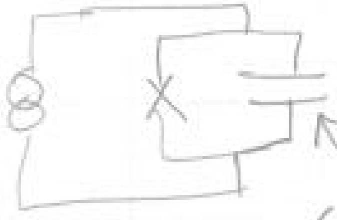
C decoherence



Imperfections in C.
(@RT, C normally lowest loss component,
@LT, worst (highest loss) element!)

(a) C in junction
(b) in crossovers (wiring); will need for any complex circuit
(c) Strays in substrate

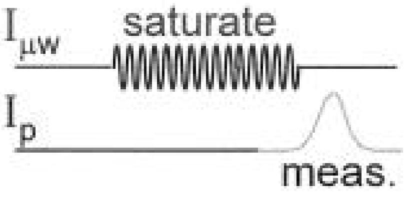
(a)+(b) typically are amorphous (no xtal) materials, turns out, these VERY lossy, but in special/interesting way
Want $Q \sim 10^5$ to 10^6, Amorph. Diel Q 10^2 to 10^3!

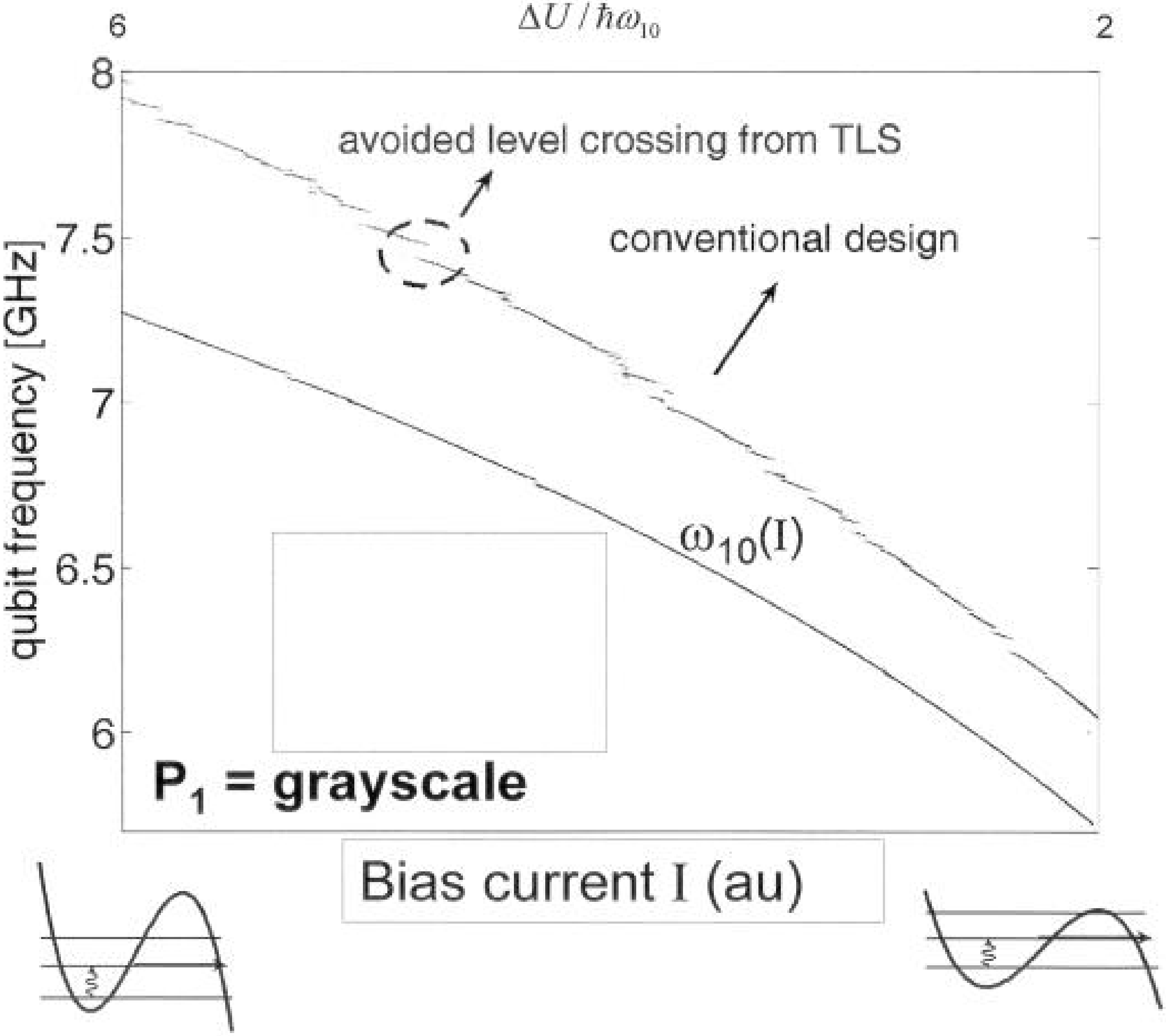
* This issue was key to improving our ϕ qubit.
Future import. for others / or design around it!
I think most impt. imperfection!

* Known since 70's, but literature difficult
- Translate it into useful for us
- Show what we know/data base.

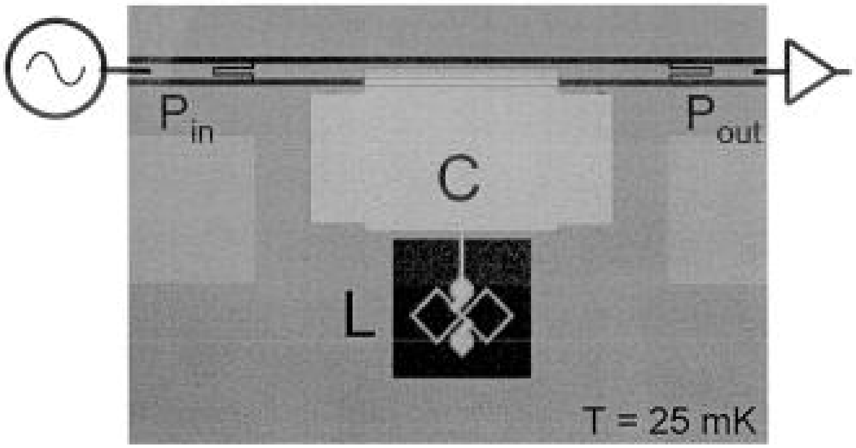
For many designs can ignore, but need to know why/how.

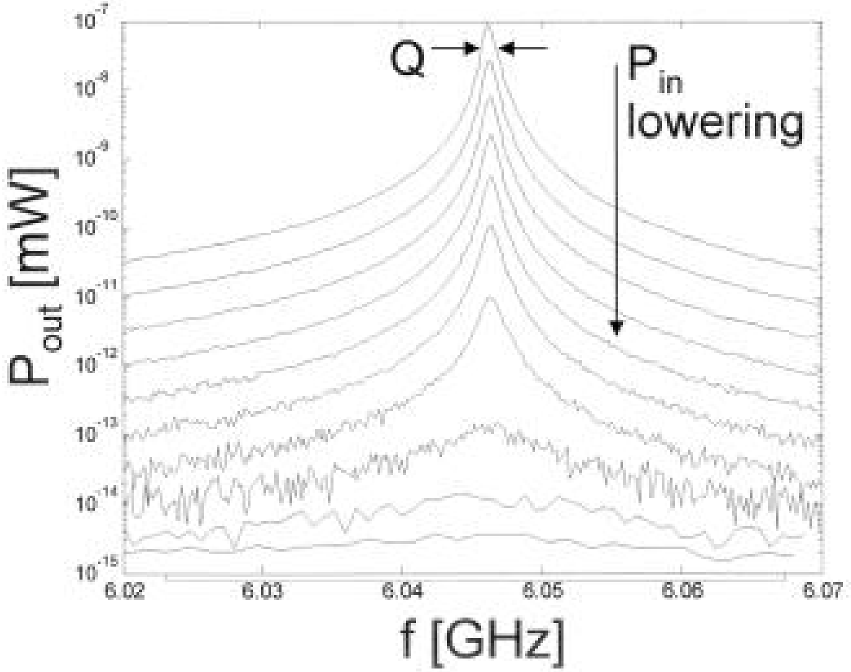
Spectroscopy



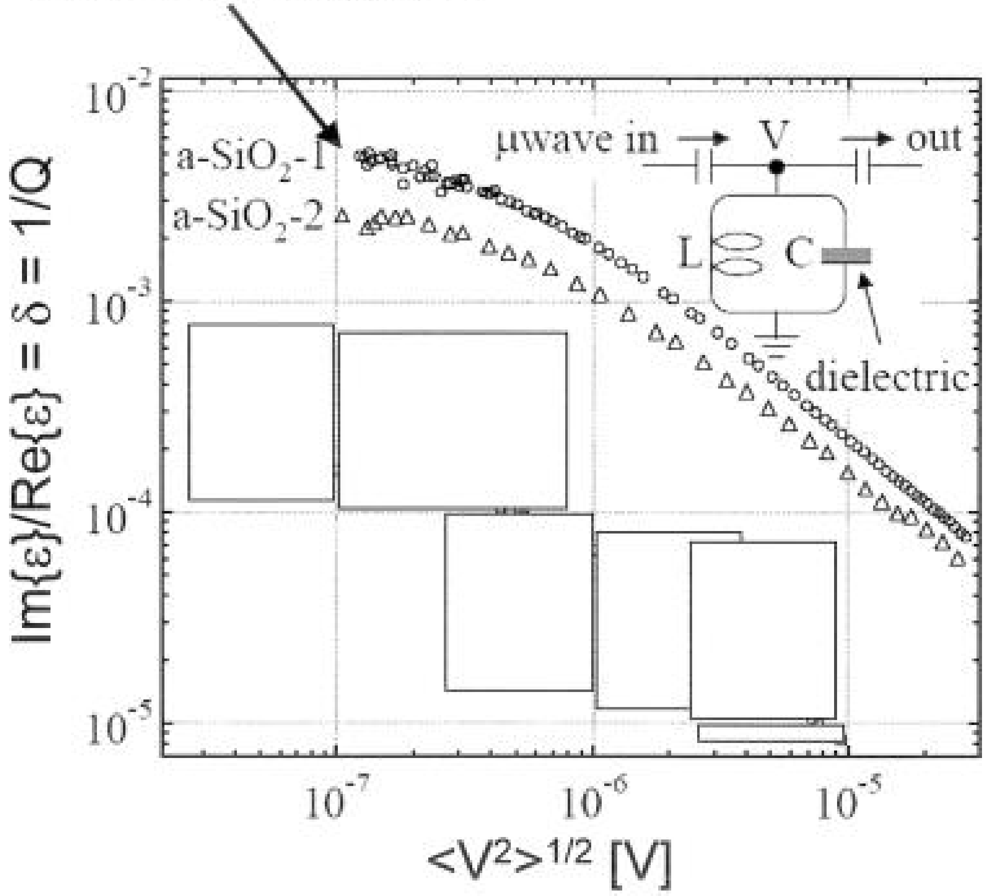


Dielectric Loss in CVD SiO_2

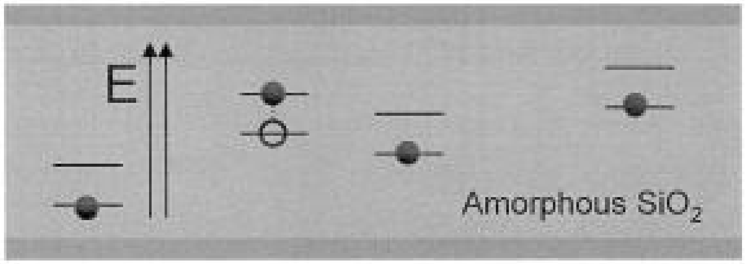




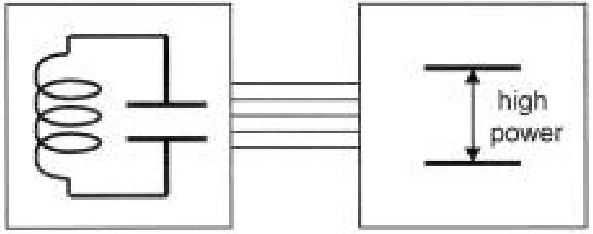
HUGE Dissipation



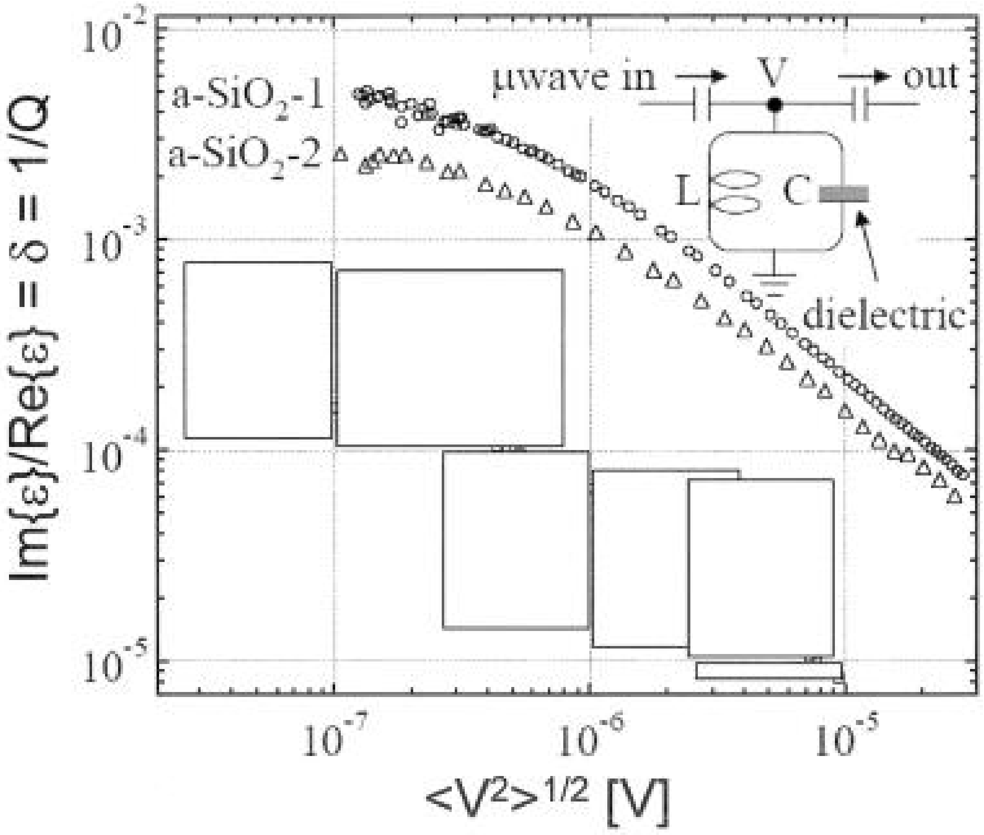
Theory of Dielectric Loss



Two-level (TLS) bath: saturates at high power, decreasing loss



von Schickfus and Hunklinger, 1977



Experimental Data:

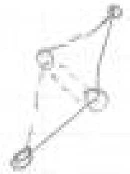
(1) Spectroscopy — Avoided TL crossings
Should be smooth.

→ ~~Not~~ Rarely seen in small junctions
Q, Φ qubits.

(2) Q measurements on common amorphous dielectrics.

Key to understanding physics → Saturation

Conceptual Model:



Random Bonds — fraction of atoms have 2 equilibr. pos — tunnels back/forth at μwave Freq. [Small # defects, but move big distance] (so important)

This motion couples qb into qubit/reson.

(1) Extra state to couple to

(2) Saturate at high P, T, so then defect "goes away"; not seen.

equal likely to absorb or emit energy

Note (2) → Materials look good classically (high P or T), but become lossy ~~at~~ quantum regime!

(why not appreciated).

Saturation slide

76Hz
=1.2mS

Calculations of Dielectric Loss from Two-Level States

John M. Martinis et al*
UCSB

(Dated: January 14, 2006)

In this note we provide detailed calculations of the theory presented in the paper "Decoherence in Josephson Qubits from Dielectric loss" The physical implications are also expanded upon.

PACS numbers:

DIPOLE HAMILTONIAN

①

In this note we show that dielectric loss can be modeled by a bath of two-level states (TLS). Each TLS has basis states $|L\rangle$ and $|R\rangle$ that correspond to two different configurations of atoms and electrons in the dielectric. In general, the dynamics of $|L\rangle$ and $|R\rangle$ can be described by the hamiltonian

$$H_{\rm TLS} = \frac{1}{2}\begin{pmatrix} \Delta & \Delta_0 \\ \Delta_0 & -\Delta \end{pmatrix} , \tag{1}$$

where $\pm\Delta/2$ is the energy of the two states and Δ_0 is the off-diagonal component that corresponds to tunneling between the two states. The eigenstates of $H_{\rm TLS}$ and their difference in energy are given by

$$|g\rangle = \sin(\theta/2)|L\rangle - \cos(\theta/2)|R\rangle \ , \tag{2}$$

$$|e\rangle = \cos(\theta/2)|L\rangle + \sin(\theta/2)|R\rangle \ , \tag{3}$$

$$E = (\Delta^2 + \Delta_0^2)^{1/2} \ , \text{ where} \tag{4}$$

$$\theta = \arctan(\Delta_0/\Delta) \ . \tag{5}$$

The case of no tunneling has $\Delta_0 = 0$, which gives $\theta = 0$ and eigenstates $|R\rangle$ and $|L\rangle$. For $\Delta = 0$, the eigenstates are the symmetric and anti-symmetric combination of these two states. In terms of the original basis states, we find

$$|L\rangle = \quad \sin(\theta/2)|g\rangle + \cos(\theta/2)|e\rangle \ , \tag{6}$$

$$|R\rangle = -\cos(\theta/2)|g\rangle + \sin(\theta/2)|e\rangle \ , \tag{7}$$

which gives

$$\begin{aligned} |L\rangle\langle L| &= \sin^2(\theta/2)|g\rangle\langle g| + \cos^2(\theta/2)|e\rangle\langle e| \\ &\quad + \sin\theta(|g\rangle\langle e| + |e\rangle\langle g|)/2, \end{aligned} \tag{8}$$

$$\begin{aligned} |R\rangle\langle R| &= \cos^2(\theta/2)|g\rangle\langle g| + \sin^2(\theta/2)|e\rangle\langle e| \\ &\quad - \sin\theta(|g\rangle\langle e| + |e\rangle\langle g|)/2. \end{aligned} \tag{9}$$

Because we are interested in electrical properties, we also model each TLS as having an electric charge distribution that changes between the two states by the dipole moment ed. As modeled in Fig. 1, each TLS can be pictured as an electron of charge e at position R or L separated by a distance d. For the configuration of a parallel plate capacitor of thickness x connected to a voltage V, a change in position induces charge $e(d/x)\cos\eta$ to move

②

through the voltage source, where η is the angle between the dipole and the electric field V/x. The interaction hamiltonian is given by

$$H_{\rm int} = \vec{D} \bullet \vec{E} \tag{10}$$

$$= ed[\ |L\rangle\langle L| - |R\rangle\langle R|\ ](V/x)\cos\eta \tag{11}$$

$$\begin{aligned} &= [\cos\theta(|e\rangle\langle e| - |g\rangle\langle g|) \\ &\quad + \sin\theta(|e\rangle\langle g| + |g\rangle\langle e|)](eVd/x)\cos\eta \end{aligned} \tag{12}$$

$$= \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix} (eVd/x)\cos\eta \ . \tag{13}$$

— static

osc.

TLS (HF) spin

Vf (LF) noise

This result corresponds to a spin placed in a static field E in the z-axis direction along with an external field $(eVd/x)\cos\eta$ at a relative angle θ. Note that $|e\rangle\langle g| + |g\rangle\langle e|$ is an oscillating component of $H_{\rm int}$ that is maximum at $\Delta = 0$, whereas the static component $|e\rangle\langle e| - |g\rangle\langle g|$ is maximum at $\Delta_0 = 0$.

TLS TUNNELING MODEL

The dielectric is modeled as a bath of TLS whose distribution of states can be calculated using the standard TLS tunneling model. In this model the variable Δ is assumed to have a constant distribution, giving the differential number of states as $dN \propto d\Delta$. The tunneling between the two states is exponentially dependent on parameters such as the effective distance z, giving $\ln\Delta_0 \propto z$. Because the parameter z is hypothesized to be uniformly distributed $dN \propto dz$, the distribution in

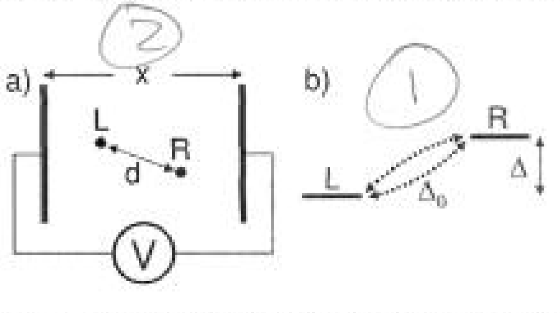


FIG. 1: a) Model of dipole moment in a parallel plate capacitor. b) Energy level diagram of TLS

Why – it works!
(but reasonable)

$P_{rdo} = \int dN =$

$\Delta_0 = \exp[-\sqrt{E}X]$ uniformity distrib.

$\frac{\Delta N}{dE}\Big|_{min}^{S} = \int_{S_m}^{S} \frac{1}{S} dS = (\ln S - \ln S_m)$

terms of the variable Δ_0 is

$$dN \propto d\ln\Delta_0 \tag{14}$$

$$\propto \frac{d\Delta_0}{\Delta_0}\,. \tag{15}$$

These two distributions can be combined into a joint density $d^2N \propto d\Delta\ d\Delta_0/\Delta_0$.

The energy E and parameter $\sin\theta$ are more physical variables than Δ and Δ_0. A change in basis states gives

$$d^2N \propto \frac{dE\ d\sin\theta/\Delta_0}{\left|\begin{array}{cc} dE/d\Delta & dE/d\Delta_0 \\ d\sin\theta/d\Delta & d\sin\theta/d\Delta_0 \end{array}\right|} \tag{16}$$

$$= \frac{dE\ d\sin\theta}{|\sin\theta\cos\theta|}\,. \tag{17}$$

A wide variety of experiments have verified this tunneling model, and the density as derived here is known to predict the actual density in a wide variety of amorphous materials. The E dependence is know to be constant to about $h\cdot 20$ GHz, where the density then typically starts to increase.

NEXT PAGE

excit & photon

PHASE QUBITS

The interaction hamiltonian for the TLS coupled to a phase qubit is given by Eq. (12) with V replaced by $\widehat{q}/C$, where $\widehat{q}$ is the charge operator of the qubit and C is the qubit capacitance. For the qubit state $|0\rangle$ and $|1\rangle$ with energy difference E_{10}, the matrix elements are approximately those given by harmonic oscillator states

$$\frac{\widehat{q}}{C} = i\sqrt{\frac{E_{10}}{2C}}\ (|1\rangle\langle 0| - |0\rangle\langle 1|). \tag{18}$$

Equation (12) may be expressed in the qubit and TLS basis states, and we find after neglecting off-resonant terms

$$H_{\rm int} \simeq -i(S/2)(|0\rangle|e\rangle\langle 1|\langle g| - |1\rangle|g\rangle\langle 0|\langle e|)\ , \tag{19}$$

$$S = S_{\rm max}\cos\eta\sin\theta\ , \tag{20}$$

$$S_{\rm max} = 2(d/x)\sqrt{E_{10}e^2/2C}\ . \tag{21}$$

where $-iS/2$ is the interaction matrix element that gives an avoided two-level crossing of magnitude $|S|$ on resonance.

We are interested in calculating TLS properties for capacitors of area A. Defining a materials constant σ for the density of states for TLS per unit area, we find using Eq. (17)

prop to Area.

$$\frac{d^2N}{dE\ d\sin\theta} = \frac{\sigma A}{|\sin\theta\cos\theta|}\,. \tag{22}$$

Changing variables from $\sin\theta$ to S using Eq. (20), we write the density of states as

$$\frac{d^2N}{dE\ dS} = \frac{\sigma A}{S\ (1-(S/S_{\rm max}\cos\eta)^2)^{1/2}}\,, \tag{23}$$

$-i\sqrt{\frac{E_{10}}{2C}}\ \frac{ed}{x} = -i\sqrt{\frac{E_{10}e^2}{2C}}\ \frac{d}{x}$

$\left(\frac{\sigma A}{S}\right)\frac{1}{(\quad)}$ ← cutoff at Smax

for $0 < S < S_{\rm max}$, and 0 otherwise. Because experimental measurements of the splitting size can only be positive, we have defined S to only have positive values. Note that the range of $S/S_{\rm max}\cos\eta$ is 0 to 1, which implies that $0 \le S/S_{\rm max} < \cos\eta$. The weighted average over the dipole angles η gives

$$\frac{d^2N}{dE\ dS} = \frac{\sigma A}{S}\int_{S/S_{\rm max}}^{1} \frac{d\cos\eta}{(1-(S/S_{\rm max}\cos\eta)^2)^{1/2}} \tag{24}$$

$$= \sigma A\frac{(1-(S/S_{\rm max})^2)^{1/2}}{S}\,. \tag{25}$$

$\approx \frac{\sigma A}{S} *$ cutoff @ S_{max}

$\left(\frac{d}{x}\right) *$ qubit params

Show Data

Don't show off new as not our work!

To calculate decoherence from these resonances, we first introduce a new quantity: the average number of resonances that couple to the qubit. An estimate of this number comes from counting the resonances that fall within $\pm S/2$ of the qubit energy E_{10}

$$N_c = \int_0^{S_{\rm max}} \frac{d^2N}{dE\ dS}dS\int_{E_{10}-S/2}^{E_{10}+S/2} dE \tag{26}$$

$$= (\pi/4)\sigma A S_{\rm max} \tag{27}$$

$$= \sqrt{A/A_c} \tag{28}$$

where $A_c \simeq 90\mu{\rm m}^2$ for AlO$_x$. Charge and flux qubits typically have $N_c \ll 1$, whereas for phase qubits $N_c \sim 1$.

For large-area junctions $N_c \gg 1$, the qubit couples to many junction resonances and the decay rate $|1\rangle \to |0\rangle$ may be calculated using the Fermi golden rule

Γ_{TLS}

$$\Gamma_1 = \frac{2\pi}{\hbar}\int_0^{S_{\rm max}} \frac{d^2N}{dE\ dS}(S/2)^2 dS \tag{29}$$

$$= (\pi/6)\sigma A S_{\rm max}^2/\hbar \tag{30}$$

$$= (2/3)N_c S_{\rm max}/\hbar \tag{31}$$

$$= \frac{\pi}{3}\frac{\sigma}{x}\frac{(ed)^2}{\epsilon}\frac{E_{10}}{\hbar}\,. \tag{32}$$

This decay rate is equivalent to a dielectric loss tangent $\delta_i = \hbar\Gamma_1/E_{10}$ that is independent of both junction capacitance and frequency, as expected. We find that the measured decay rate $\Gamma = 1/10$ ns in our largest qubit implies that the loss tangent is large $\delta_i \simeq 1.6\ 10^{-3}$ for the AlO$_x$ of the tunnel barrier. We note that the density of states is often written as $\sigma/x = \rho$, where ρ is the density of states per unit volume.

The above calculation was for fixed qubit frequency. This model can also be used to calculate decoherence from a change in the bias that moves the qubit frequency past junction resonances. When both states are in the ground state $0g$, there is no change in the state when passing through resonances. However, when the qubit is in the excited state, a zener tunneling transition $1g \to 0e$ is produced with the probability to remain in the $1g$ state given by $\boxed{P = \exp[-\pi S^2/2\hbar(dE_{10}/dt)]}$. The probability after passing through a large number of resonances (la-

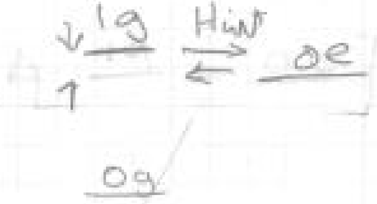
Interaction of TLS + Qubit

$$H_{int} = \overset{TLS}{\begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix}} \left(e \frac{d}{x} \cos n \right) \left(\hat{V} = \frac{\hat{q}}{c} = i \sqrt{\frac{E_{10}}{2C}} \overset{Qubit}{\left(|1\rangle\langle 0| - |0\rangle\langle 1| \right)} \right)$$

$\underline{1C}$

4 possible states

$(|0\rangle, |1\rangle) \otimes (|e\rangle, |g\rangle)$



Main (dominant) interaction is when

$E_{10} \simeq E_{eg}$, photon from $1 \to 0$

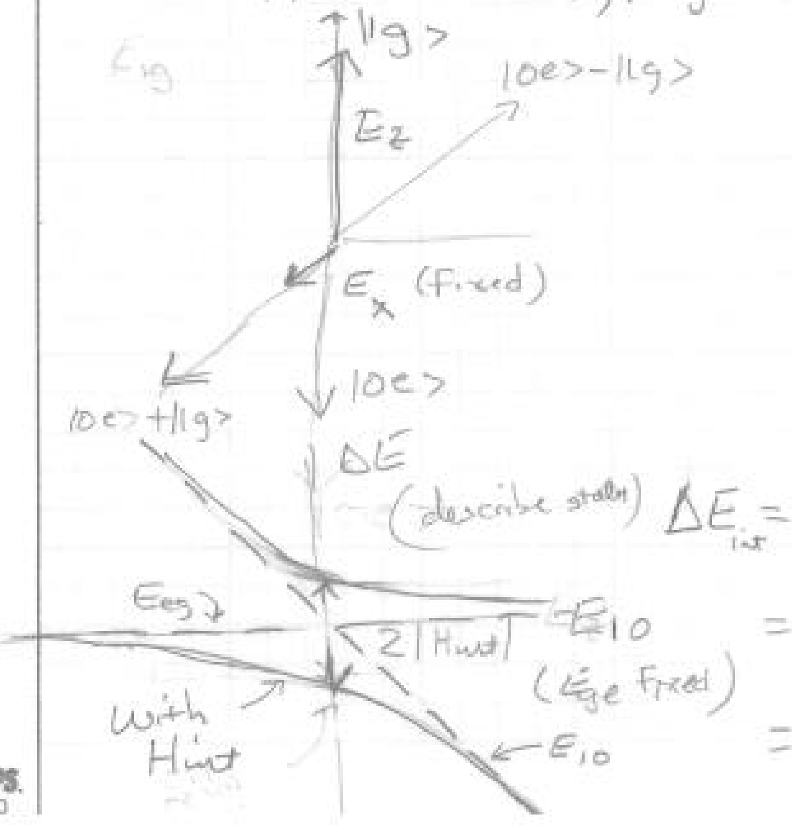
interacts $e g >$ $(1 \leftrightarrow 0 + g \leftrightarrow e)$

$\Rightarrow$ Diag. terms in Hint

$$H_{int} = i e \frac{d}{x} \sqrt{\frac{E_{10}}{2C}} (\sin\theta \cos n) \left(|g\rangle|1\rangle\langle e|\langle 0| \xrightarrow{c.c.} - |e\rangle|0\rangle\langle 1|\langle g| \right)$$

Detour: 2 coupled qubits (1st time).

Treat $|0e\rangle, |1g\rangle$ as 2 state system.



$B_z \propto$ detuning

$B_x \propto$ (fixed) H_{int}

$E_z = \frac{1}{2}(E_{1g} - E_{0e})\Big|_{H_{int}=0}$

(see pict. above)

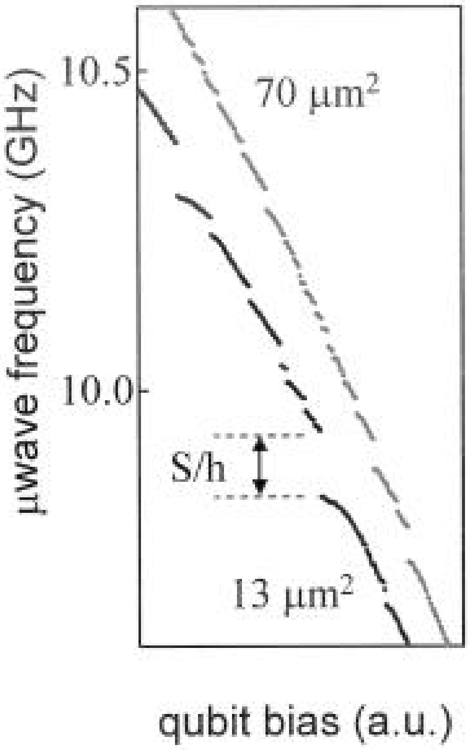
$E_x = |H_{int}|$

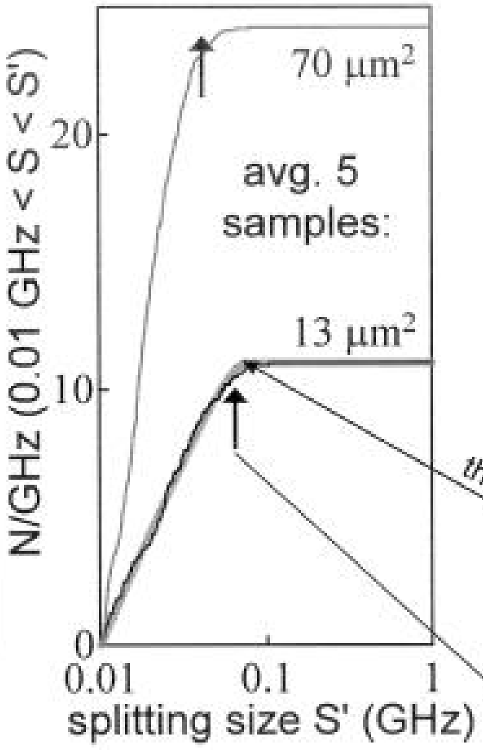
$$\Delta E_{int} = 2\sqrt{\left[\tfrac{1}{2}(E_{1g} - E_{0e})\right]^2 + |H_{int}|^2}$$

$$= \sqrt{(E_{1g} - E_{0e})^2 + 4|H_{int}|^2}$$

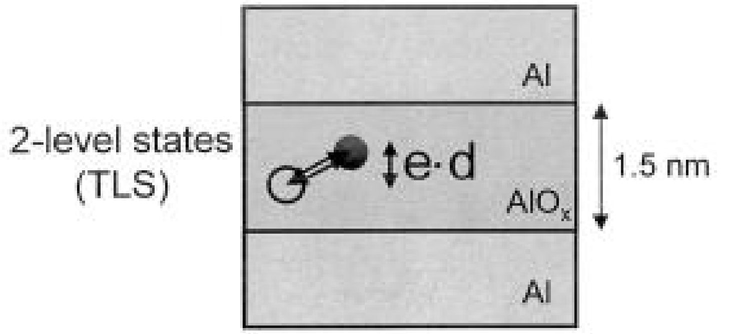
$= 2|H_{int}|$ on resonance

Junction Resonances:
Dielectric Loss at the Nanoscale





New theory (Martin *et al*, Martinis *et al*):



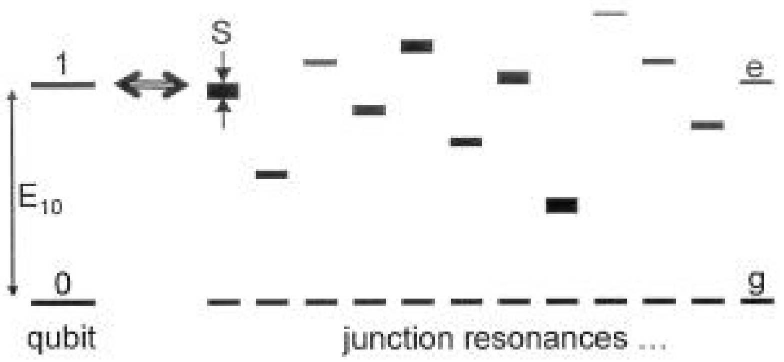
$$\frac{d^2N}{dEdS} = \sigma A \frac{[1-(S/S_{\max})^2]^{1/2}}{S}$$

$$S_{\max} = \frac{d}{1.5\text{nm}} 2\sqrt{E_{10}e^2/2C}$$

Explains sharp cutoff
d=0.13 nm (bond size of OH defect!)

S_{max} in good agreement with TLS dipole moment:
Charge fluctuators at ~10 GHz explain resonances

Junction Resonances: Coupling Number N_c



Number resonances coupled to qubit:

$$N_c \cong \int_0^{S_{max}} \frac{\sigma A}{S} dS \int_{E_{10}-S/2}^{E_{10}+S/2} dE$$

$$= \sigma A S_{max}$$

$$\cong \sqrt{A / 90\ \mu\text{m}^2}$$

Statistically avoid with N_c << 1 (small area)

N_c >> 1, Fermi golden rule for decay of 1 state:

$$\Gamma_1 \cong \frac{2\pi}{\hbar} \int_0^{S_{max}} \frac{\sigma A}{S} \left(\frac{S}{2}\right)^2 dS$$

$$= (\pi / 6\hbar) \sigma A S_{max}^2$$

$$= \delta_i E_{10} / \hbar \longleftarrow$$

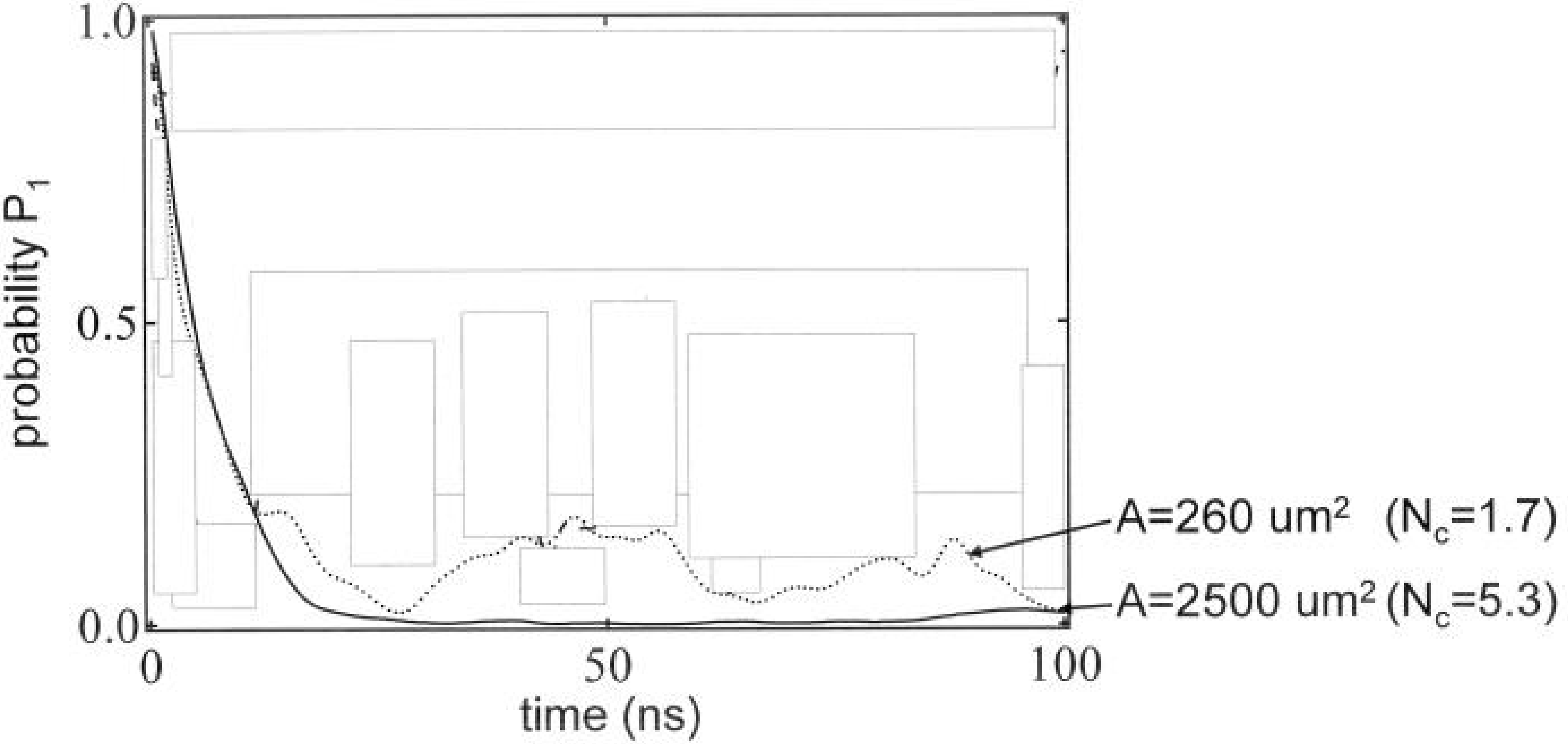
Same formula for δ_i as bulk dielectric loss

$$\cong (1/10\,\text{ns}) A^0 \longrightarrow$$

Implies δ_i = 1.6x10^{-3}, AlO_x similar to SiO_x (~1% OH defects)

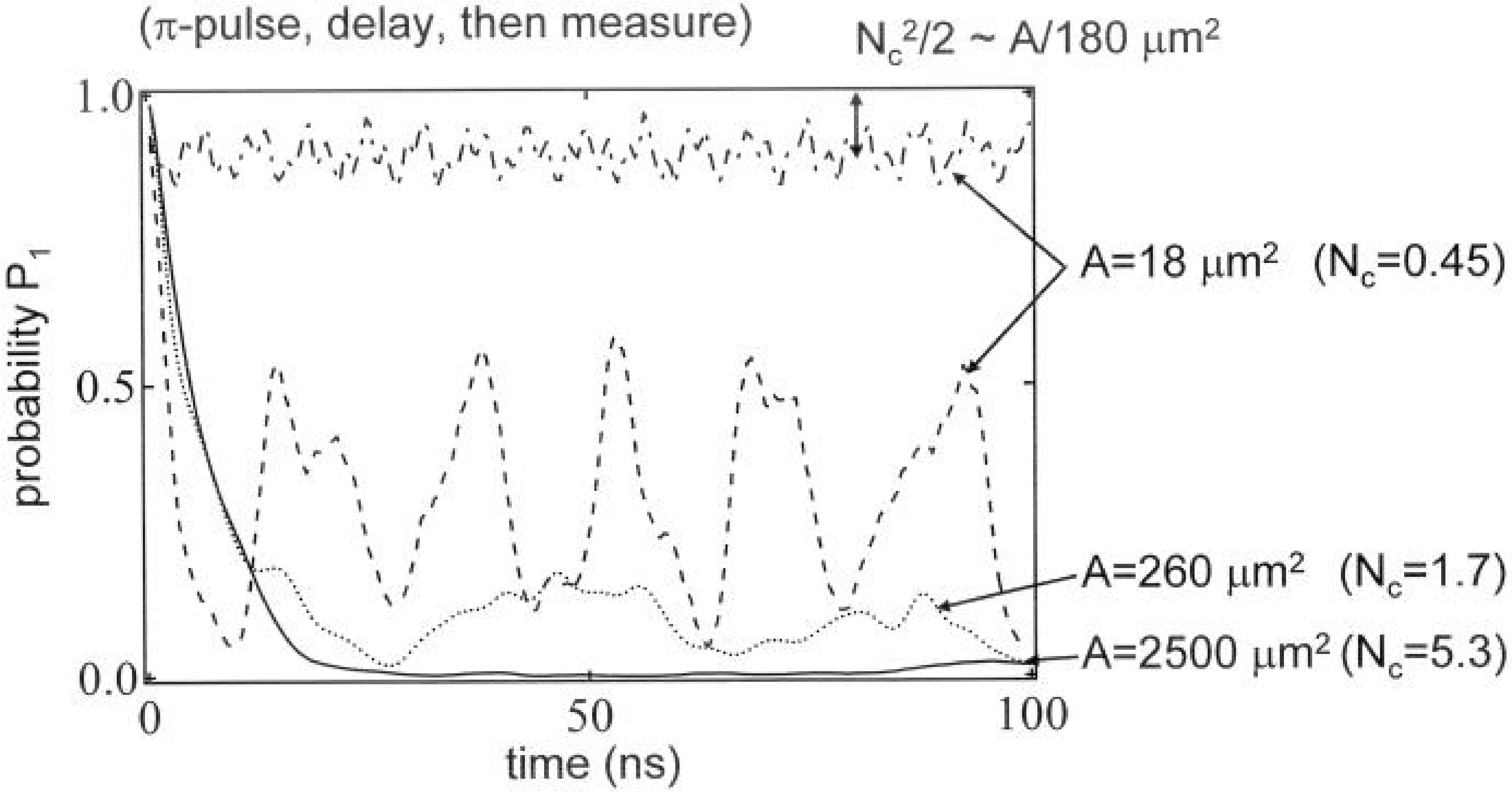
State Decay *vs.* Junction Area

Monte-Carlo QM simulation:
(π-pulse, delay, then measure)



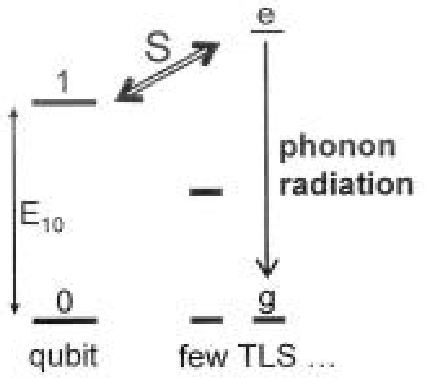
State Decay *vs.* Junction Area

Monte-Carlo QM simulation:
(π-pulse, delay, then measure)



Need $N_c \lesssim 0.3$ ($A \lesssim 10\ \mu m^2$) to statistically avoid resonances
Then observe <u>decrease</u> in coherence <u>amplitude</u>!

Small Junctions – Off Resonant Decay



(1) Qubit state 1 now “dressed” by off-resonant coupling to e states

(2) e loses energy to phonons

$$\Gamma_{1e}(E_{eg}) \sim (400\mathrm{ns})^{-1}(E_{eg}/h10\,\mathrm{GHz})^3$$

(1st TLS data: 7 GHz gave T_1=1.2 μs)

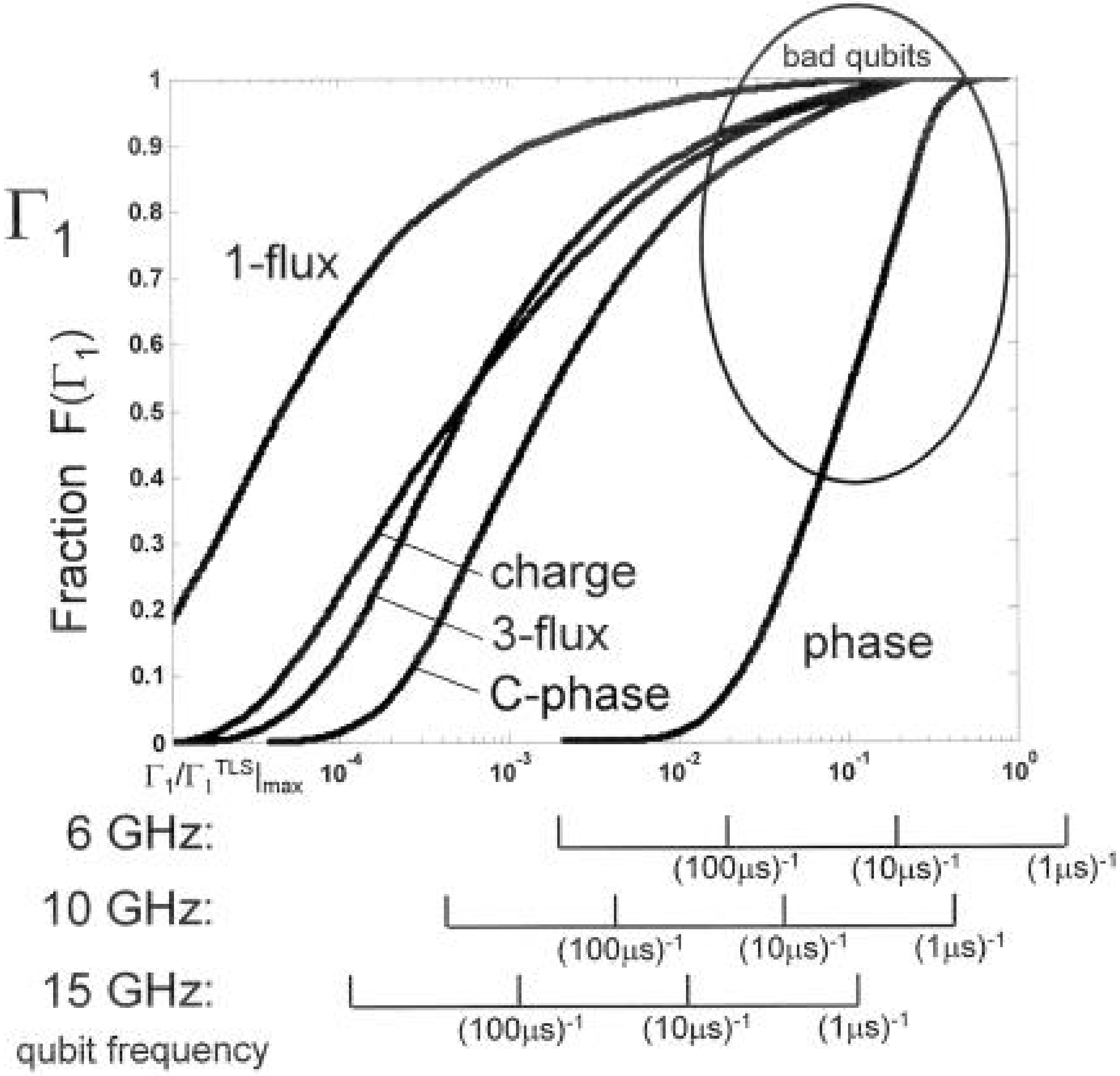
(3) Decay rate via 2nd order Fermi-Golden rule

$$\Gamma_1 \cong \frac{1}{4}\sum_i \frac{S_i^2}{(E_i - E_{10})^2}\Gamma_{1e}(E_{10})$$

(4) Decay rate depends on exact distribution of TLS. Performed Monte-Carlo calculation of distribution function of Γ_1 for 10^5 random sets of TLS

Results of Monte Carlo Calculation

fraction with
decay rate < Γ_1



Qubit decay rate Γ_1

(1) All qubits similar
(2) Most qubits have low loss
(3) Use low qubit frequency
(4) Anecdotal evidence:
~20% qubits
have short T_1 !

* Coupling to TLS statistical

large Area; see bad dielectric

small Area; Most of time ok

(Publish best data any way)

* If Area is small, don't see TLS,

Then assume no effect?

→ wrong.

(1) Off-reson. coupling can affect $|1\rangle$ state!

⋮

Effect is small.

TLS as memory(?)

(2) See TLS states during measurement!!

LZ: $P = e^{-\pi S^2/2\hbar(dE_{10}/dt)}$

(remain 1 state)

iF

beled by i) is

just calc; S_i known!

$$P = \prod_i \exp[-\pi S_i^2/2\hbar(dE_{10}/dt)_i] \quad (33)$$

$$= \exp[-\frac{\pi}{2\hbar}\sum_i S_i^2/(dE_{10}/dt)_i] \quad (34)$$

physically!

$$= \exp[-\frac{\pi}{2\hbar}\int_0^{S_{\max}} \frac{d^2N}{dEdS}S^2dS \underbrace{\int \frac{dE_{10}}{dE_{10}/dt}}_{t_p}] \quad (35)$$

$$= \exp[-\boxed{\Gamma_1}t_p] \; . \quad \int \sigma S dS \quad (36)$$

$\Gamma \propto S$

where Γ_1 is given by Eq. (29) and $t_p = \int dt$ is the total duration of the pulse. Note that this result explains why with $\Gamma_1 = 10$ns and $t_p \simeq 10$ns we observe a fidelity loss during measurement of $\sim 50\%$.

Similar to the discussion for the coupling number, Eq. (36) is valid only when the qubit bias passes through a large number of resonances. The total number of resonances in an energy range of ΔE_{10} is

$$N_c' = \Delta E_{10}\int_{S_{\min}}^{S_{\max}} \frac{d^2N}{dEdS}dS \quad (37)$$

$$= \sigma A \Delta E_{10}\ln(2S_{\max}/S_{\min}) \; , \quad (38)$$

$$= N_c\frac{\Delta E_{10}}{S_{\max}}\frac{\ln(2S_{\max}/S_{\min})}{\pi/4} \; . \quad (39)$$

The resonances with $S \simeq S_{\max}$ contribute mostly to the fidelity loss. By setting $S_{\max}/S_{\min} = 10$, the number of resonances evaluated for aluminum-oxide tunnel junctions scales as

$$N_c' \simeq 1.5\,\frac{\Delta E_{10}/h}{\text{GHz}}\frac{A}{\mu\text{m}^2} \; . \quad (40)$$

For phase qubits with $A = 10\mu\text{m}^2$ and a change in bias of $\Delta E_{10}/h = 1$ GHz, we obtain $N_c' \simeq 15$. This result indicates that the continuum limit given by Eq. (36) is justified for large area junctions.

LARGE AMPLITUDE RESPONSE OF A TLS

The Fermi golden rule was used to calculate the decay rate for a bath of TLS in their ground state. We are also interested in the response of the TLS for large temperature or drive amplitude where the excited state might be significantly populated. We introduce here notation and techniques that will be used to calculate this more general case using a description that will be appropriate for the $1/f$ noise calculation in a later section.

The transition rates between the states $|e\rangle$ and $|g\rangle$ are defined to be

$$\Gamma_{e\to g} = \Gamma + \Gamma_1 \; , \quad (41)$$

$$\Gamma_{g\to e} = \Gamma \; , \quad (42)$$

where Γ_1 is the decay rate for spontaneous emission $|e\rangle \to |g\rangle$, and Γ is the stimulated emission rate between the two states produced by an external signal, either from the temperature bath, noise, or an external drive. The steady-state population of the ground $\langle n_g\rangle$ and excited $\langle n_e\rangle = 1 - \langle n_g\rangle$ state can be solved for by equating the transition probabilities

$$\langle n_g\rangle\Gamma_{g\to e} = \langle n_e\rangle\Gamma_{e\to g} \; , \quad (43)$$

which when solved gives the population difference

$$\langle n\rangle \equiv \langle n_g\rangle - \langle n_e\rangle \quad (44)$$

$$= \frac{1}{1+2\Gamma/\Gamma_1} \; . \quad (45)$$

The effect of temperature T is to produce transitions $\Gamma_T = \Gamma$ with equal rates between the two states. It's effect can be understood through the standard definition of setting the relative population of states equal to the Boltzman factor

$$\exp(-E/kT) \equiv \langle n_e\rangle/\langle n_g\rangle \quad (46)$$

$$= \frac{\Gamma_T}{\Gamma_T + \Gamma_1} \; . \quad (47)$$

Using this definition, it is easy to show that the standard factor for thermal occupation is equivalent to that give by Eq. (45)

$$\langle n_T(E)\rangle = \tanh(E/2kT) \quad (48)$$

$$= \frac{1-\exp(-E/kT)}{1+\exp(-E/kT)} \quad (49)$$

$$= \frac{1}{1+2\Gamma_T/\Gamma_1} \; . \quad (50)$$

We will next consider the case of two-level system with an external drive *and* thermal transitions. In this case $\Gamma = \Gamma_D + \Gamma_T$, where Γ_D is the transition rate due to the drive. The population difference is

$$\langle n\rangle = \frac{1}{1+2(\Gamma_D+\Gamma_T)/\Gamma_1} \quad (51)$$

$$= \frac{1}{1+2\Gamma_D/(\Gamma_1+2\Gamma_T)}\;\frac{1}{1+2\Gamma_T/\Gamma_1} \quad (52)$$

$$= \frac{\langle n_T\rangle}{1+2\Gamma_D/\Gamma_1(T)} \; , \quad (53)$$

where we have defined the temperature dependence to the decay rate to be

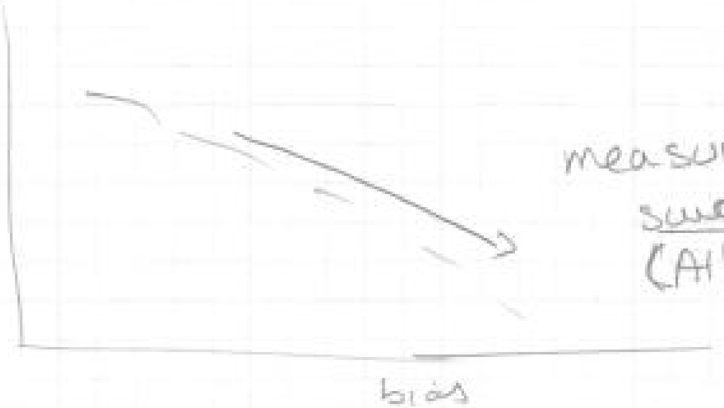
$$\Gamma_1(T) \equiv \Gamma_1 + 2\Gamma_T \quad (54)$$

$$= \Gamma_1/\langle n_T\rangle \; . \quad (55)$$

This derivation justifies the presence of a separate factor $\langle n_T\rangle$ to account for temperature, but shows that the temperature dependence to $\Gamma_1(T)$ is not intrinsic but comes from its definition in order to simplify the denominator term of Eq. (53). For qubit research one usually wants to compare Γ_1 with a fundamental prediction, so we will explicitly show its $\langle n_T\rangle$ temperature dependence.

TLS + Meas. error

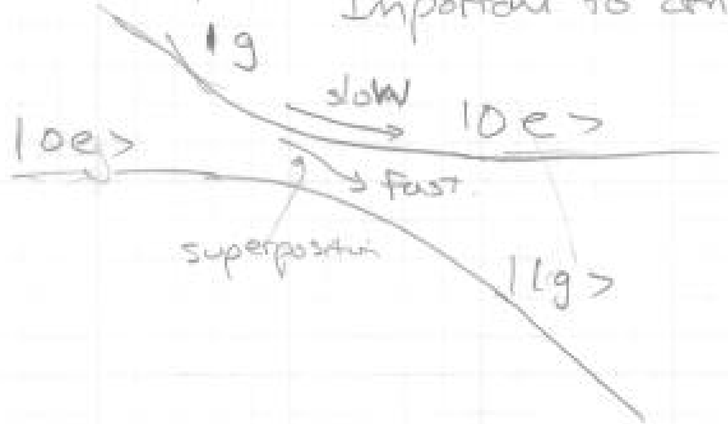
This is $\overset{\text{likely}}{\wedge}$ error Mech for __all__ qubits

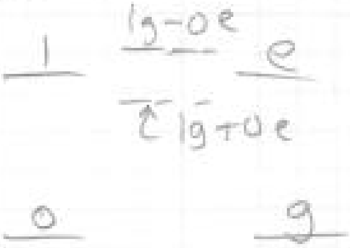


measure I_b increase, __sweep__ through resonances (All qubits may do this)

H[illegible]!

Sweep → See more resonances
Important to consider





Measure fast ⇒ Fewer errors; E lost to TLS.

start P (stay in 1)

standard loss from TLS → $= e^{-\Gamma_1 t_p}$ large # resonance "turns on TLS dissip."

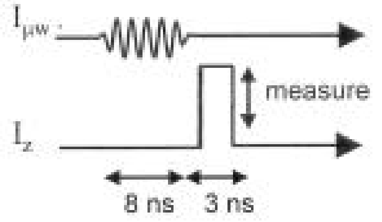
AlO_x: $\Gamma_1 \sim 10ns$, need to pulse fast

→ loss in meas. fidelity

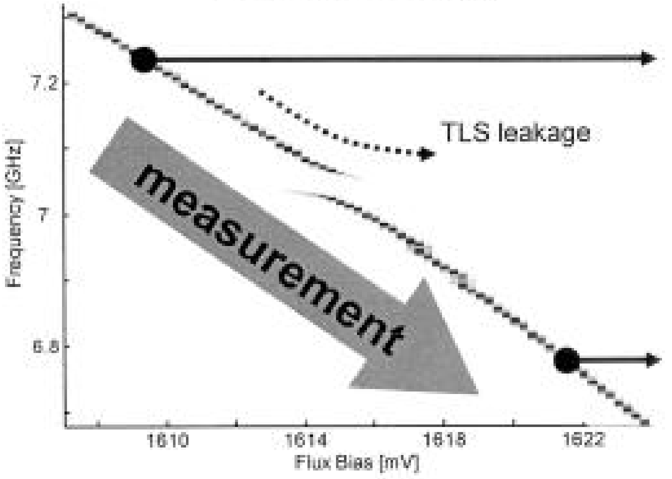
(but not qubit fidelity)

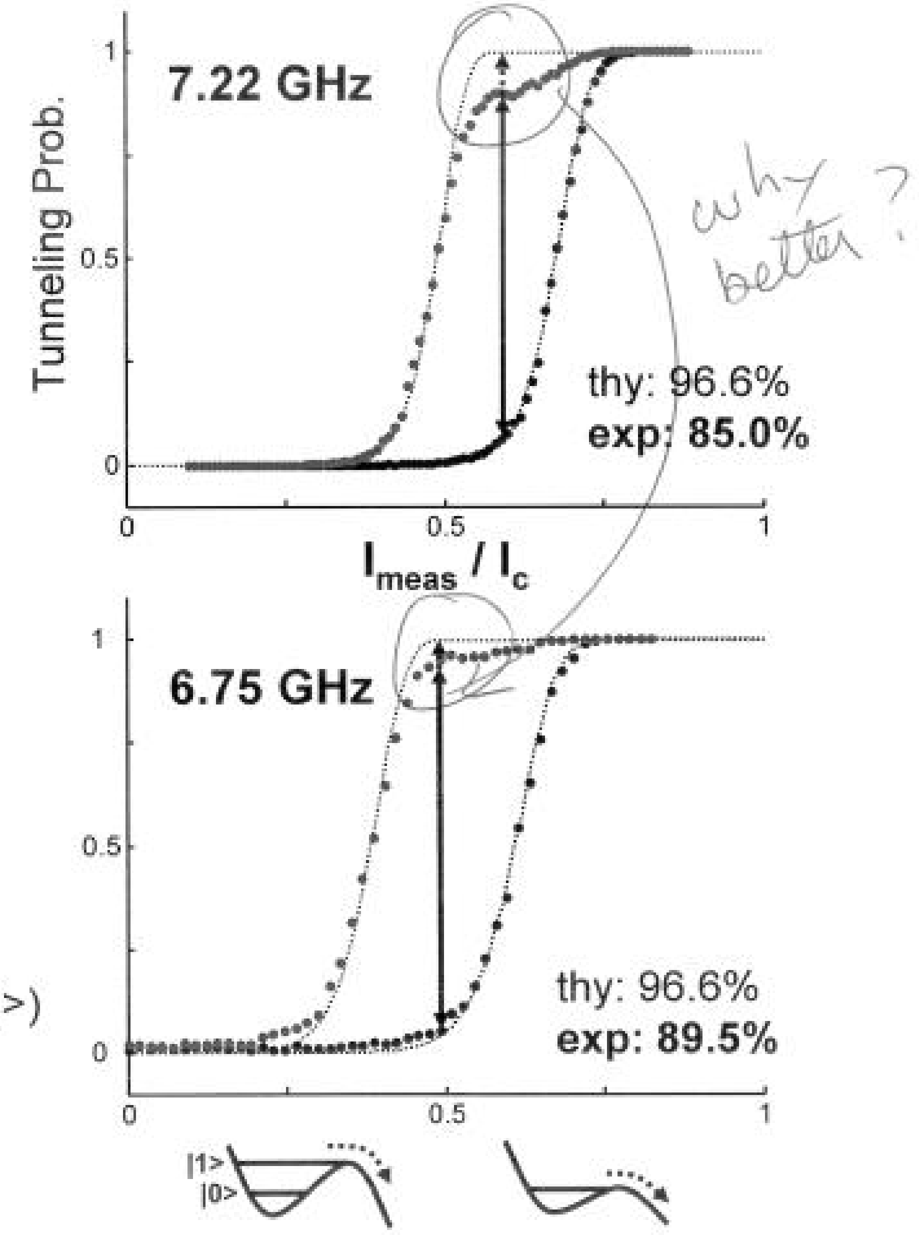
Single Qubit Gate Errors: Measurement Errors

nothing or π-**pulse**



Spectroscopy





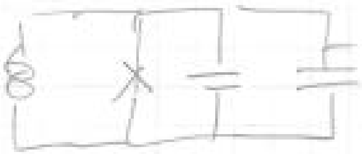
why better?

Error Budget

|1> (misidentified as |0>)
- 4.5% splitting at 7GHz
- 3-5% other splittings
- 1% T_1 during measurement

|0> (misidentified as |1>)
- 3.4% stray tunneling

TLS in crossover dielectrics



stray cap in wirings; crossovers, etc.

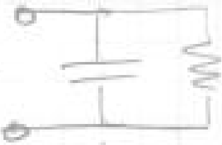
* Need to have crossovers in any complex IC!

* Normal dielectric material, (SiO_x) very bad!

⇒ Won't go into detail calc's on T, P dependence of loss, except summarize results —

Define loss tangent (μwave property)

$Y =$



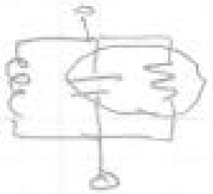
↖ dissipative part

↖ dispersive

$$\tan\delta = \frac{Re\{Y\}}{Im\{Y\}}$$

$$\delta = \frac{1/R}{(\omega C)}$$

For Resonator, easy to show:



$$\boxed{\delta = \frac{1}{Q}}$$

200mV

$$\delta_{meas} = \underset{\text{intrinsic}}{\delta_i} \frac{\langle n_T \rangle}{\sqrt{1 + \bar{E}^2/\bar{E}_c^2}}$$

therm occup of $\langle n_g \rangle - \langle n_e \rangle$
$= \tanh(E_{eg}/2kT)$

Saturation due to high drive power. (depends on T_1, T_2 of TLS)

$\bar{E} =$ E field

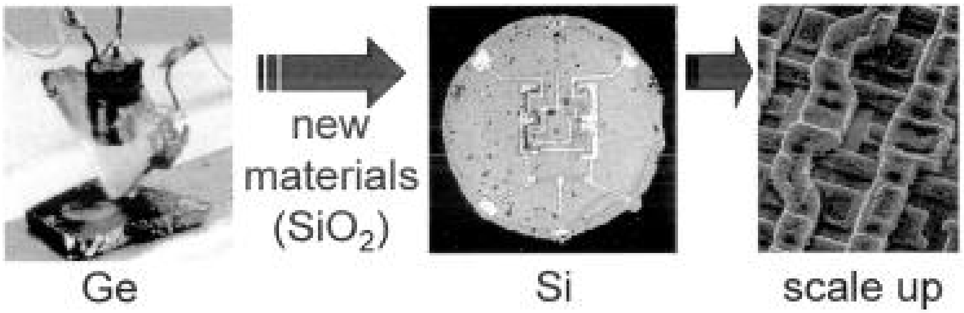
$$\bar{E}_c \simeq \frac{200\,\mu V}{.2\,\mu m} \simeq 1\,mV/\mu m$$

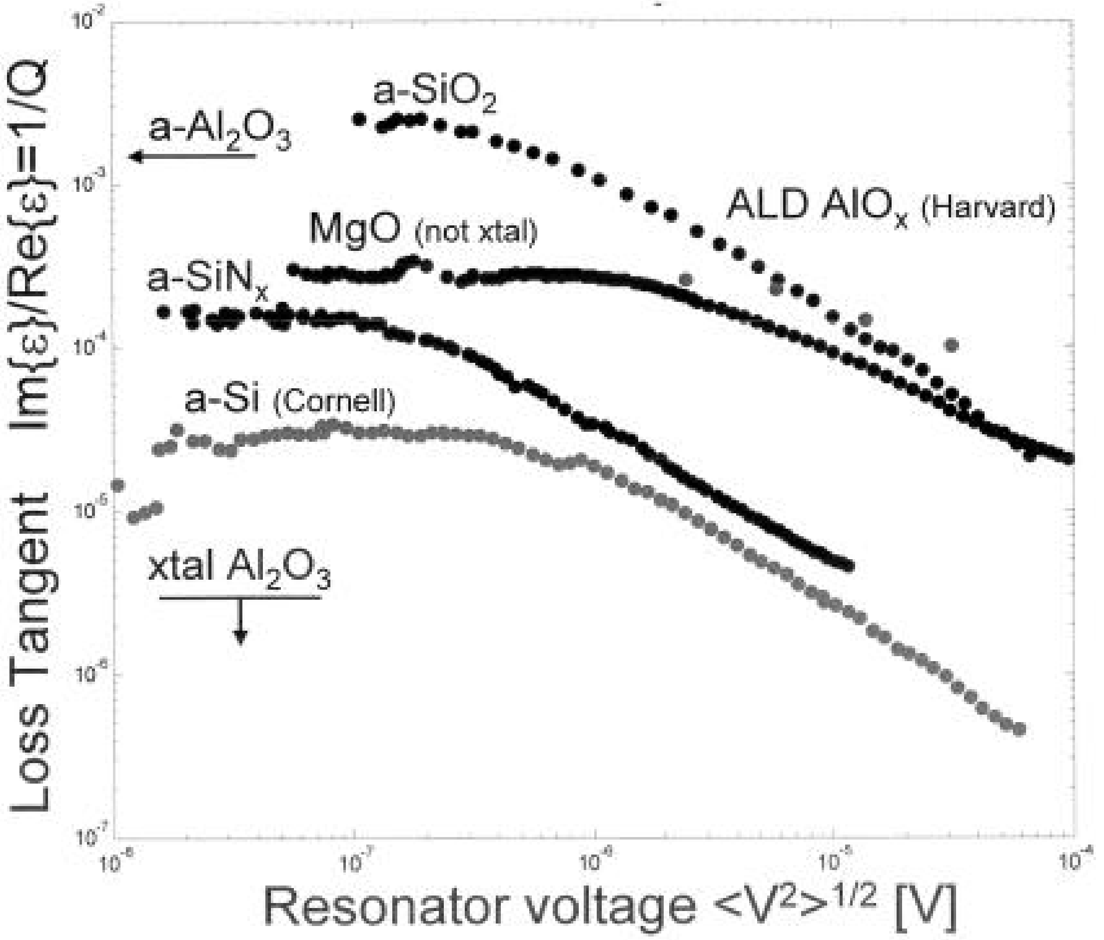
$= 1$ V/[illegible]

For typical TLS.

Optimistic about future: Improve loss tangent δ_i

- Phonon TLS: large literature (100x)
- TLS density (1 defect / 10^7 atoms): electrical similar to phonons
- Phonon TLS – universal loss except Si, Ge
- Crystals are very good





Present Dielectrics
Not Optimized

"Superinsulator" exists
How to fab?

- observe loss drops (higher Q resonances) at high P or T!

⇒ Careful, "Classical" (high P, T) meas's make you thing dielectric is <u>better</u> than actually is.

Why should you worry about this?

Want Q's in 10^5 to 10^6 (or more)

<u>Real</u> materials are ~~bad~~ horrible!

better

<u>Mat'l</u>	<u>δ_i</u>	
a-SiOx	3 to 5×10^{-3}	most common
a-AlOx	2×10^{-3}	tunnel juncts.
MgO	3×10^{-4}	(better t-i?; xtal?)
(HT-th) SiO_2	10^{-3} to 10^{-5}	(Oxide on Wafers; variable)
a-SiN	2×10^{-4}	
a-Si:H	3×10^{-5}	(need H to relax bonds)
XTALS (Si, Al_2O_3)	$< 10^{-6}$?	

TLS literature explains this –

More bonds (O/2 ; N/3 ; Si/4)

↳ More constrained atoms

↳ Few TLS states.

- What to do?

(1) Calc. loss from dielectrics

(2) If need LT deposited dielectr –

a-Si:H best

Should be good for X-overs

(3) X-tal Dielectrics best ⇒ HT deposit → hard

$1/f$ noise – Last, but not Least

complicated ↗ ↖ important

- Parameters + Bias change/fluctuate

low freq. noise on transitions.

→ Why short dephasing times

why use degen. points

Really defines what exp's work!

3 <u>known</u> $1/f$ sources ((everything) has $1/f$)

$\delta Q \sim 10^{-3} e$

$\delta \Phi \sim 10^{-5} \Phi_0$

$\delta I_0 \lesssim 10^{-6} I_0$; most impt param, good that small!

Spectral density increases at LF ($\propto 1/f$)

$$\langle \text{Noise}^2 \rangle \propto \int \frac{1}{f} df \sim \ln f$$

↳ const. contribution per decade of f.

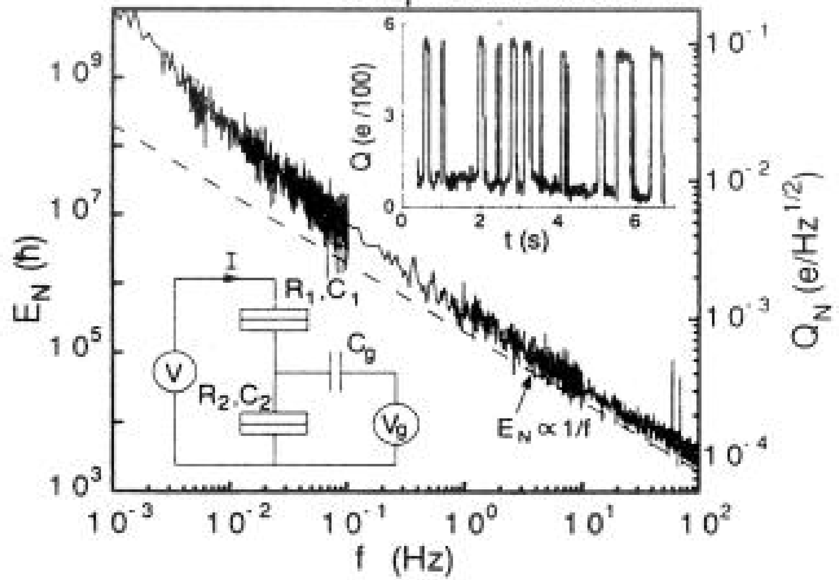
(Show Data)

To understand (partially) where comes from, let's work out Q noise from TLS theory.

1/f Noise

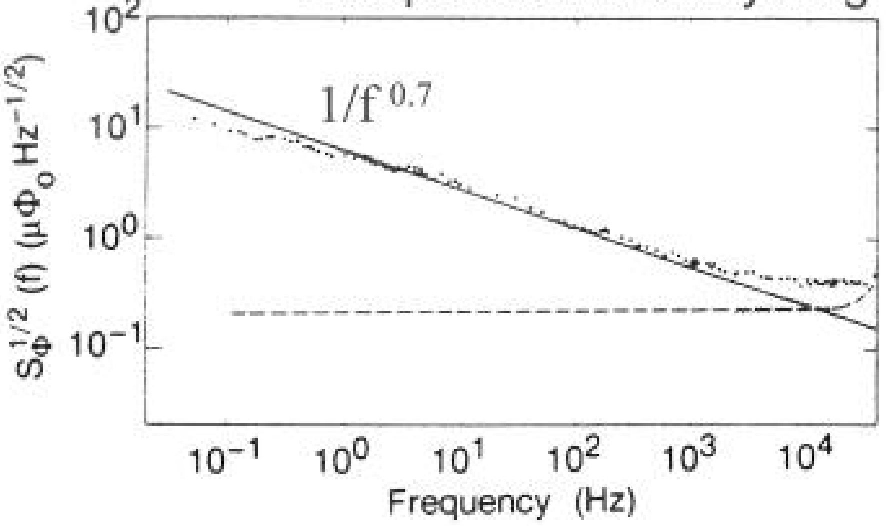
Charge:

Proportional to C



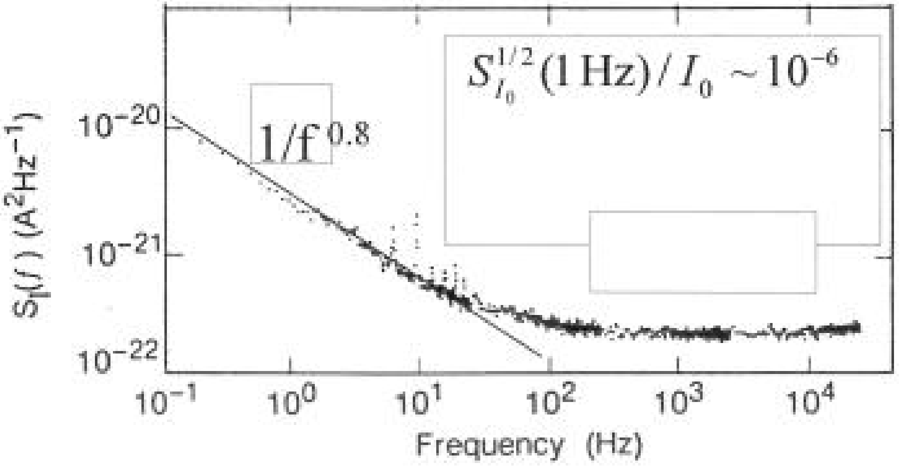
Flux:

Independent of everything



I_0:

$S_{I_0} \propto T^2 I_0^2$ / **Area**



Real Calc.

$$S_Q(F) = \left(\frac{d}{x}e\right)^2 \int_0^\infty dE \int_0^1 d\sin\theta \int_0^1 d\cos\eta \, \overset{\text{Density of TLS}}{\frac{\sigma A}{|\sin\theta\cos\theta|}}$$

$$\times\ 2\pi\hbar \underbrace{\cos^2\theta\cos^2\eta}_{\text{charge magn.}} \underbrace{\left[1-\tanh^2(E/2kT)\right]}_{\text{Therm Fluct}} \underbrace{\frac{2\Gamma_1}{\Gamma_1^2+(2\pi F)^2}}_{\text{Lorentz Spectrum of a TLS}}$$

with $\boxed{\Gamma_1 = \Gamma_{1,max}\sin^2\theta}$

↓ Math

$$\boxed{\frac{S_Q(F)}{e^2} = \underbrace{\frac{kT}{(e^2/2C)}}_{\frac{100mK}{1K}\sim 0.1} \cdot \underset{\sim 10^{-3}}{\frac{\delta_i}{2\pi}} \frac{1}{F}}$$

Only TLS ≲ kT contribute

(Γ_1's log-normal distrib.)

$\sigma \propto \delta_i$;

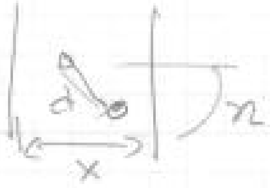
Obtain from H.F. dissipation

- Reasonably close to observed value!
- See individual TLS fluctuators in time trace

Why is charge noise so high?

⇒ Making SET devices with bad (high δ_i) capacitors!

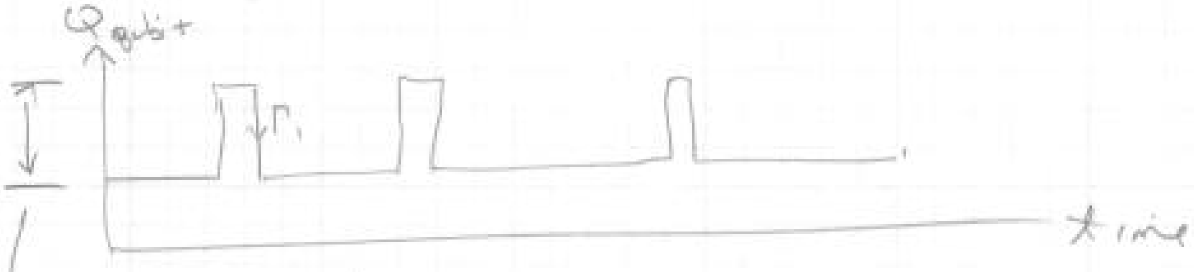
$$H_{INT} = \frac{d}{x} eV \cos\eta \begin{bmatrix} \cos\theta\{|e\rangle\langle e| - |g\rangle\langle g|\} + \\ \sin\theta[|e\rangle\langle g| + |g\rangle\langle e|] \end{bmatrix} \begin{matrix} \text{— LF} \\ \text{— HF} \end{matrix}$$



Phonon Radiat gives $e \to g$, rate $\Gamma_\downarrow$

Therm flucts (T) give $e \leftrightarrow g$

① For TLS with $E_{eg} \lesssim kT$, get thermal population of e; Transitions from this phonon noise give LF charge flucts



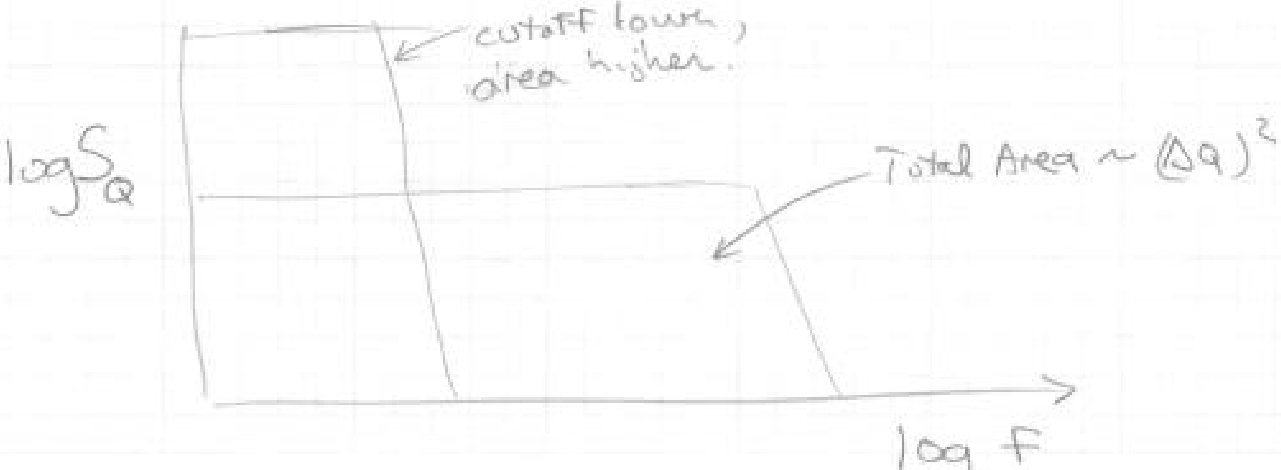
$\Delta Q \propto \underbrace{\frac{d}{x} e}_{} \cos\eta \cos\theta$

→ image charge on plates.

This gives "Random Telegraph Signal"

Lorentzian freq. spectrum.

(White noise to $f \sim 1/\Gamma_\downarrow$, then drops off).



② Distribution of cutoff freq's $f_c \propto \frac{1}{\Gamma_1}$

Phonon Radiation (& coupling)

$$\Gamma_1 \propto \underbrace{\Gamma_{1max}}_{\text{some number}} \sin^2\theta \quad \leftarrow |M.E.|^2 \text{ term}$$

~$10^6/s$ — some number ~

$$d^2N = \frac{dE\, d\sin\theta}{|\sin\theta \cos\theta|}$$

$$\frac{d\Gamma_1}{\Gamma_1} = \frac{2\Gamma_{1max} \sin\theta\, d\sin\theta}{\Gamma_{1max} \sin^2\theta}$$

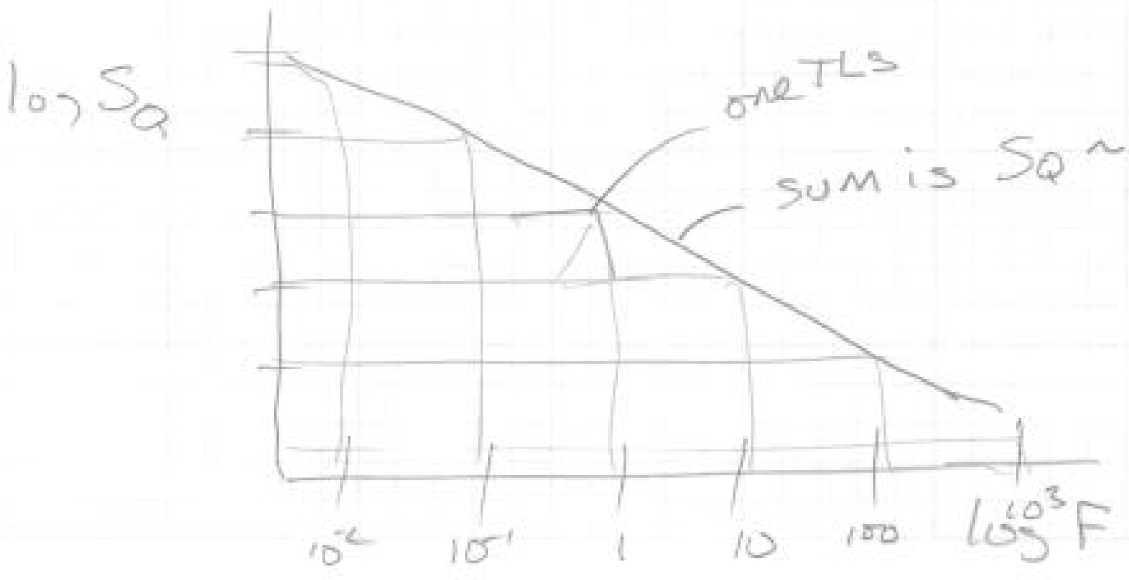
$$= 2\frac{d\sin\theta}{\sin\theta}$$

$$d^2N = \frac{dE\, d\Gamma_1}{2\Gamma_1}$$

for slow (LF) TLS where $\sin\theta \to 0$ ($\cos\theta = 1$)

↑ log normal distrib. of radiation times (comes from log-norm tunnel Δ_0).

⇒ Think of const # of Γ_1's per decade of Freq.



Summary 1/f Noise

Q: Some exp's see T^2, other T^0 (no).
Possibly 2nd meachanism at work?

I_0: TLS Fluct's in barrier causes tunneling to change.
Can build a reasonable model.

Φ: Unknown Mechanism
(Can eliminate possibility of
- nuclear spin noise
- e moment noise from TLS Flucts

⇒ Possible strange surface noise mechanism?

→ Conclusions:

(1) Critical to Qbit coherence.

(2) Much work needs to be done here

- Hard work
- Solution will enable this qubit technology.
(but I + few others will appreciate)