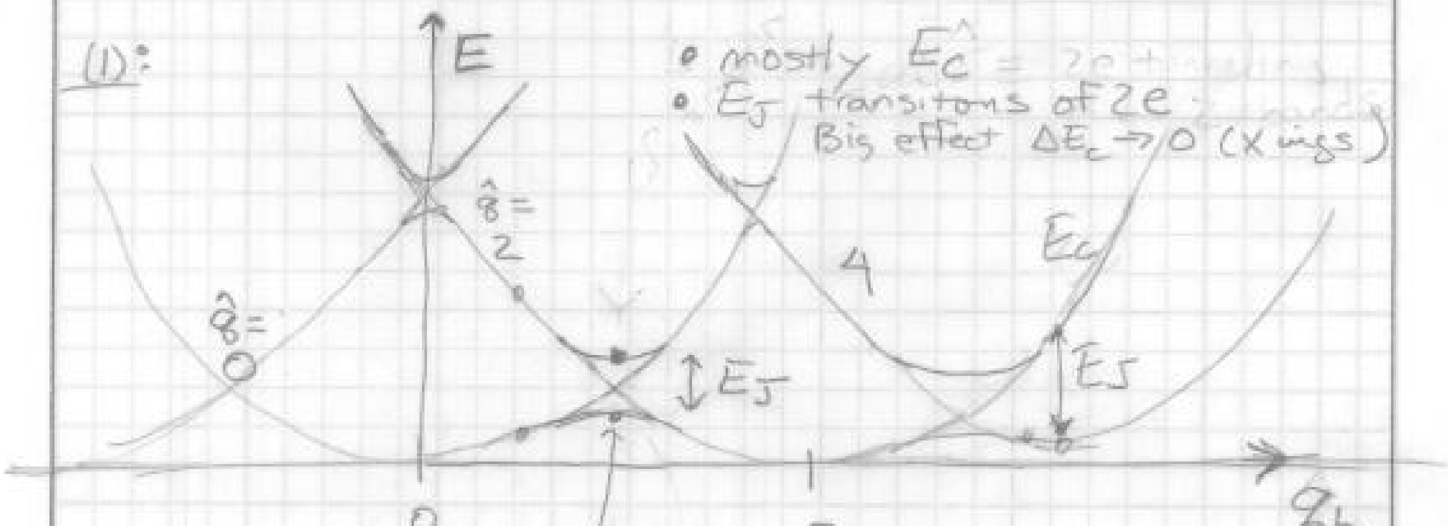
(1) $E_c \gg E_J$; $\hat{q}$ more classical coord. better basis (discreet values $\pm 2e$)

$E_J \gg E_c$; $\hat{\delta}$ is better basis

(1):

- mostly $\hat{E_c}$
- E_J transitions of $2e$

Big effect $\Delta E_c \to 0$ (X ings)



Near Resonance, basis $|\hat{q}=0\rangle, |\hat{q}=2\rangle$

$$H \simeq 2E_c(1-q_b)\,\sigma_z - \frac{E_J}{2}\,\sigma_x$$

"Avoided crossing"

$$E = \pm\sqrt{(\quad)^2 + (\quad)^2}$$

$\underline{\underline{q_b = 1}}$ $|0\rangle = (|\hat{q}=0\rangle + |\hat{q}=2\rangle)/\sqrt{2}$

$|1\rangle = ($ $-$ $)$

Charge Noise Problem:

All fine, except nature not so kind!

Example of limitations to thy, from exp'l observation!

q_b random, sample-to-sample (have to tune, ok)

(Why so large? Calc. later) → q_b Fluct's over time by 10^{-2} to 10^{-3} (charge noise)

↳ Fluct's $E_{10}(t)$, random Z oper, ϕ noise

~ns coherence time.

Big problem! (I orig. thought S.C. qubits never would work)

(1) Solution (Saclay):

Operate at $q_b = 1$, where $\frac{\partial E_{10}}{\partial q_b} = 0$;

Insens. to noise (1st order, 2nd order signif!)

(2) Also, make band flatter

E_J big; $E_J > E_C$ useful limit!

This is param's for more modern design

(can't really use this $\hat{q}$ basis well)

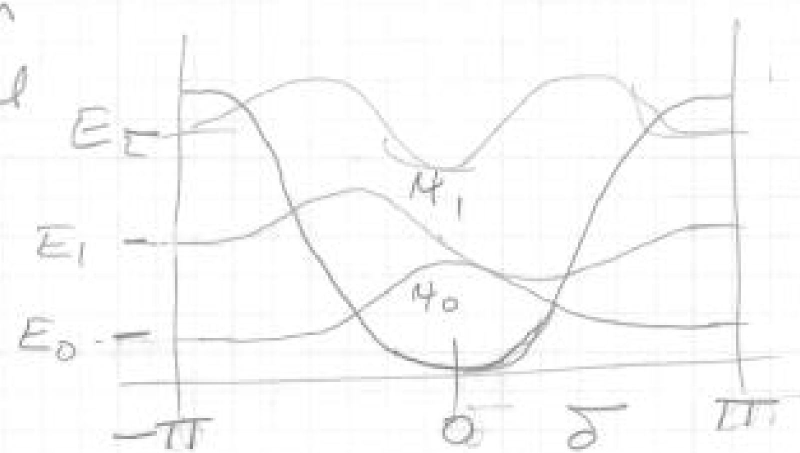
since ψ is superp of many $|\hat{q}=0\rangle$, $|\hat{q}=2\rangle$, $|\hat{q}=4\rangle$, ... states)

Solution for $E_J > E_C$ ($\hat{\delta}$ basis)

(1) Charge quantiz. : Periodic $\Psi(\hat{\delta} \pm 2\pi) = e^{-i 2\pi q_b / 2e} \Psi(\delta)$
δ from $-\pi$ to π

(2) Solve S.E in $\cos\delta$ potential

(H.O.-like states, but non-linear)



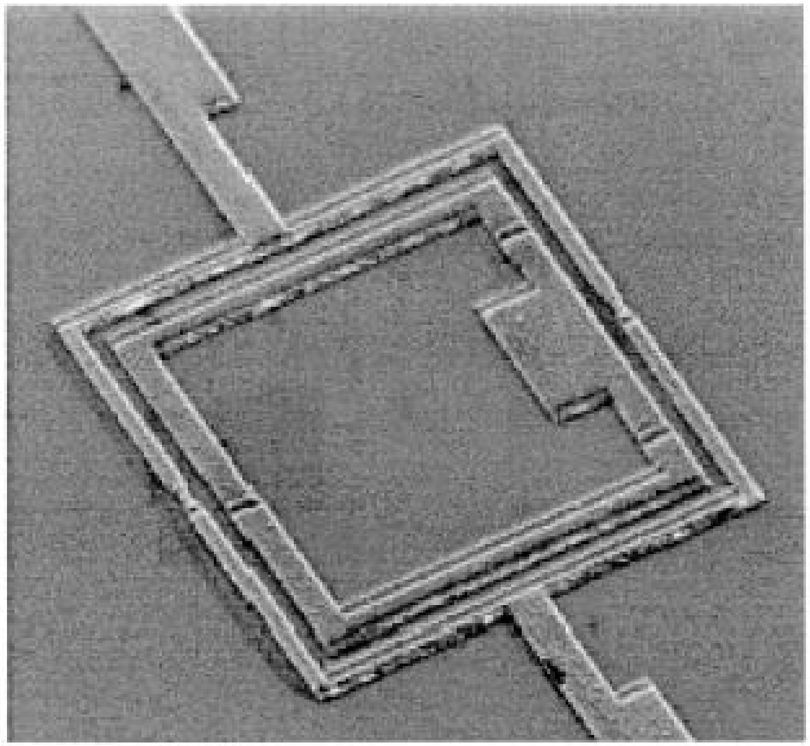
(3) See non-linear from non quad cos potential.

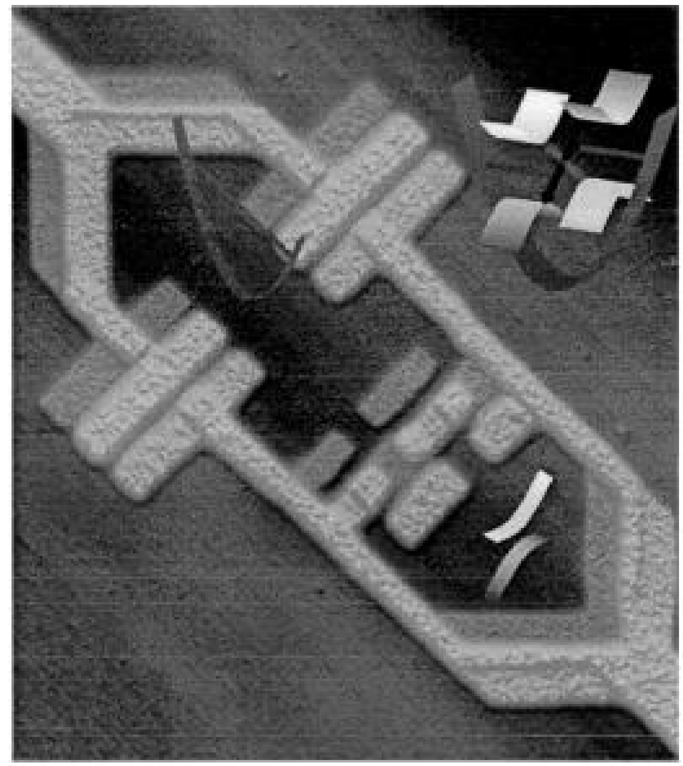
(4) Make $E_J \gtrsim 5 E_c$ so Ψ is small at $0, 2\pi$, then small change with charge q_b

(5) Possible to get exp. small charge noise, but reasonable non-lin $1 \leftrightarrow 2 / 0 \leftrightarrow 1$
(Transmon circuit from Yale)

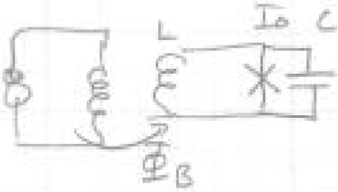
(If q does not affect the charge qubit, why still call it that?)

Flux Qubits





FLUX qubits

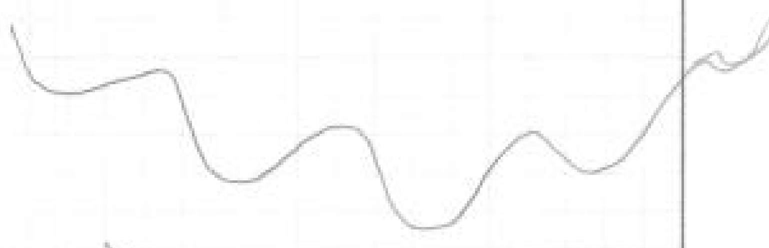
(1) 

DC short (L) across junction, $\hat{q}$ is continuous, $\hat{\delta}$ not periodic

(2) $$H = E_c \hat{q}^2 + \frac{\left(\Phi_b - \hat{\delta}\,\Phi_0/2\pi\right)^2}{2L} - E_j \cos\hat{\delta}$$

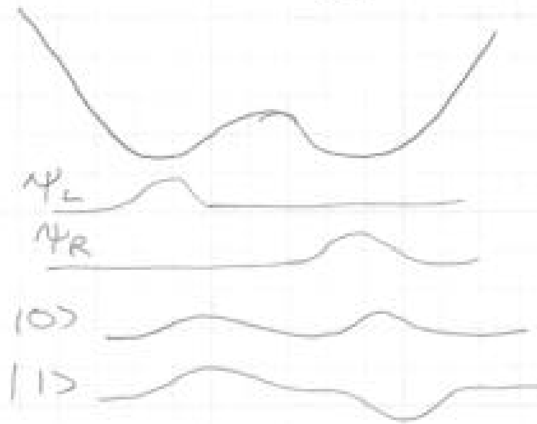
Parab. + cosine pot

(3) =



(4) Idea: Make quartic potential, tunneling between 2 diff Φ states

tunnel



(5) Why interesting?

E_{10} low because determ by tunneling

good → E_{21} high, so VERY nonlinear potential

~~forget~~ about other states!

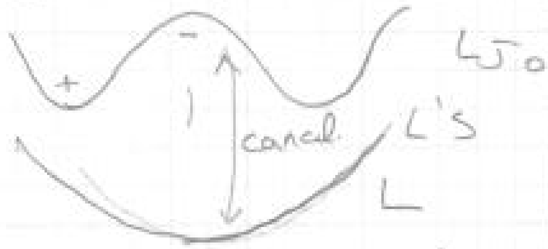
(6) How get highly non-linear (quartic) potential?

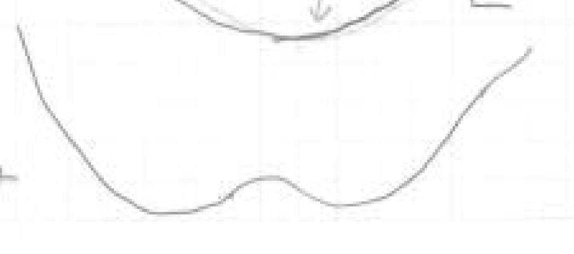
Cancel $-L_{J0}$ → bias at $\Phi_0/2$

hard → with L

(careful design with

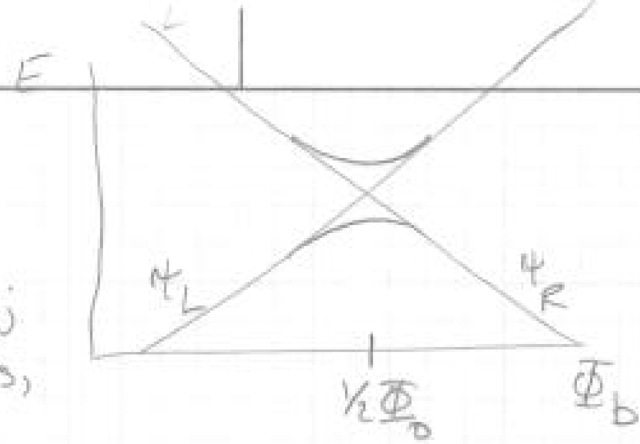
$$L \gtrsim L_{J0}$$





→ Make C small so tunnels fast (wide ψ's)

(7) In basis of
$\psi_L, \psi_R \longrightarrow$



Tunneling mixes states; avoided crossing E_s, determ by param's

~~hard~~ → (expon. depend)

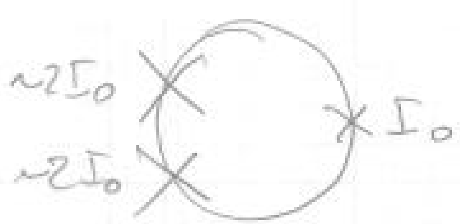
$$H = \frac{\alpha \Phi_0^2}{2L}\left(\Phi_b/\Phi_0 - \frac{1}{2}\right)\sigma_z - \underbrace{\frac{E_s}{2}\sigma_x}_{\text{tunneling}}$$

(ψ_L, ψ_R) basis

α, E_s calculated; depends on parameters

(8) Nature: Flux noise small; $\sim 10^{-5}\,\Phi_0$, but gives decoher $\sim$ nS if operate away from deg. pt. So operate at $\Phi_b = \frac{1}{2}\Phi_0$.

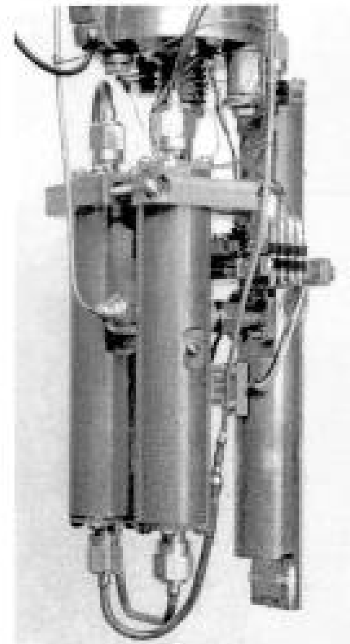
(9) Real device; Hard to match $\underline{L}$, $L_{J0} = \frac{\Phi_0}{2\pi \underline{I_0}}$
Solve with device design

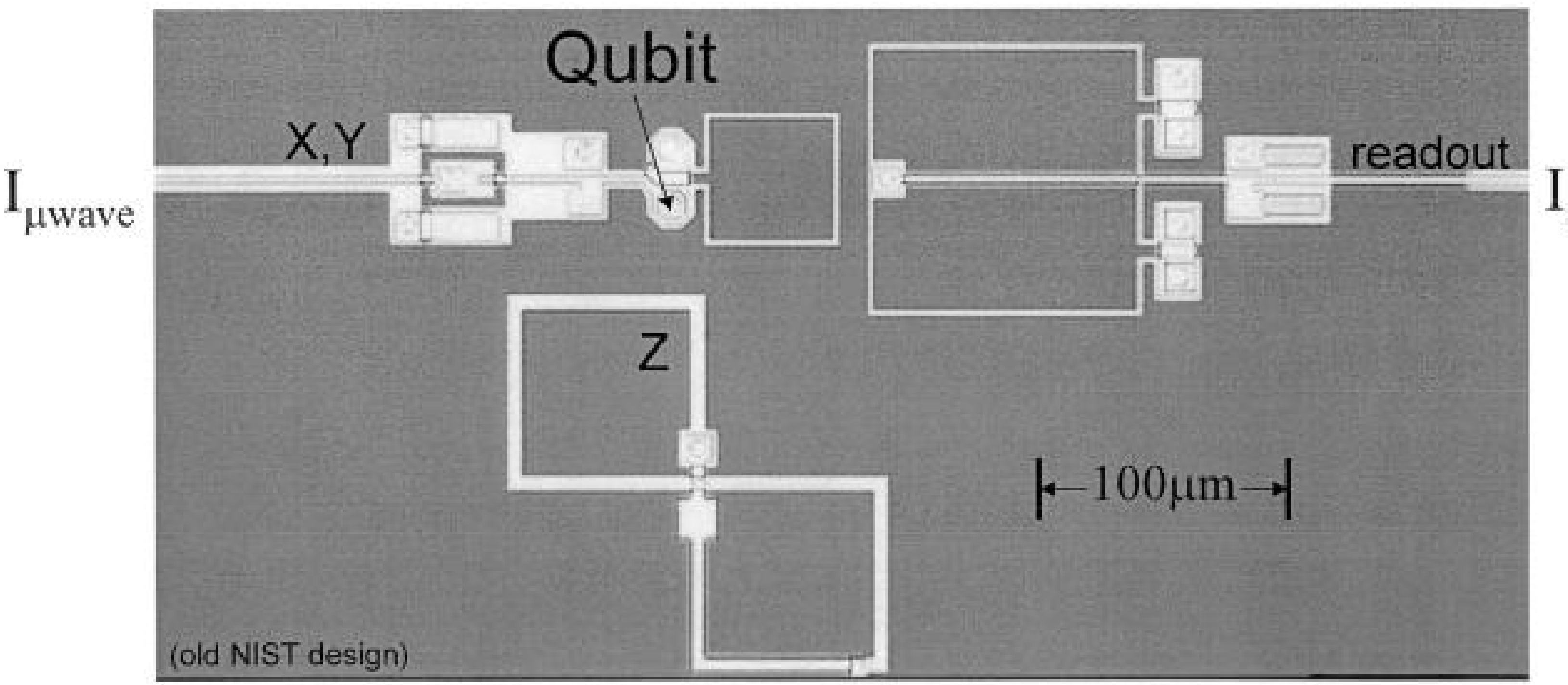


2 juncts; $\frac{1}{2}$ induct; $\simeq L_{J0}$

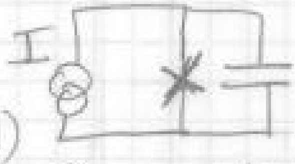
- Good because I_0's <u>all</u> scale with oxid. changes
- In practice, Solve Q.M. of entire system, Φ qubit mode dominates
  $2I_0 \to \sim 1.6\,I_0$ for best design.
  (Don't make C's too small or will see charge noise effects!)

Phase Qubits





Phase Qubits

(1) 

Large area junctions

$I \to I_0$; $\sin\delta \to 1$ $\frac{1}{\cos\delta} \to \infty$

for large non-linearity

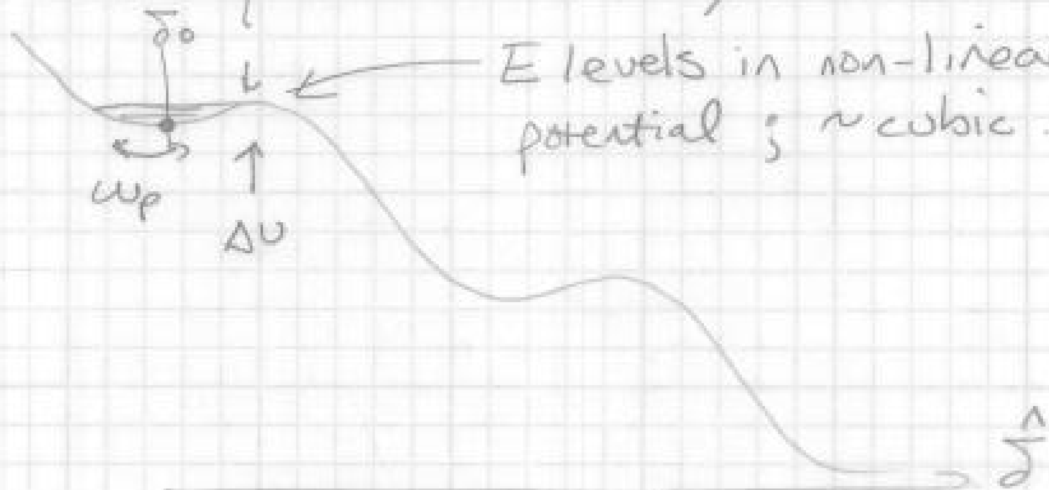
$\hat{\delta}, \hat{q}$ contin. var's (I gives arb charge)

(2) $$H = \frac{\hat{q}^2}{2C} - \frac{I_0 \Phi_0}{2\pi}\cos\hat{\delta} - \frac{I\Phi_0}{2\pi}\hat{\delta}$$

C   junct   bias

$$\left[\int I V dt = \int I \frac{\Phi_0}{2\pi}\frac{\partial\delta}{\cancel{dt}}\cancel{dt} = \frac{I\Phi_0}{2\pi}\delta \right]$$

cosine potential tilted by bias current

(3) 

E levels in non-linear potential ; ~ cubic.

(4) $$\omega_p = \frac{1}{\sqrt{L_J C}} = \frac{1}{\sqrt{L_{J0} C}}\sqrt{\cos\delta_0}$$

$I = I_0 \sin\delta_0$

$\sin^2\delta_0 = (I/I_0)^2$

$$= \frac{1}{\sqrt{L_{J0}C}}\left[1 - (I/I_0)^2\right]^{1/4}$$ ← slow with I

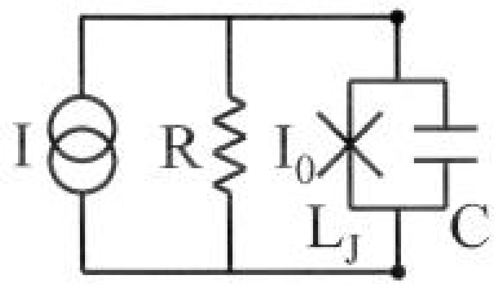
(5) $$\Delta U \simeq \frac{4\sqrt{2}}{3}\frac{I_0\Phi_0}{2\pi}\left(1 - I/I_0\right)^{3/2}$$ ← fast with I

ω_p, ΔU changes with I → tunable

(6) No Q, Φ noise, so no degen pt fine (ex'l more complicated)

Nature?

Qubit: Nonlinear LC resonator



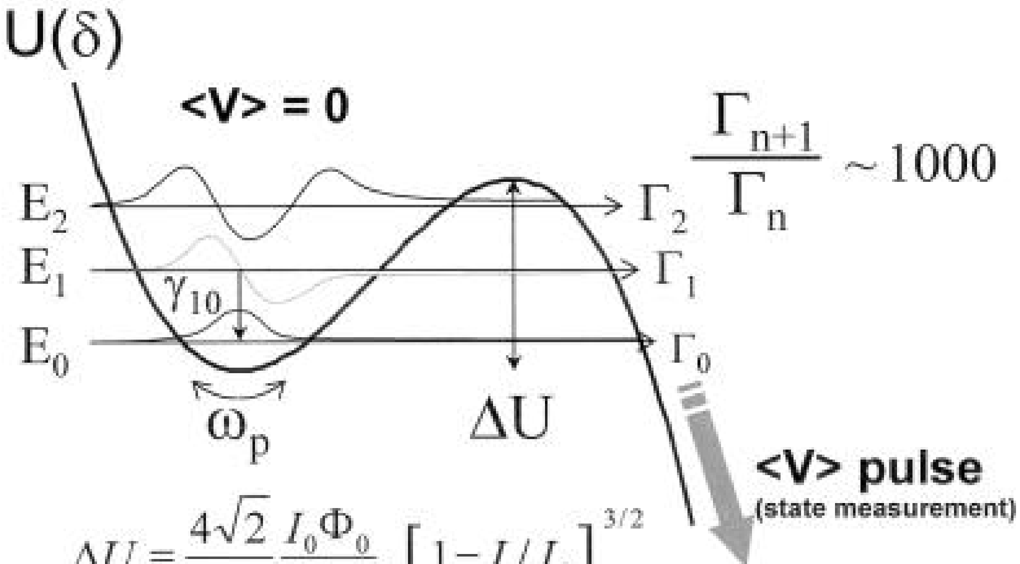
$$I = I_0 \sin\delta$$

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

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

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

nonlinear inductor

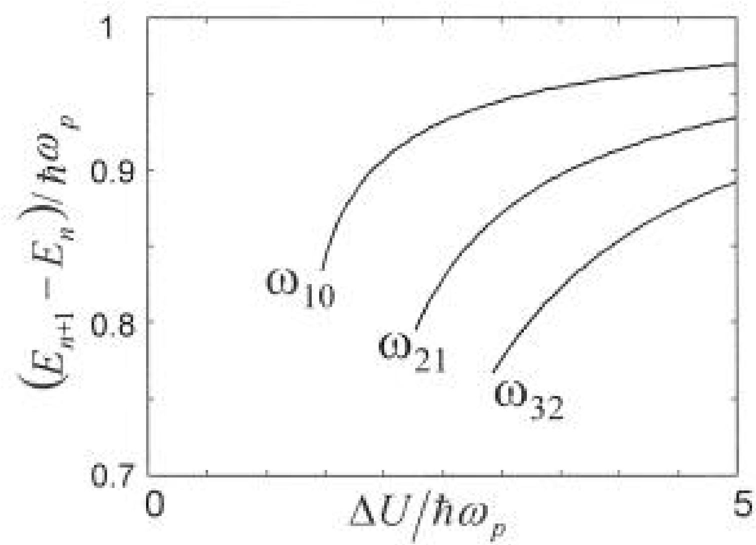


$$\frac{\Gamma_{n+1}}{\Gamma_n} \sim 1000$$

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

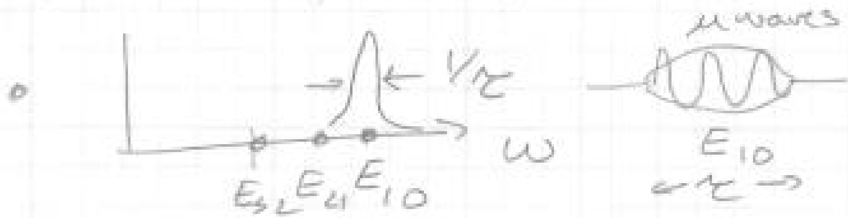
$$\omega_p = \left(\frac{2\sqrt{2}\pi}{\Phi_0}\frac{I_0}{C}\right)^{1/2}\left[1 - I/I_0\right]^{1/4}$$

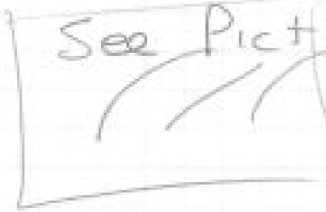
$\gamma_{10} \cong 1/RC$ Lifetime of state |1>



1: Tunable well (with I)
2: Transitions non-degenerate
3: Tunneling from top wells
4: Lifetime from R

(7) Small Non-linearity (~5%)

- 



- Use ~ 5-10ns μwave pulses
- Practically, ok since
  a) Hard to accurate + cheap shape faster pulses.
  b) Rot. Wave Approx breaks down faster pulses
  (Logic errors then)

(8) Qubit control ; $I + \Delta I$
in $|0\rangle, |1\rangle$ of eigen states

$$H = \begin{pmatrix} 0 & 0 \\ 0 & E_{10} \end{pmatrix} - \frac{\Phi_0}{2\pi} \Delta I \begin{pmatrix} \langle 0|\hat{\delta}|0\rangle & \langle 0|\hat{\delta}|1\rangle \\ \langle 1|\hat{\delta}|0\rangle & \langle 1|\hat{\delta}|1\rangle \end{pmatrix}$$

std H.O. M.E's

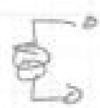
not zero (non lin)

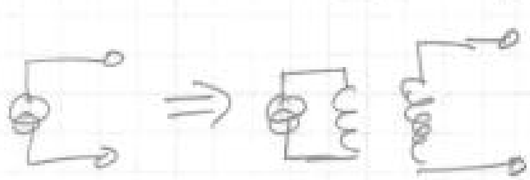
$$= \frac{E_{10}}{2} \sigma_z - \sqrt{\frac{\hbar}{2\omega_{10} C}} \Delta I \left(\sigma_x + \sqrt{\frac{E_{10}}{3\Delta U}} \sigma_z \right)$$

H.O. coupling

tunable E_{10}

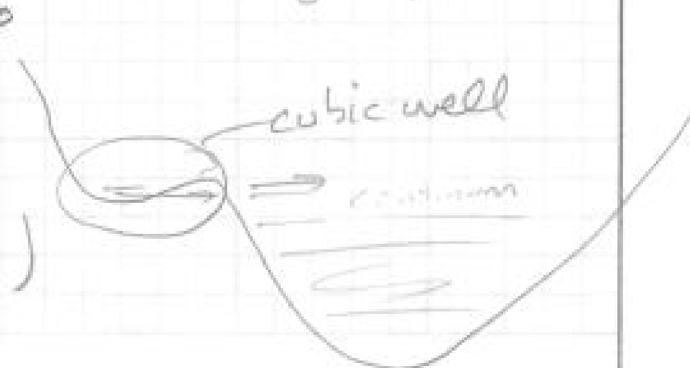
(9) LF (ΔI) give σ_z : Z
HF (ΔI) gives σ_x : XY
rotations

(10) Practical:  with large R does not exist!
(thy model only)



Transf I bias
Like Φ qubit; but not deg.

- Note: Now sens. to Φ noise
  (100-200 ns decoh, can be made smaller!)



Experiments

Go through my standard ϕ qubit descr.

1) Init state — easy

2) Rotate — review

3) Meas. ⟵ NEW, go slow!

4) Fabrication

Our / std S.C using special materials

Al, $T_c > 1K$ ok

Fabrication of small junction (e beam)

5) Meas. Setup in DR

Low T

Filtering

Generation of μwaves pulses.

6) Sequence to take data

0 or 1 ; 1000x for prob.

7) Spectr.

8) Rabi's . . .

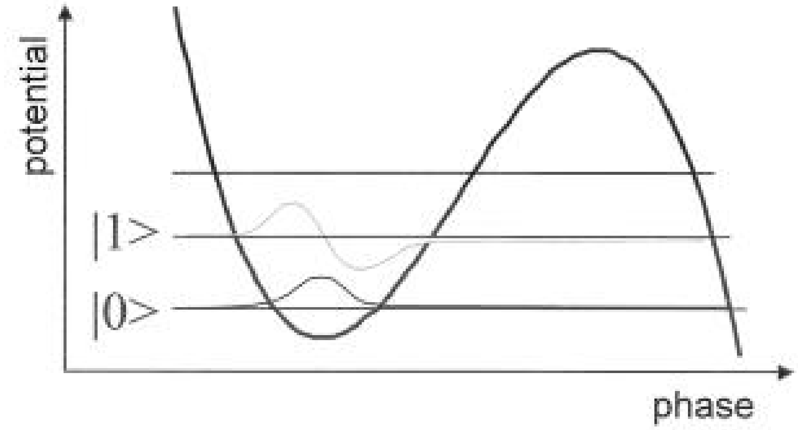
TOPS 35500

Josephson-Junction Qubit

(1) State Preparation

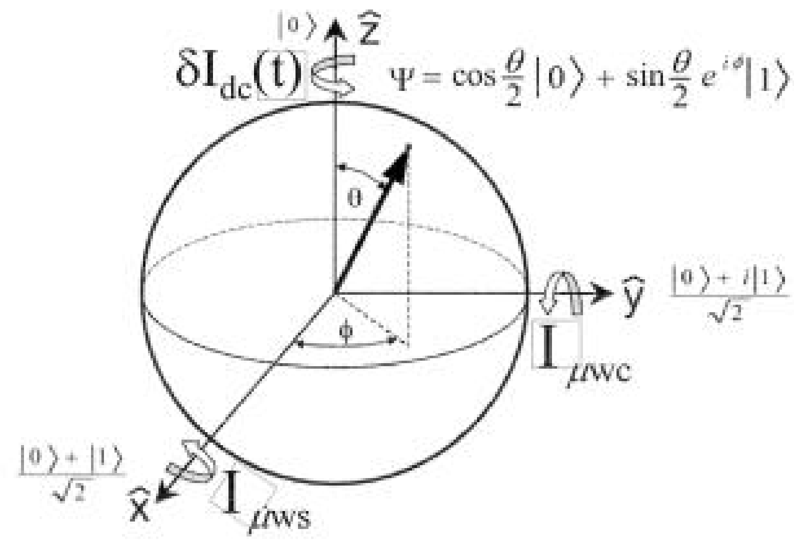
Wait $t > 1/\gamma_{10}$ for decay to $|0\rangle$

$(20\,\mathrm{mK}\,;\, kT << \hbar\omega_{10}\,;\, 6\,\mathrm{GHz})$



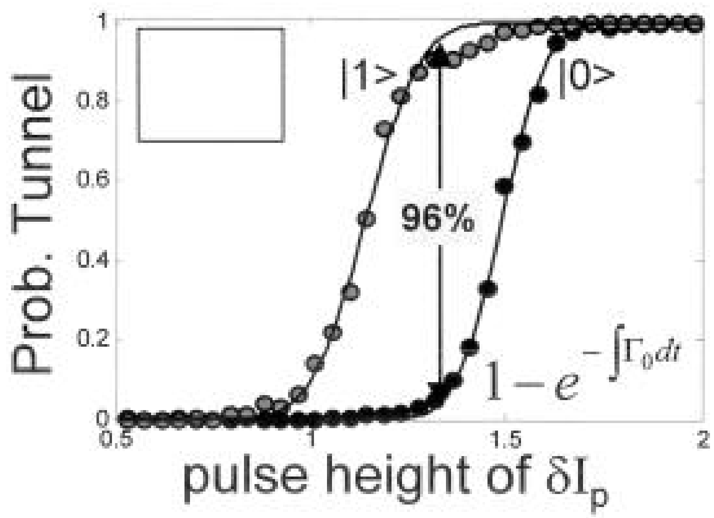
(2) Qubit logic with current bias

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



(3) State Measurement: $\Delta U(I_{dc}+\delta I_p)$

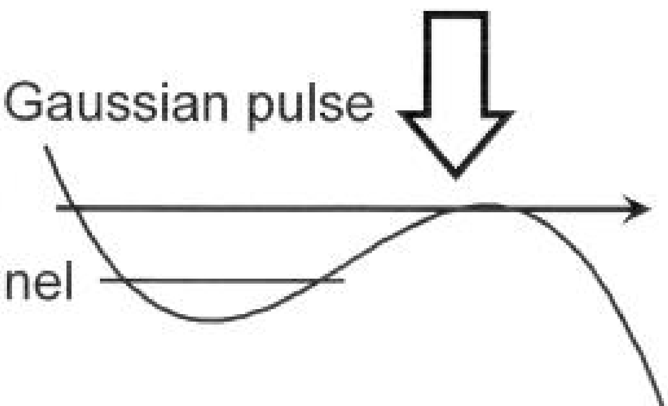
Fast single shot – high fidelity



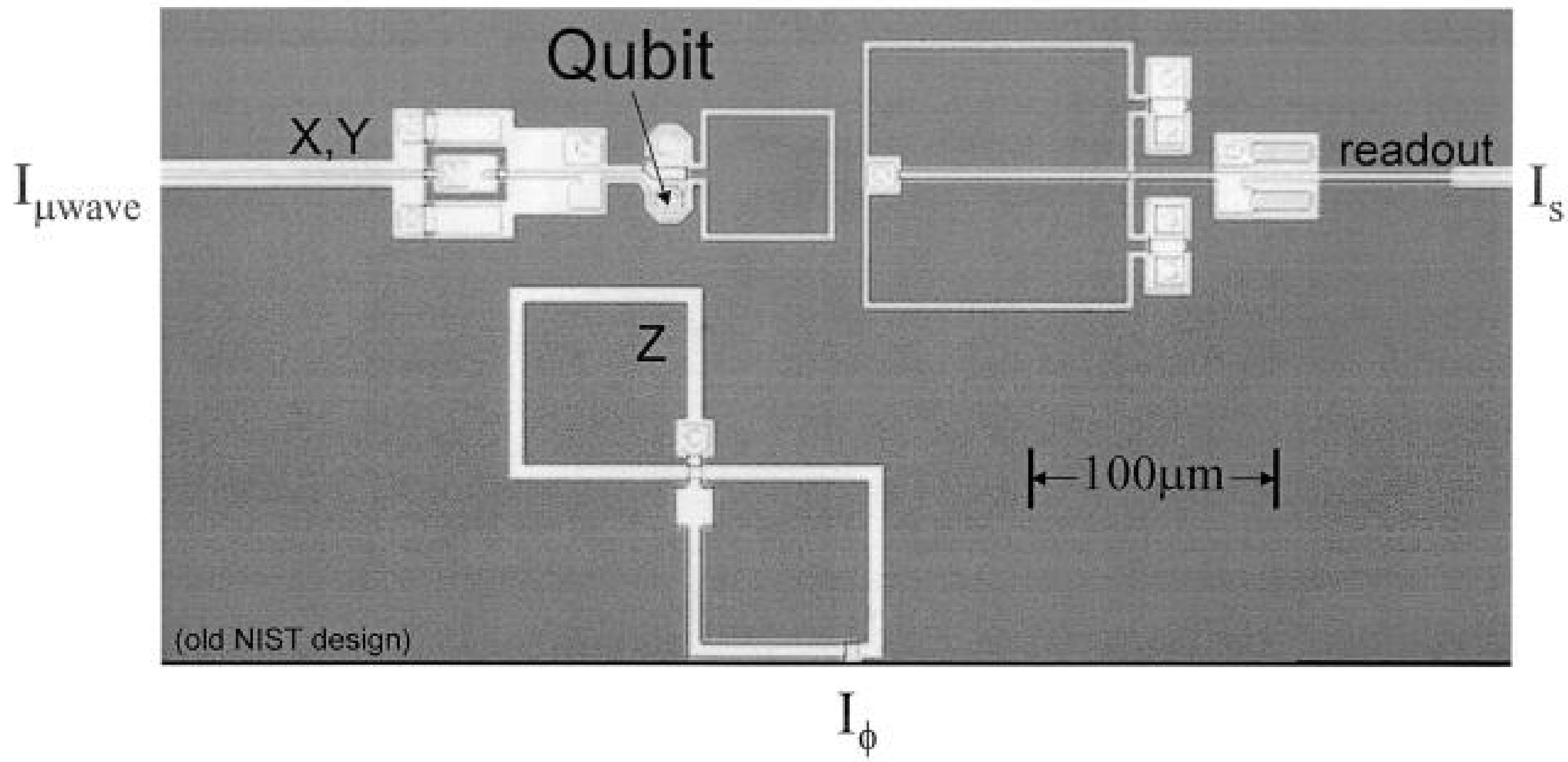
3 ns Gaussian pulse

|1> : tunnel

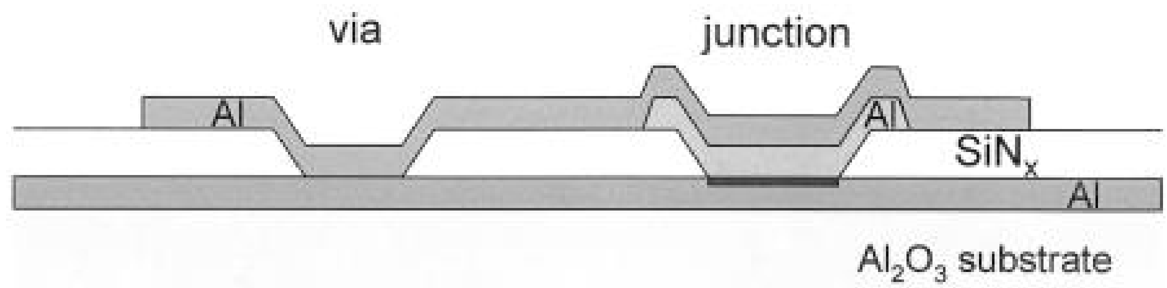
|0> : no tunnel



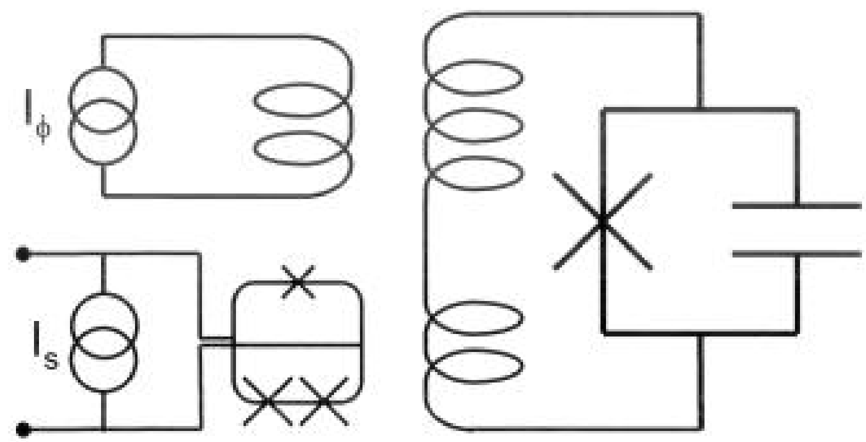
IC Fabrication

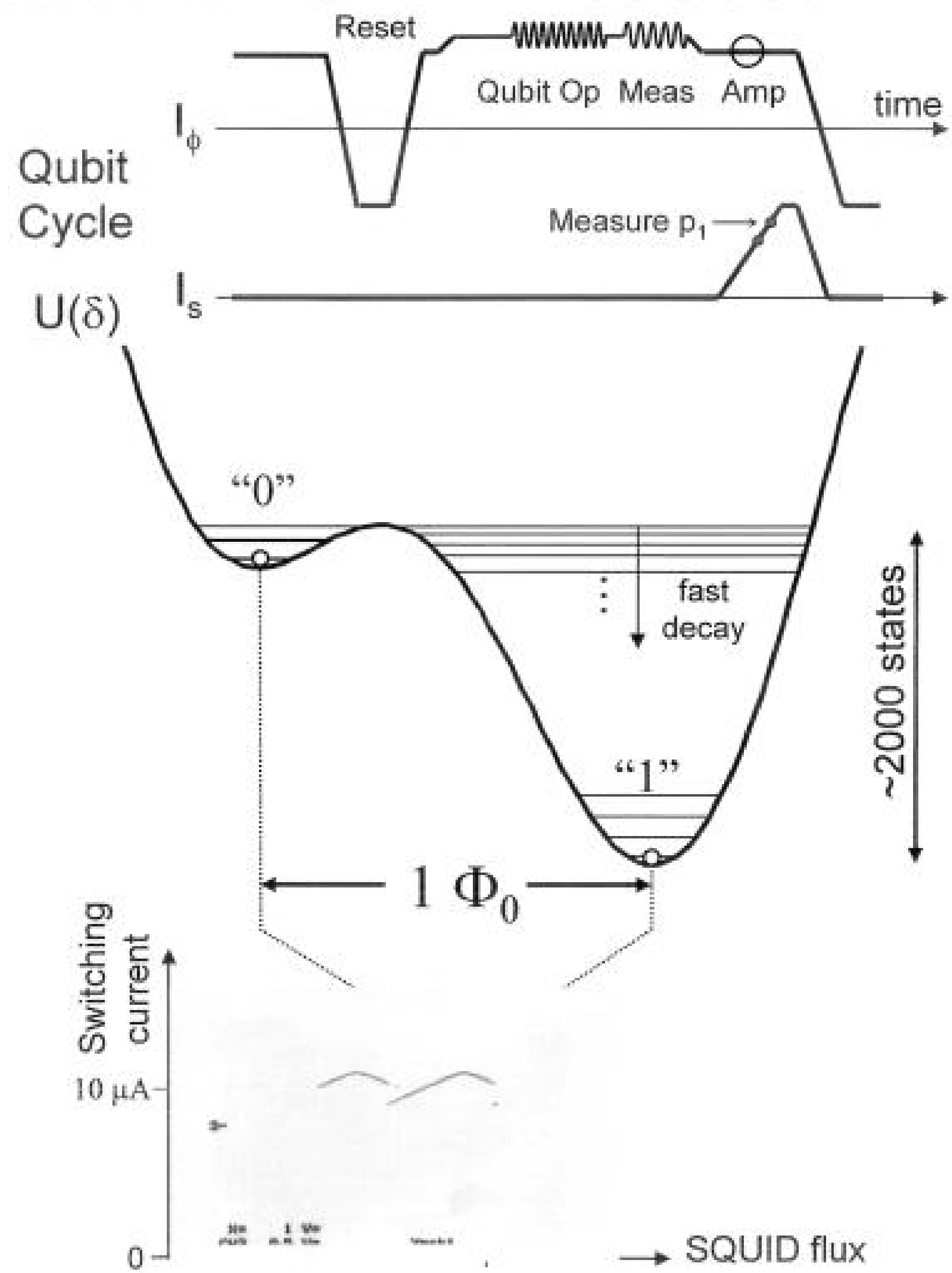


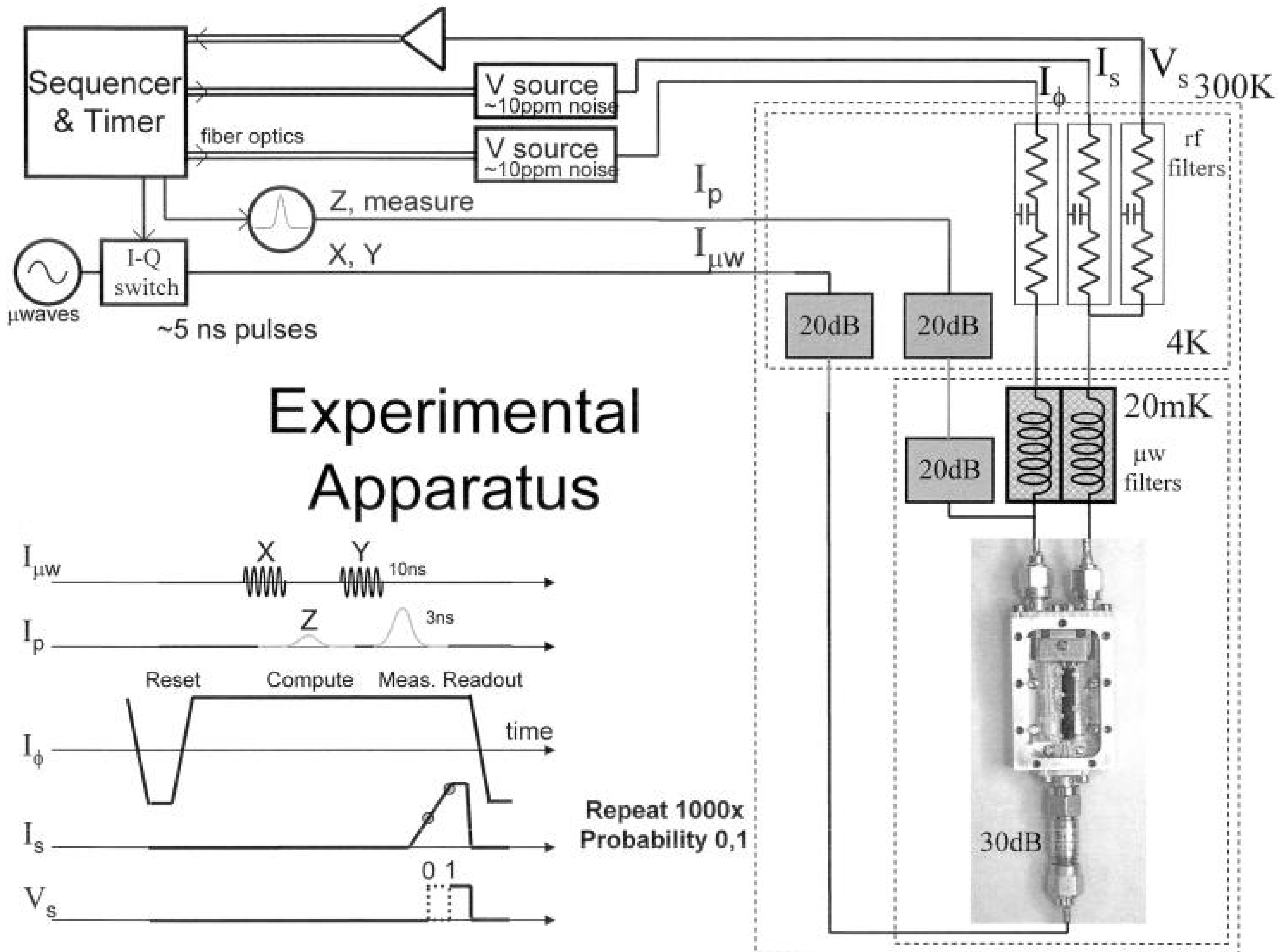
Al junction process
& optical lithography



Qubit operation → Measurement → Readout

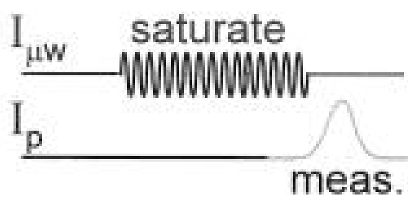


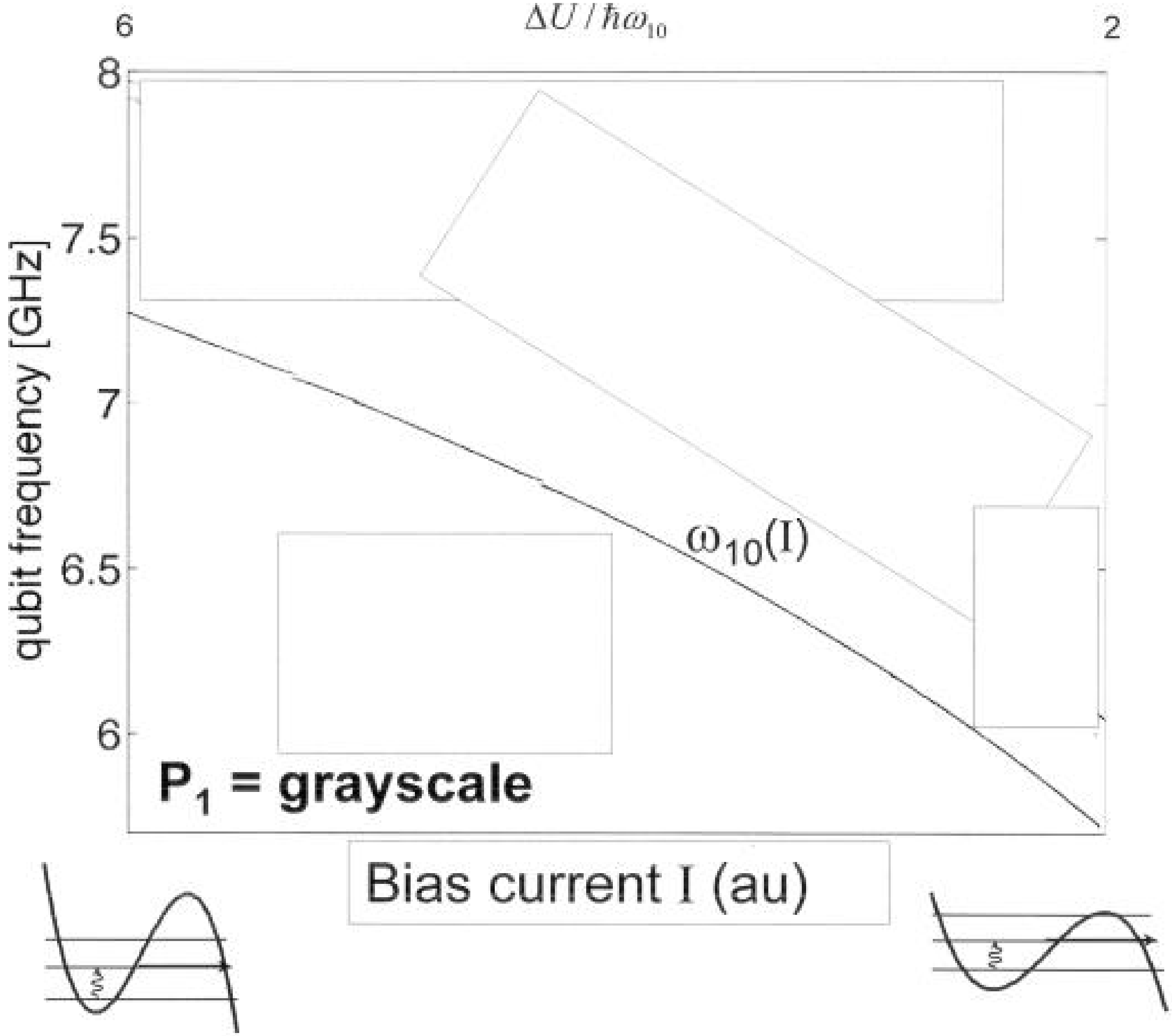




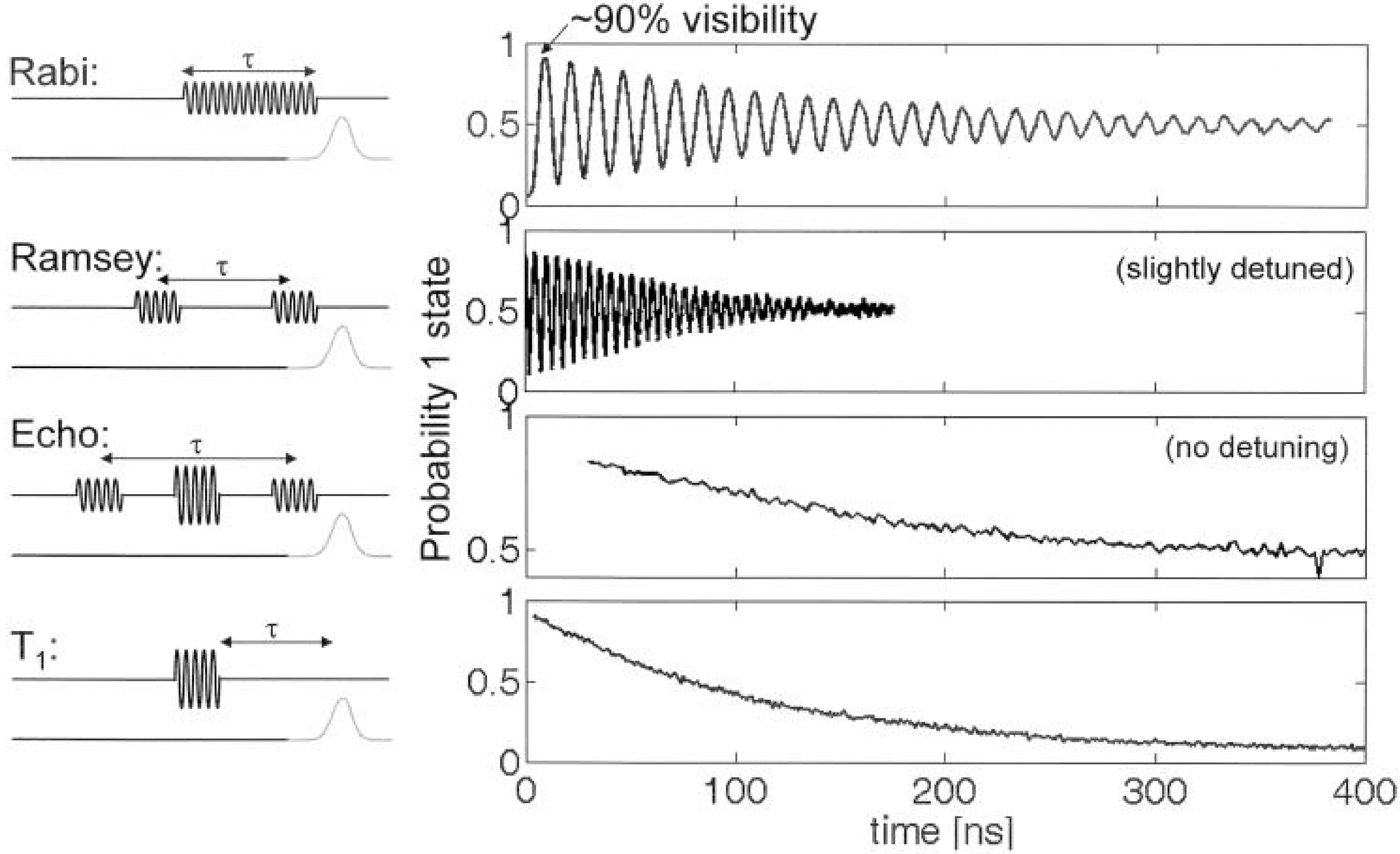
Experimental
Apparatus
Sequencer & Timer
V source ~10ppm noise
V source ~10ppm noise
fiber optics
Z, measure
X, Y
I-Q switch
μwaves
~5 ns pulses
I_p
$I_{\mu w}$
I_ϕ
I_s
V_s
300K
rf filters
4K
20dB
20dB
20dB
20mK
μw filters
30dB
$I_{\mu w}$
X
Y
10ns
I_p
Z
3ns
Reset
Compute
Meas. Readout
time
I_ϕ
I_s
V_s
0 1
Repeat 1000x
Probability 0,1

Spectroscopy



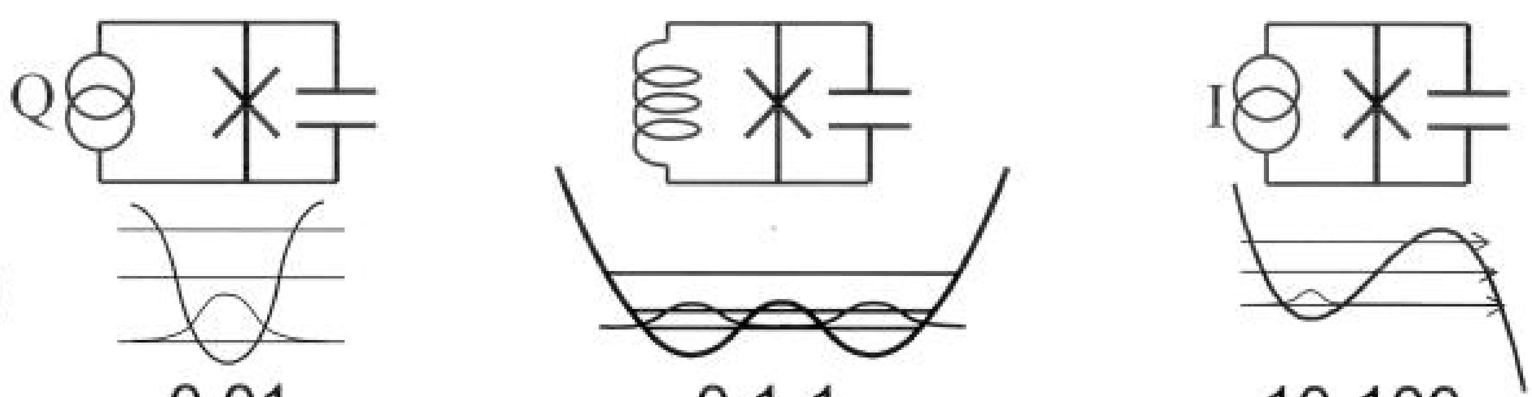


Qubit Fidelity Tests



Large Visibility! T_1 = 110 ns, T_ϕ ~ 85 ns

Qubit Taxonomy



	Charge	**Flux**	**Phase**
Circuit			
Potential (in δ)			
Area (μm^2)	0.01	0.1-1	10-100
$\frac{E_J}{E_C} = \frac{I_0 \Phi_0 / 2\pi}{e^2 / 2C}$	1-10	$10\text{-}10^2$	$10^2\text{-}10^4$

Experimentally Important:

	Charge	Flux	Phase
	Small C	Very sens. to parameters $L \cong L_{J0}$	$I \rightarrow I_0$
Non-linearity	50% - 5%	>100%	~5%
Impedance $1/\omega_r C$	30 kΩ	1 kΩ	50 Ω
Noise intrinsic	Q_N - 1 ns	Φ_N - 10 ns	Φ_N – 200+ ns
Noise degeneracy	1 μs	1 μs	(no degen)

(more complex coupling)
(how tune resonances also)

No Φ_N Φ_N in thy model, Φ_N from practical Bias, Not opt. yet, can be improved