Application of superconducting Resonators for Study of Two Level Defect States in Dielectrics

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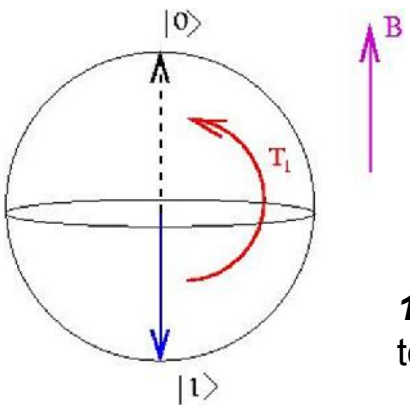
The Laboratory for Physical Sciences

Outline:

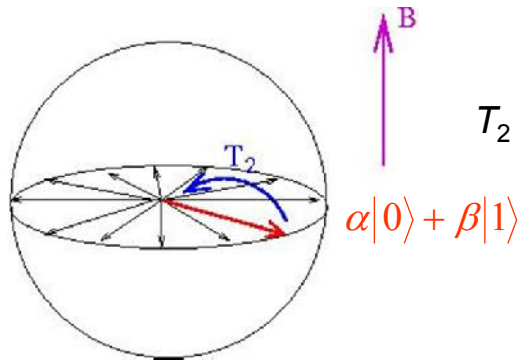
- Common problems of superconducting quantum computing
- Two-level defect states in dielectric is a powerful source of decoherence in superconducting qubit
- Resonance methods of study of defect states in dielectric.
- Experimental observation of TLS-TLS interaction
- Resonance absorption of dielectric in the swept DC field

Relaxation and Dephasing



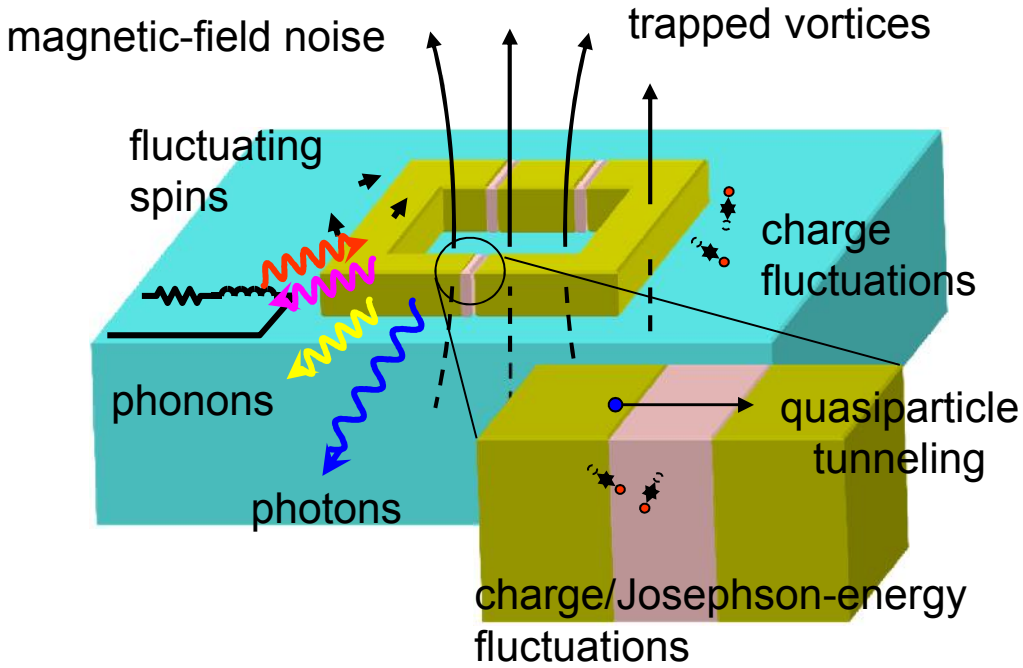
T_1 = Relaxation time

1/T₁ - radiation to the environment



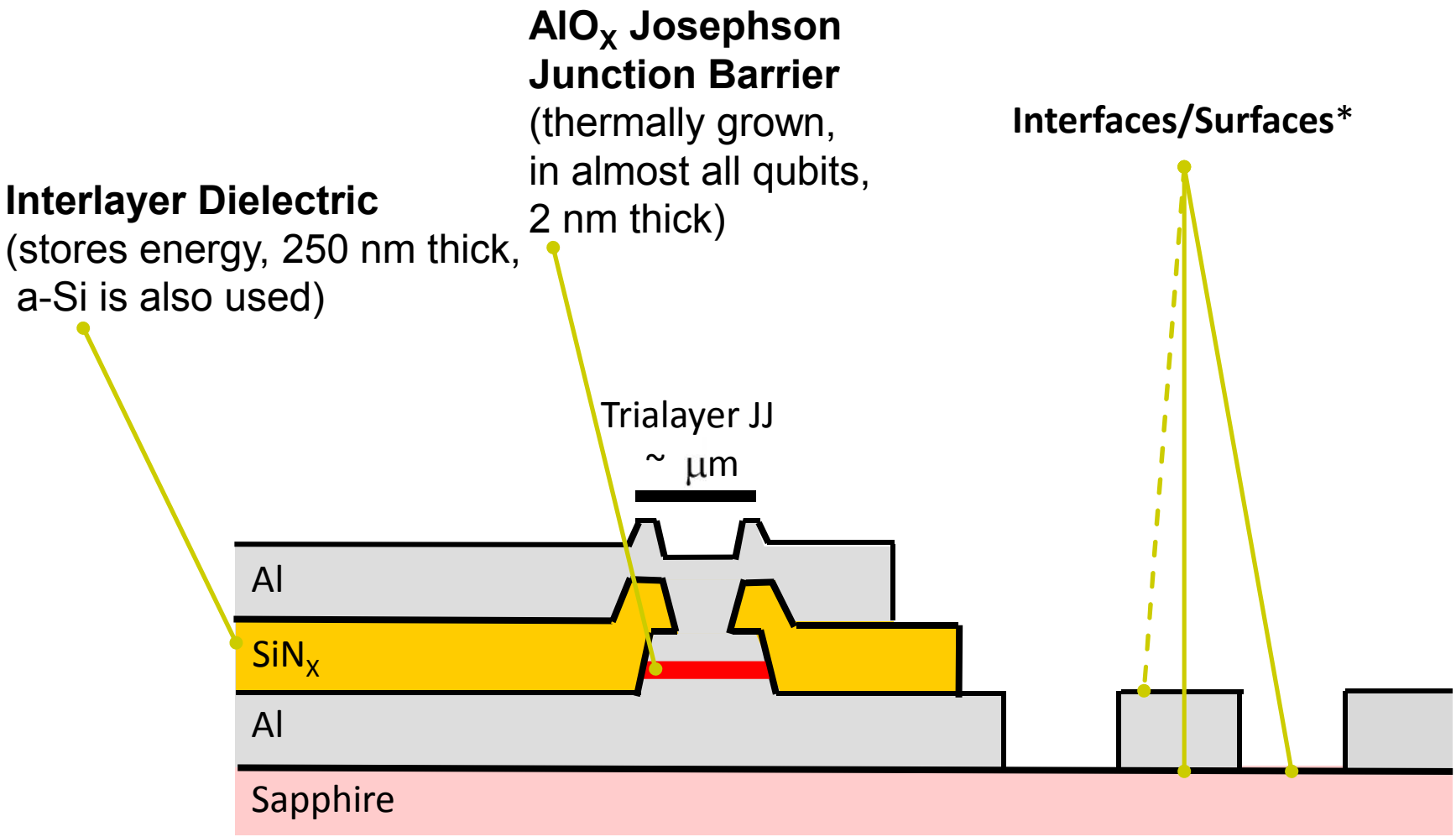
T_2 = Dephasing time

1/T₂ - parameter fluctuations



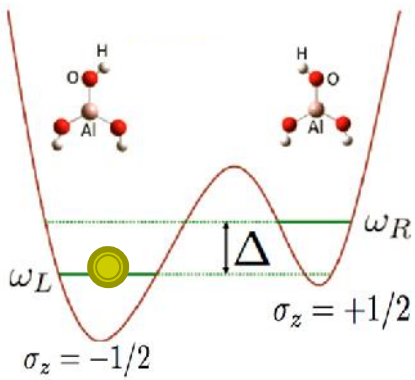
A short decoherence time: the qubits are strongly affected by ***local noises*** (such as critical current fluctuations, charge noise, flux noise and quasiparticle poisoning).

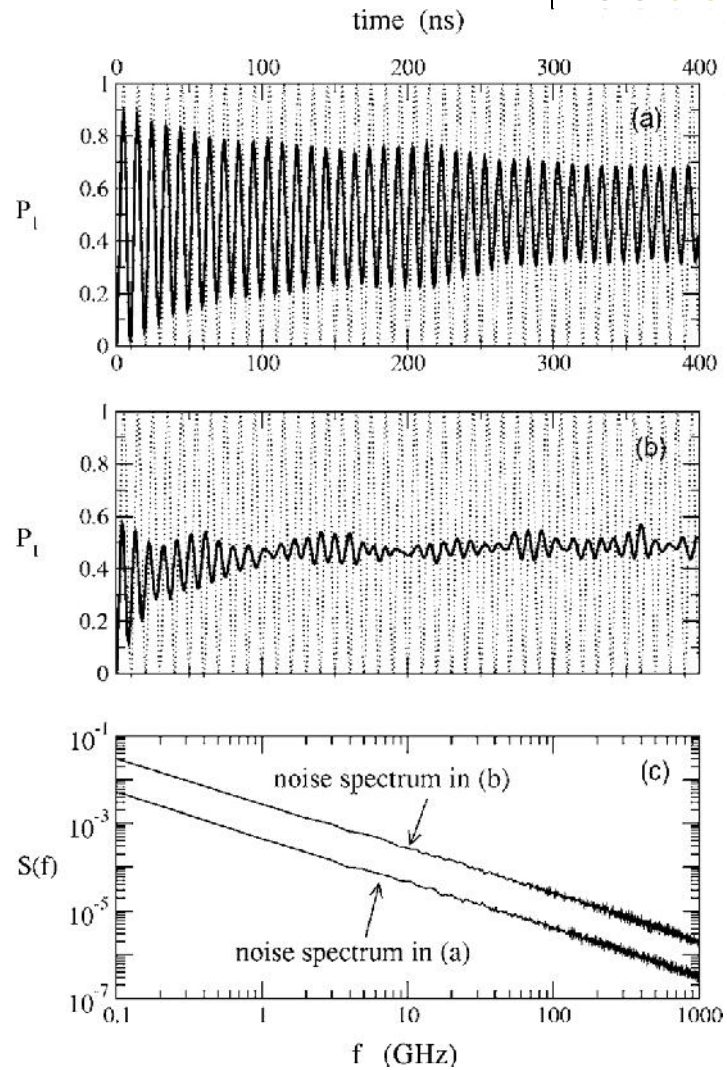
Source of dielectric loss in superconducting qubit



Two-level defect states in Josephson qubit

Loss in the amorphous dielectric arise from resonant absorption from two level system (TLS) defects with a dipole moment coupling to the electric field .



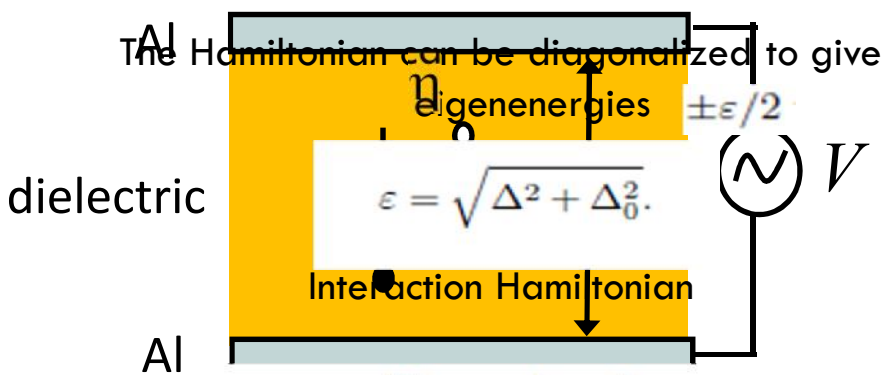


Li-Chung Kuo and Gar PRL 98, 0 (2006)

Defect in ... tor

$$H = \frac{1}{2}\begin{pmatrix} -\Delta & \Delta_0 \\ \Delta_0 & \Delta \end{pmatrix},$$

The Hamiltonian can be diagonalized to give the eigenenergies



$$\varepsilon = \sqrt{\Delta^2 + \Delta_0^2}.$$

$$H^e_{\text{int}} = \left[\frac{\Delta}{\varepsilon}\sigma_z + \frac{\Delta_0}{\varepsilon}\sigma_x\right]\vec{d}_0 \cdot \vec{E}.$$

moment from modified Δ: p=qr

TLS contribution to the dielectric function

$H = H_0 + H^e_{\text{int}}$ Hamitonian of TLS in the electric problem

$H = -\hbar\gamma\vec{B}\cdot\vec{S} = -\hbar\gamma(\vec{B}_0\cdot\vec{S}) - \hbar\gamma(\vec{B}'\cdot\vec{S})$ Hamitonian of a spin 1/2 system in a magnetic field

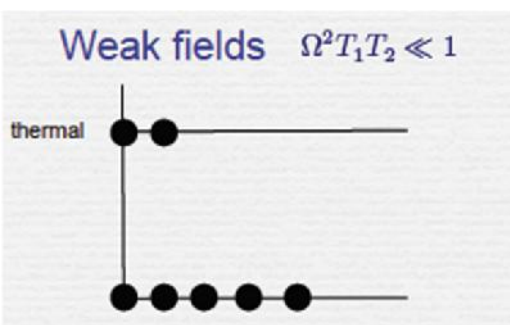
Correspondence between TLS and spin system: $-\hbar\gamma\vec{B} = (0,\ 0,\ \varepsilon)$ and $-\hbar\gamma\vec{B}' = (2\vec{d}\cdot\vec{E},\ 0,\ \vec{d}'\cdot\vec{E})$.

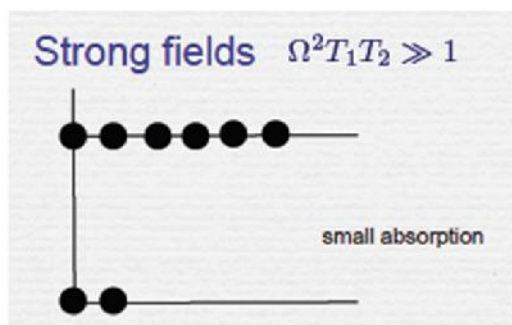
$$\vec{d}' = 2\vec{d}_0\frac{\Delta}{\varepsilon} \qquad \vec{d} = \vec{d}_0\frac{\Delta_0}{\varepsilon}$$

Resonant TLS contribution to the (isotropic) dielectric function:

$$\epsilon_{\text{TLS}}(\omega) = \iiint \left[\hat{e}\cdot\overleftrightarrow{\chi}_{\text{res}}(\omega)\cdot\hat{e}\right]\frac{P}{\Delta_0}d\Delta d\Delta_0 d\hat{d} = \epsilon'_{\text{TLS}}(\omega) - j\epsilon''_{\text{TLS}}(\omega)$$

$$\begin{aligned}\epsilon_{\text{TLS}}(\omega) &= \int_0^{\varepsilon_{\max}} \frac{Pd_0^2}{3}\tanh\left(\frac{\varepsilon}{2k_BT}\right)\left[\frac{1+(\omega_\varepsilon-\omega)^2T_2^2}{1+\overline{\Omega}^2T_1T_2+(\omega_\varepsilon-\omega)^2T_2^2}\right] \\ &\times \left[\frac{1}{\omega_\varepsilon-\omega+jT_2^{-1}}+\frac{1}{\omega_\varepsilon+\omega-jT_2^{-1}}\right]d\varepsilon\end{aligned}$$





$$\overline{\Omega} = \frac{2d_0|\vec{E}|}{\sqrt{3}\hbar}\frac{\Delta_0}{\varepsilon}$$

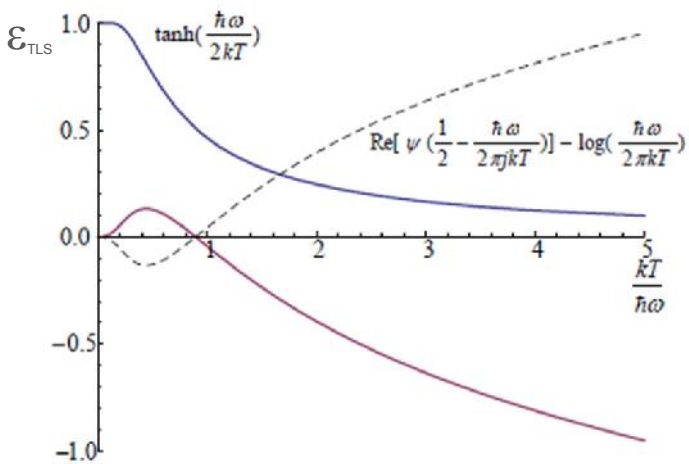
Rabi frequency

Approximations of strong and weak fields

Weak field

$$\delta_{\mathrm{TLS}} = \frac{\epsilon''_{\mathrm{TLS}}(\omega)}{\epsilon} = \delta^0_{\mathrm{TLS}} \tanh\left(\frac{\hbar\omega}{2k_BT}\right)$$

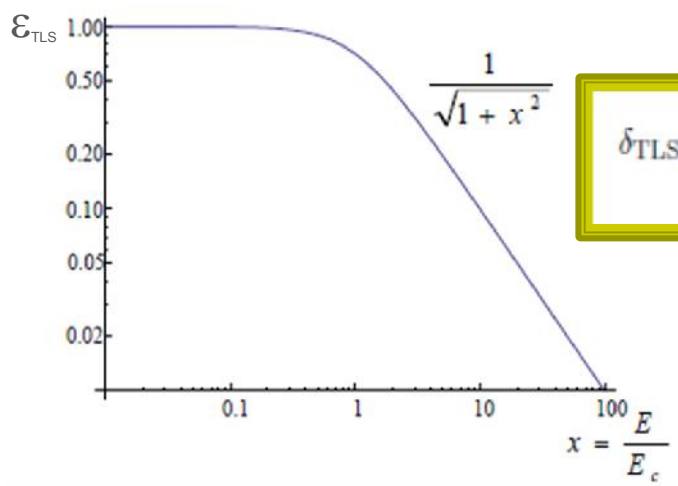
$$\frac{\epsilon'_{\mathrm{TLS}}(\omega)}{\epsilon} = -\frac{2\delta^0_{\mathrm{TLS}}}{\pi}\left[\mathrm{Re}\Psi\left(\frac{1}{2} - \frac{\hbar\omega}{2j\pi k_BT}\right) - \log\frac{\varepsilon_{\max}}{2\pi k_BT}\right]$$



Field Dependence of TLS Loss

$$\left[\frac{1+(\omega_\varepsilon-\omega)^2T_2^2}{1+\overline{\Omega}^2T_1T_2+(\omega_\varepsilon-\omega)^2T_2^2}\right] \times \mathrm{Im}\left[\frac{1}{\omega_\varepsilon-\omega+jT_2^{-1}}\right] = \frac{-T_2^{-1}}{\left[T_2^{-1}\sqrt{1+\overline{\Omega}^2T_1T_2}\right]^2+(\omega_\varepsilon-\omega)^2}$$

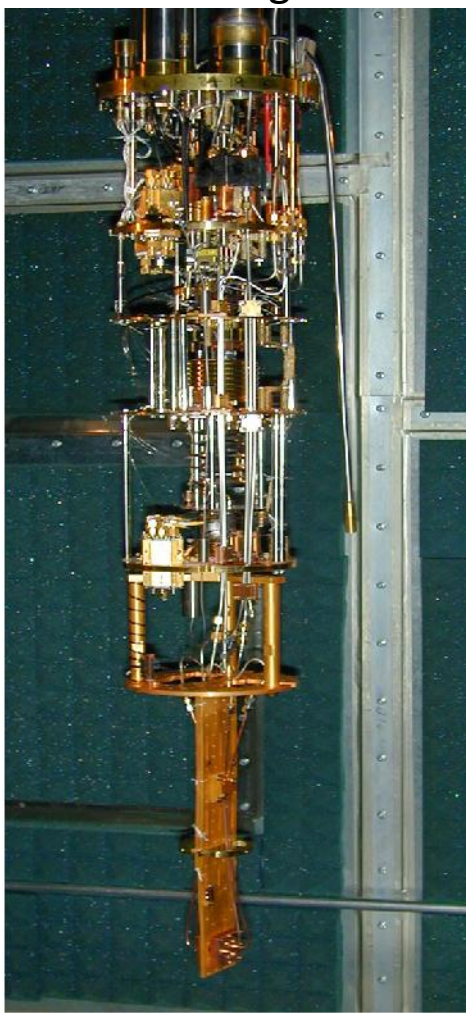
$$\delta_{\mathrm{TLS}} = \delta^0_{\mathrm{TLS}}\frac{\tanh\left(\frac{\varepsilon}{2k_BT}\right)}{\sqrt{1+\overline{\Omega}^2T_1T_2}} \qquad E_c = \frac{\sqrt{3}\hbar}{2d_0|\vec{E}|\sqrt{T_{1,\min}T_2}}.$$



$$\delta_{\mathrm{TLS}}(|\vec{E}|) = \frac{\delta_{\mathrm{TLS}}(|\vec{E}|=0)}{\sqrt{1+|\vec{E}/E_c|^2}}$$

Experimental setup

Dilution Refrigerator

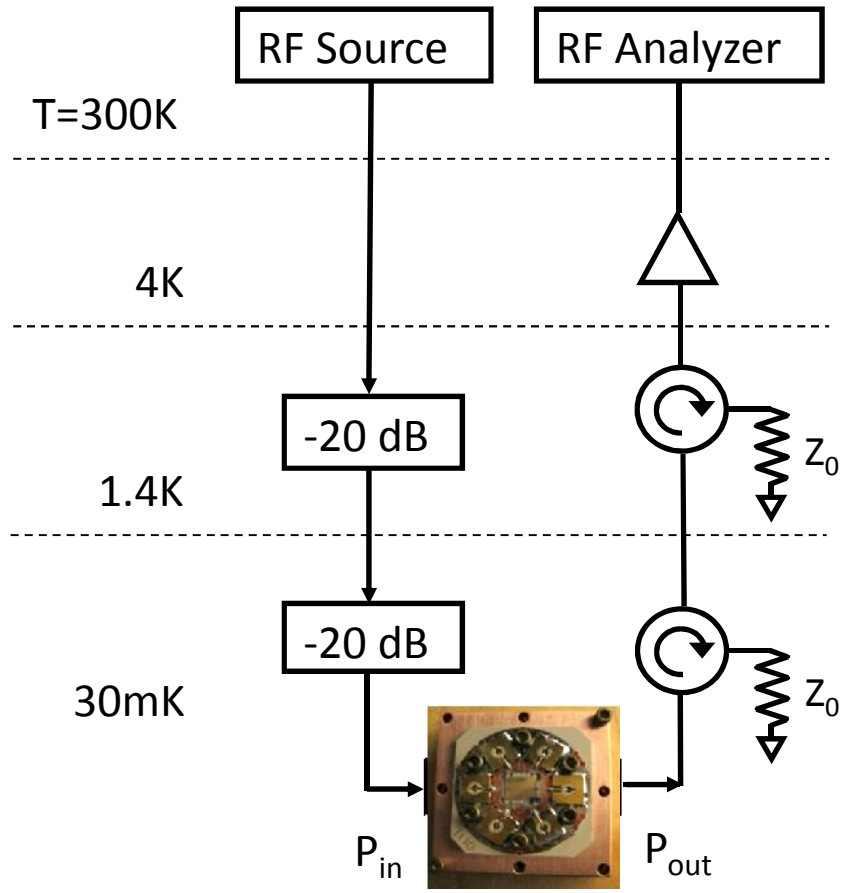


T=4K

1.4K

30mK

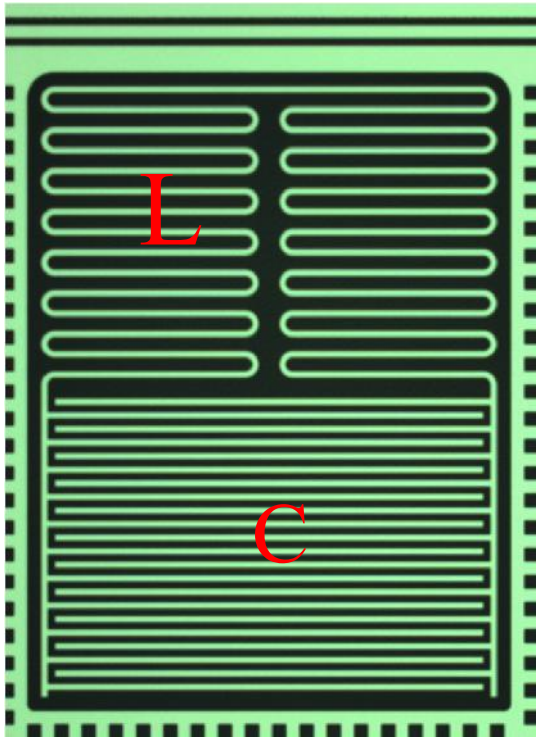
RF setup for $|S_{12}|$ measurement



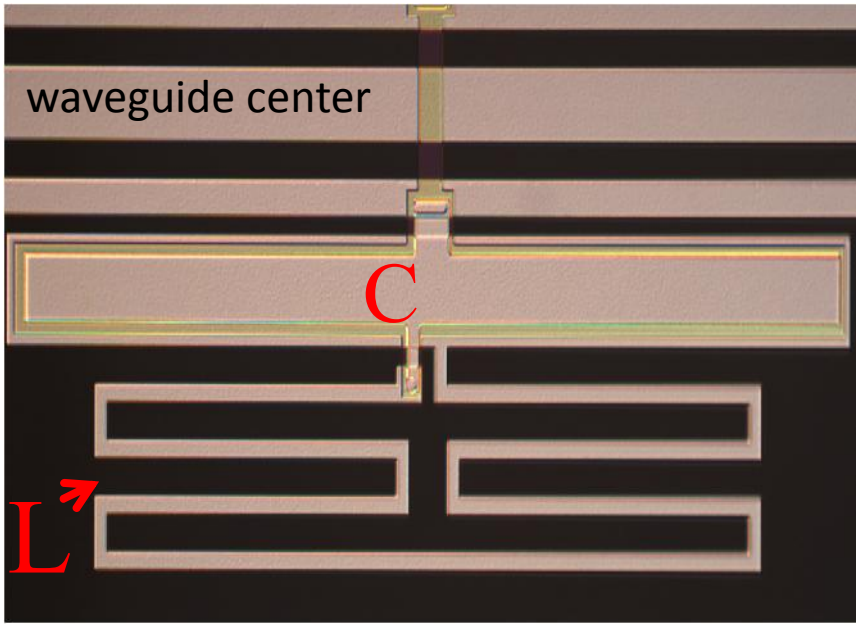
Resonator + Sample Box

Resonance dielectric studies

Quasi-lumped element coplanar resonators

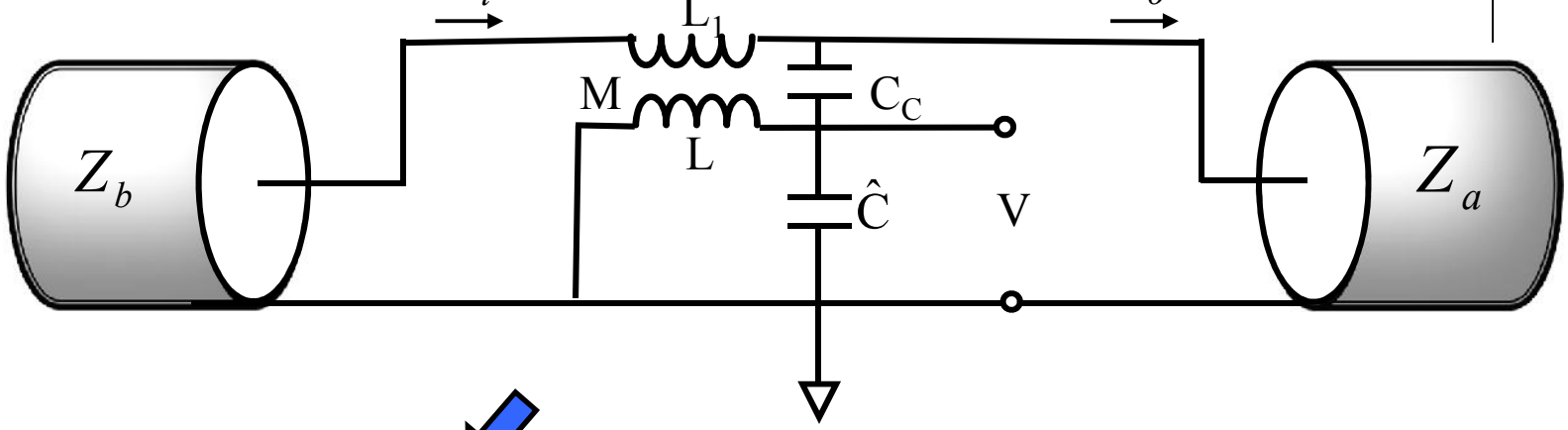


Lumped element resonators with parallel plate capacitor

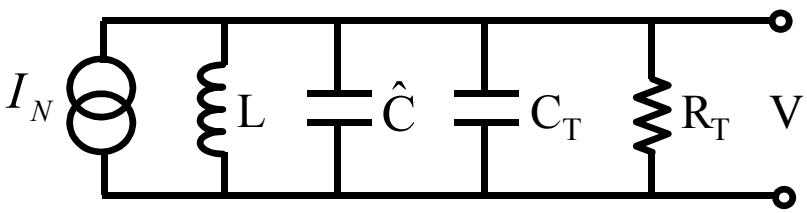


Equivalent model of the experimental device

voltage wave amplitudes: V_i^+ V_o^+



Norton Equivalent



Resonance Lineshape

$$S_{0i} = V_0^+ / V_i^+ = c\left(1 - \frac{Q/\tilde{Q}_e}{1 + i2Q(\omega - \omega_0)/\omega_0}\right)$$

FWHM= $1/Q$

$$Q^{-1} = \left(R^{-1} + R_T^{-1}\right)\omega_0 L$$

$i\omega\,\mathrm{Im}[\hat{C}]$ $\quad \frac{Z_a Z_b}{Z_a + Z_b}(\omega C_C)^2 + \frac{(M/L)^2}{Z_a + Z_b}$

Resonance Frequency

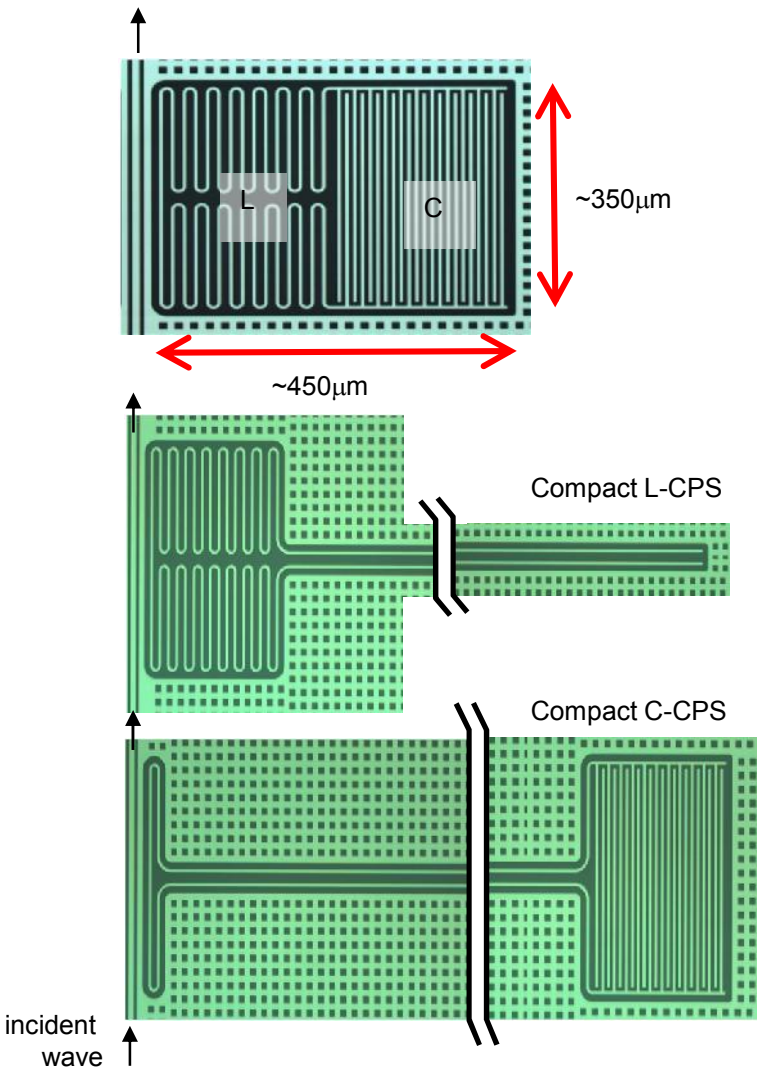
$$\omega_0 = 1/\sqrt{L(C + C_T)}$$

Obtain internal quality $Q_i \equiv R/(\omega_0 L)$

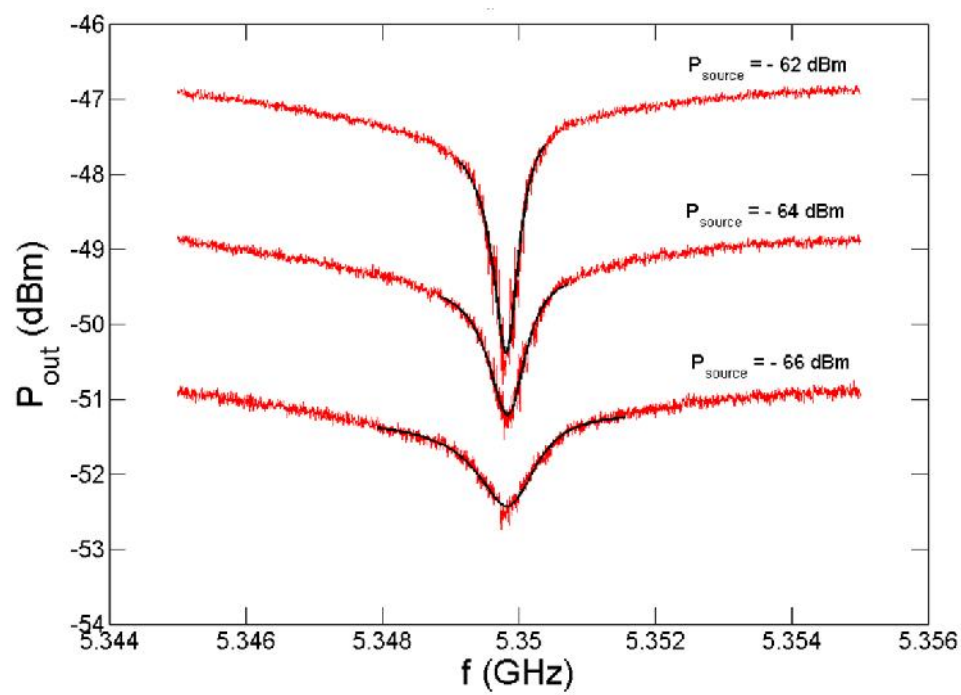
with fit parameters : $Q_i^{-1} = Q^{-1} - \mathrm{Re}(\tilde{Q}_e^{-1})$

$$\omega_0 L\left(R_T^{-1} + i\omega_0 C_C \frac{M}{L}\frac{Z_b - Z_a}{Z_b + Z_a} + \ldots\right)$$

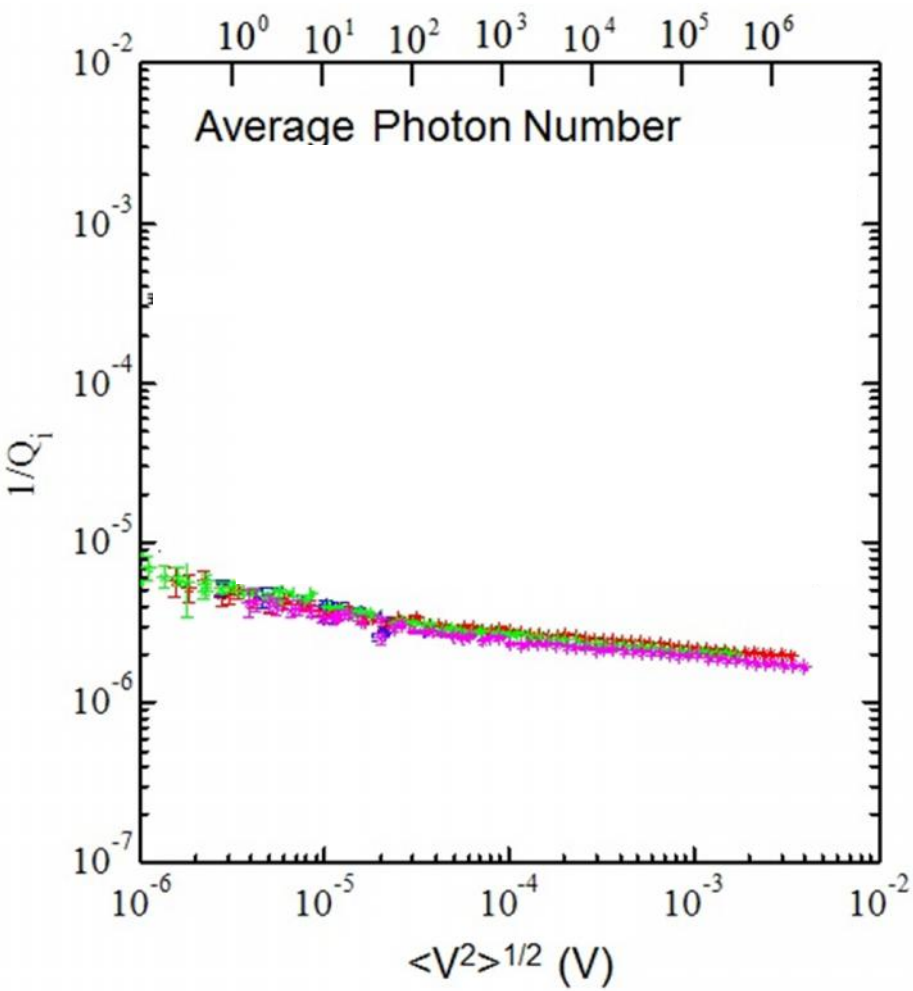
Coplanar resonators



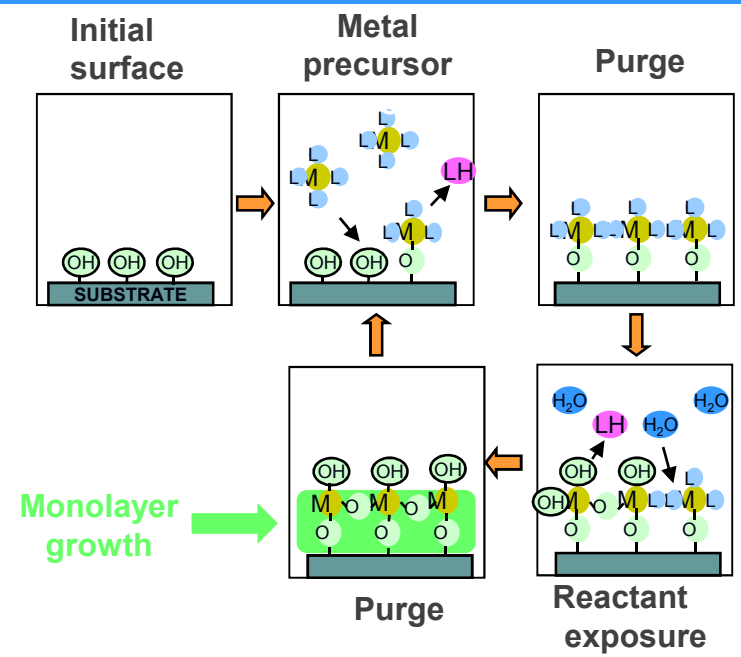
$$\left|V_0^+/V_i^+\right|^2 = c^2\left|1-\frac{Q/\tilde{Q}_e}{1+i2Q(\omega-\omega_0)/\omega_0}\right|^2$$

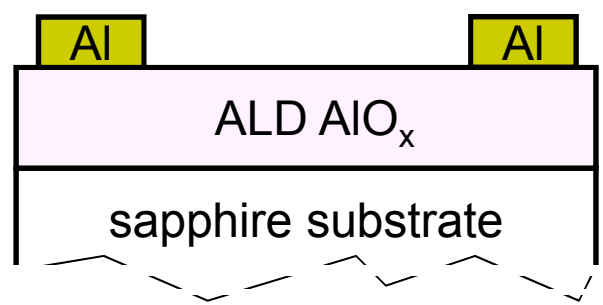


ALD dielectric research with coplanar resonators



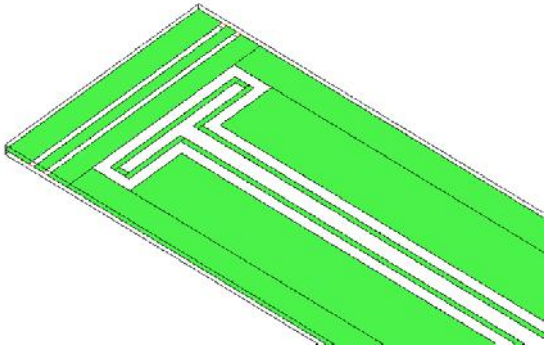
Process sequence during one ALD cycle





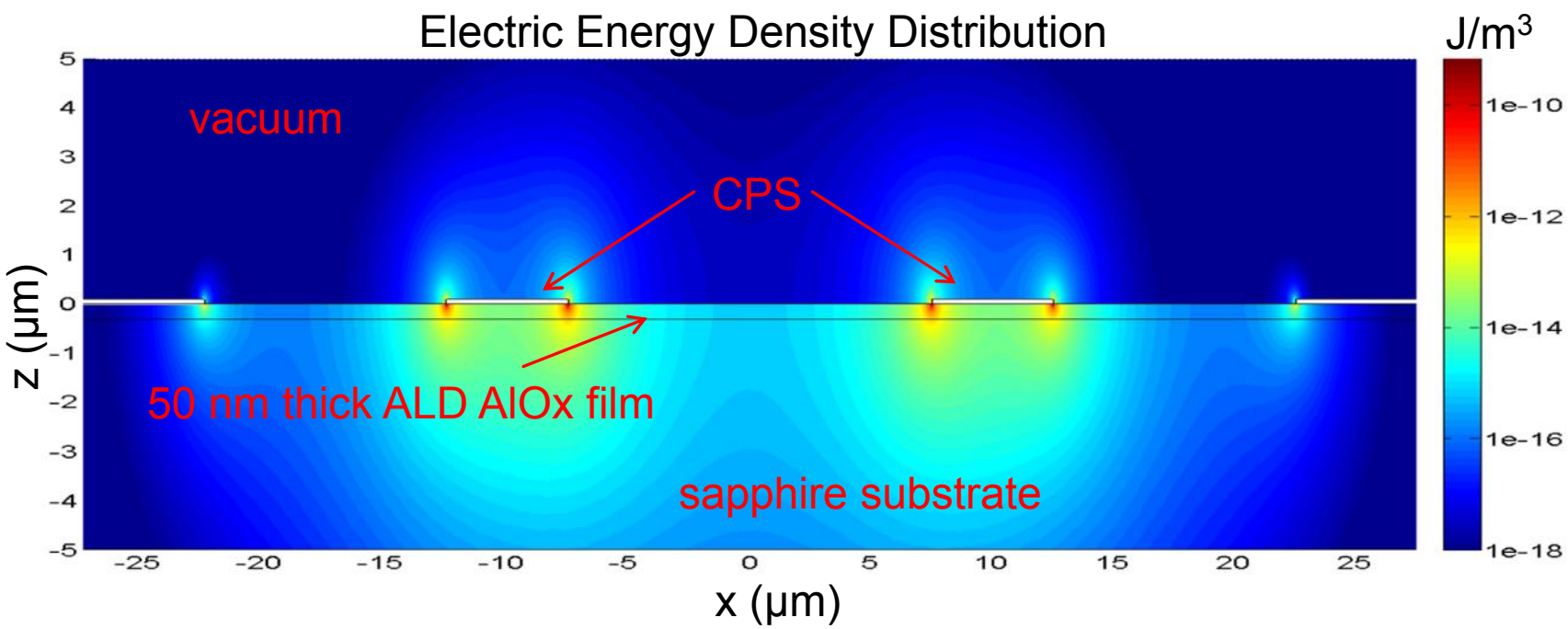
Simulation of electric field distribution

Coplanar Strip (CPS)



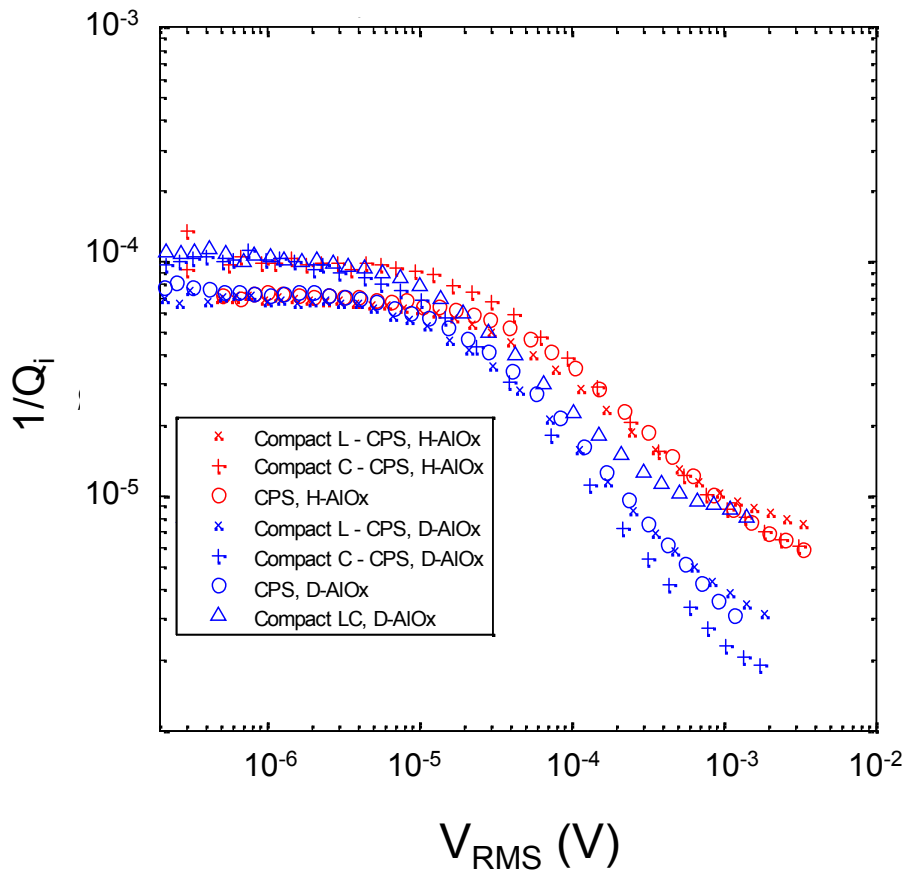
$$\frac{1}{Q_S} = F \tan \delta_s$$

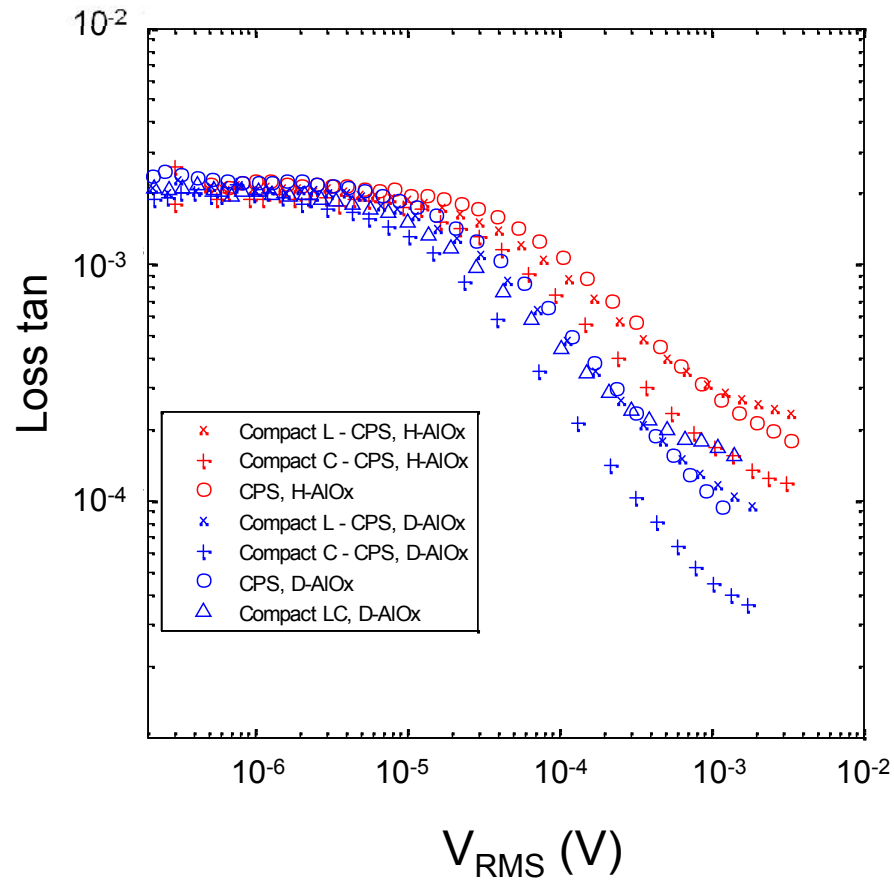
$$F = \frac{\int_{V_h} \varepsilon_h \vec{E}\left(\vec{r}\right)^2 d\vec{r}}{\int_V \varepsilon \vec{E}\left(\vec{r}\right)^2 d\vec{r}} = \frac{w_h^e}{w^e} = \frac{\text{Energy Stored in Lossy Volume}}{\text{Total Energy Stored in Resonator}}$$



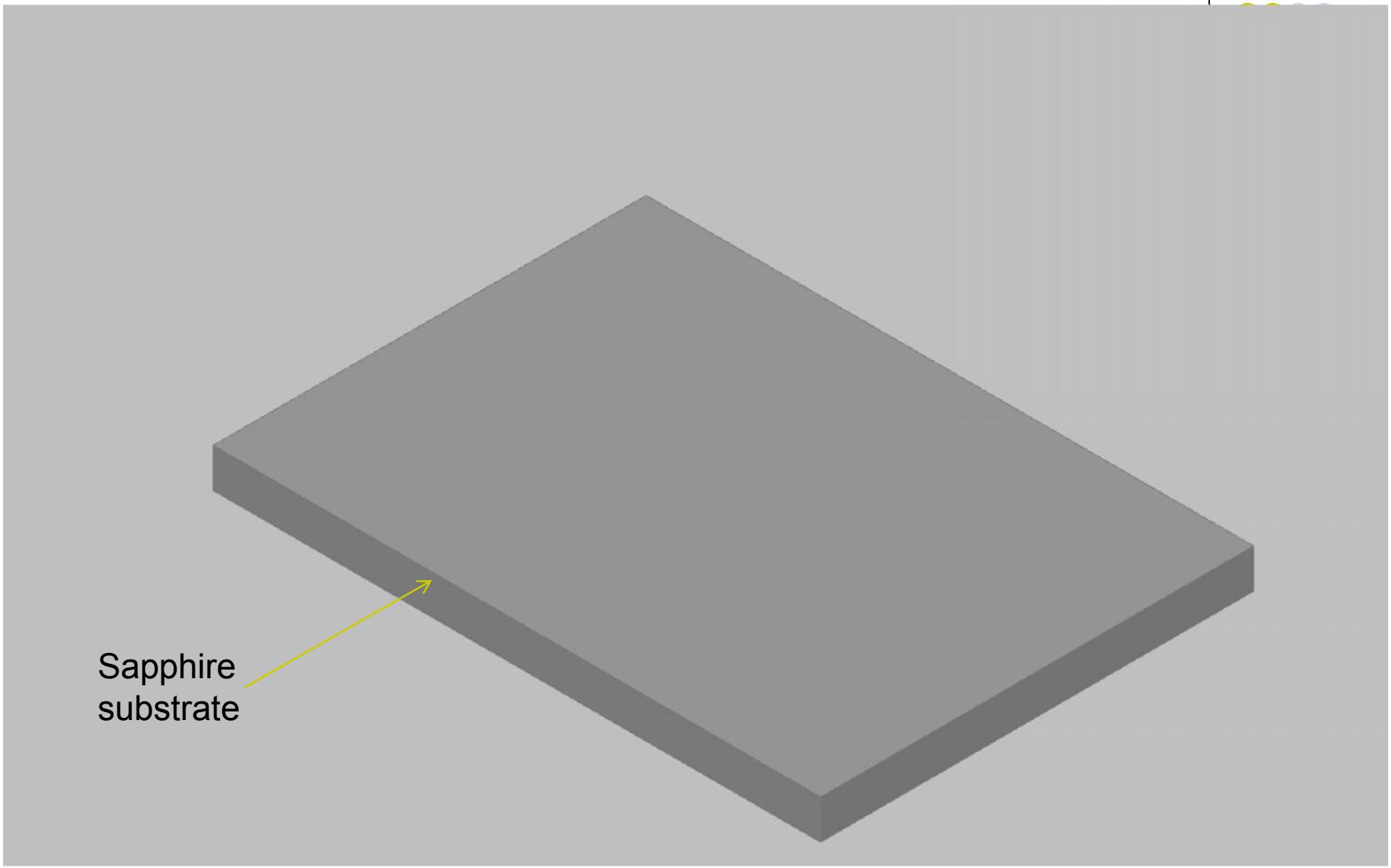
Loss tangent of ALD AlOx

$$\frac{1}{Q_i} = \frac{\int_{\substack{Lossy \\ Volume}} \varepsilon(r) E^2 \tan\delta(r,E)\, d^3r}{\int_{\substack{Total \\ Volume}} \varepsilon(r) E^2\, d^3r}$$

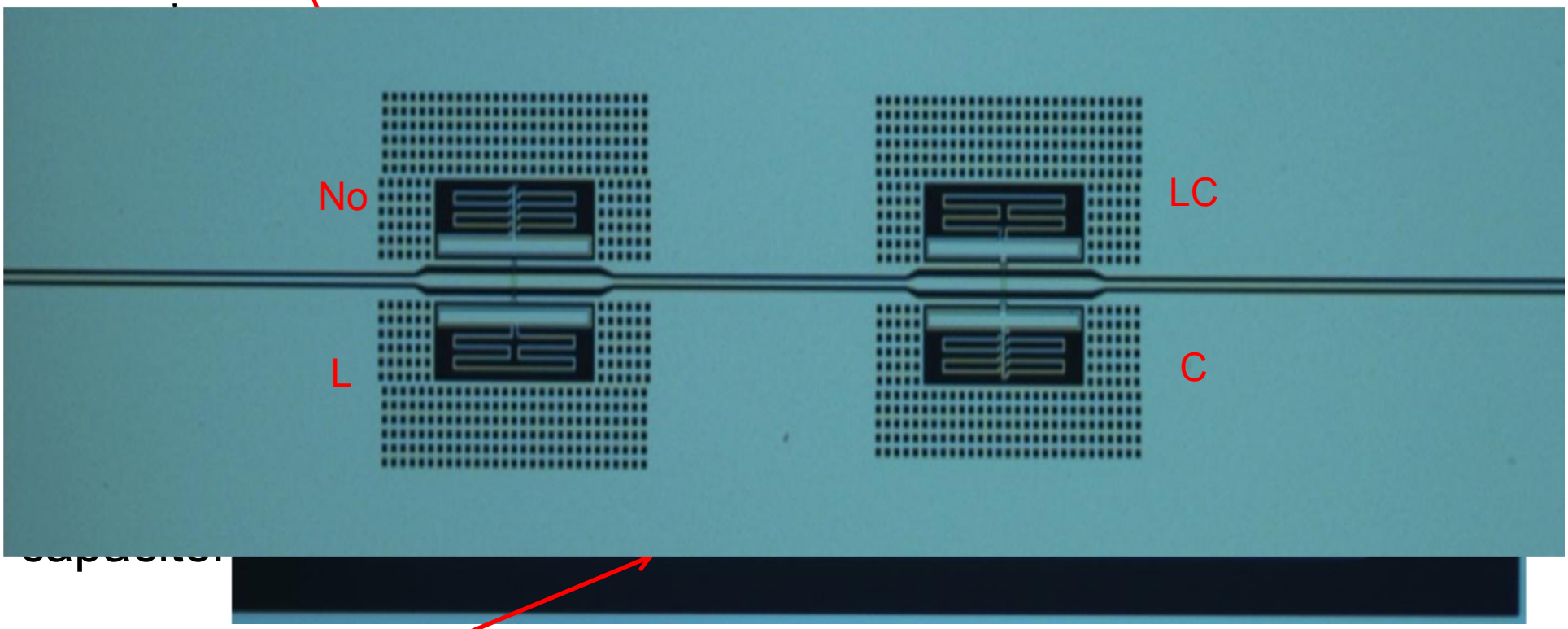




Fabrication of the parallel plate capacitor superconducting resonator



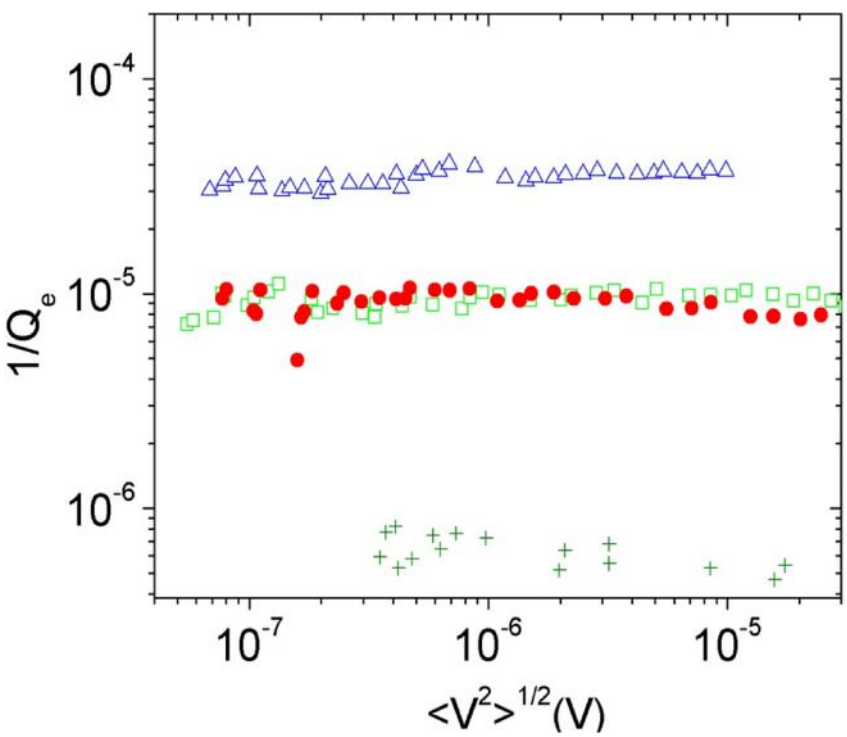
Fabrication of the superconducting resonator

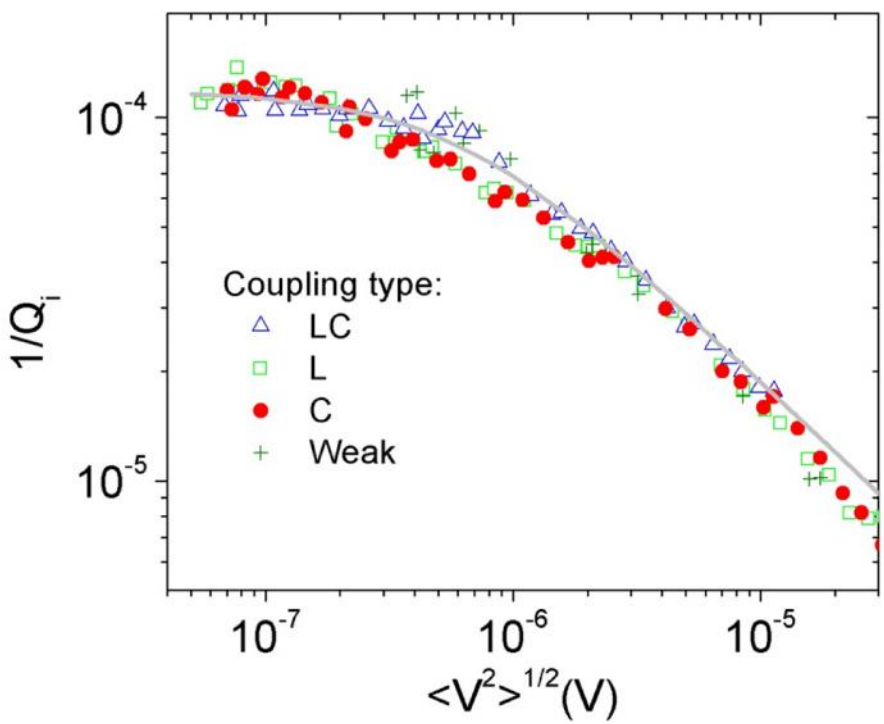


Coupling strength of the microwave resonators

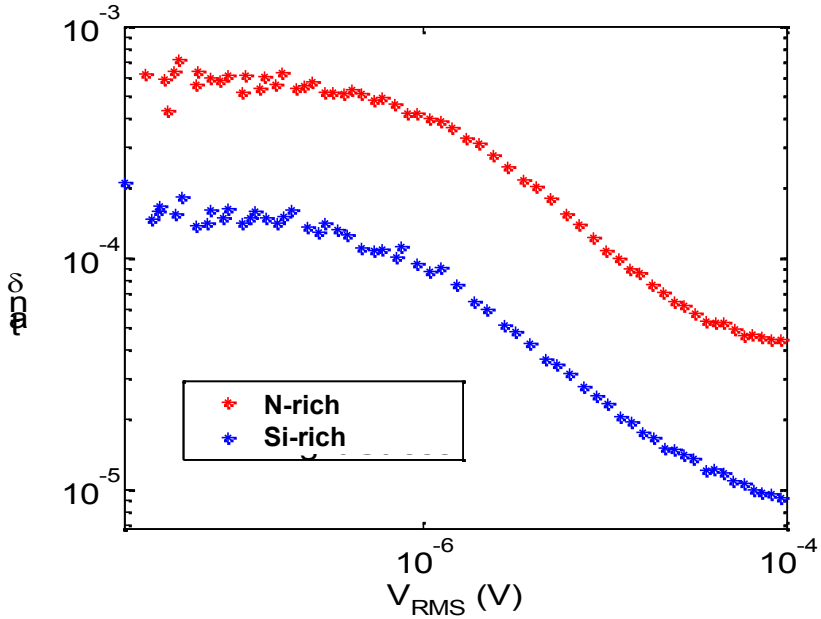
Qe describes interaction of resonator with the transmission line and inversely proportional to square of coupling coefficient.

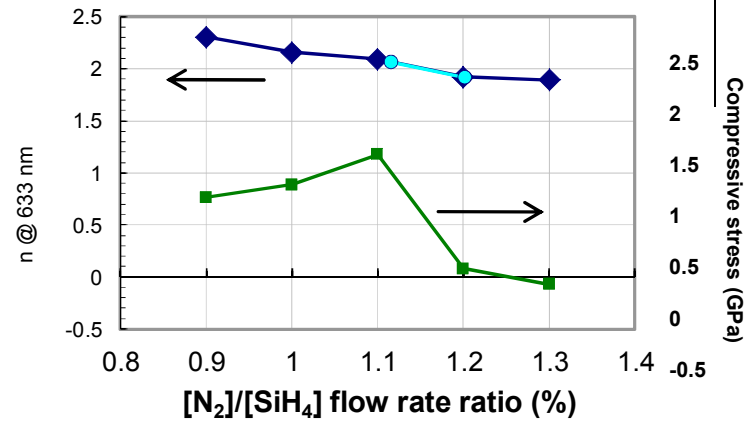
Internal quality factor is defined by $Q_i^{-1} = \tan\delta(V)$ and attributed to the dielectric loss in capacitor.





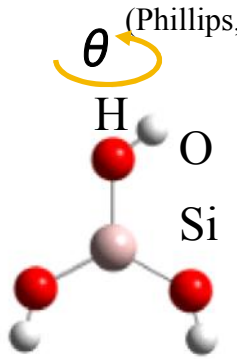
TLS in amorphous SiN_x



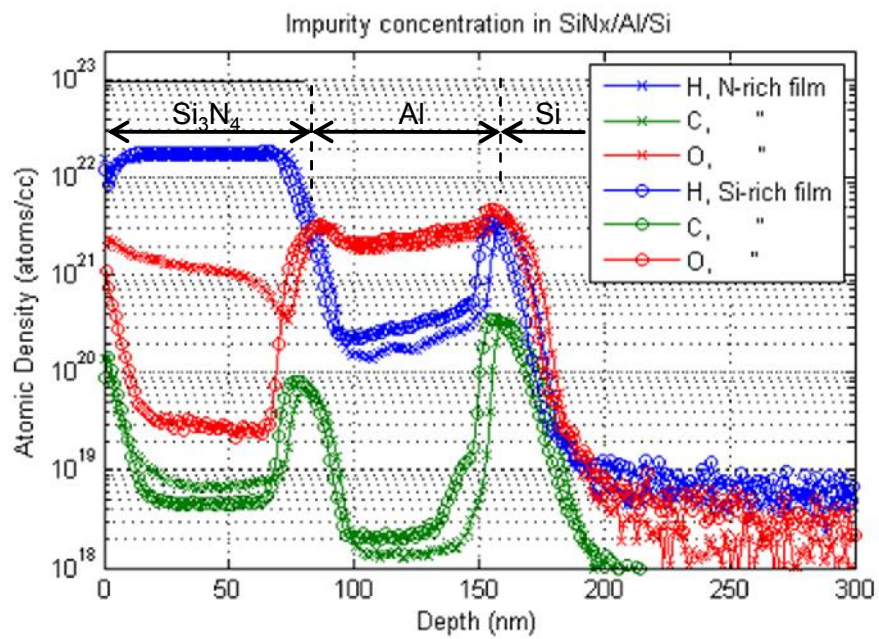


$$3\ SiH_4 + 4\ NH_3 \rightarrow Si_3N_4 + 12\ H_2$$

"Classic" TLS model: OH rotor (point defect)
(Phillips, 1981; Hutt, Phillips, Butcher, 1989)



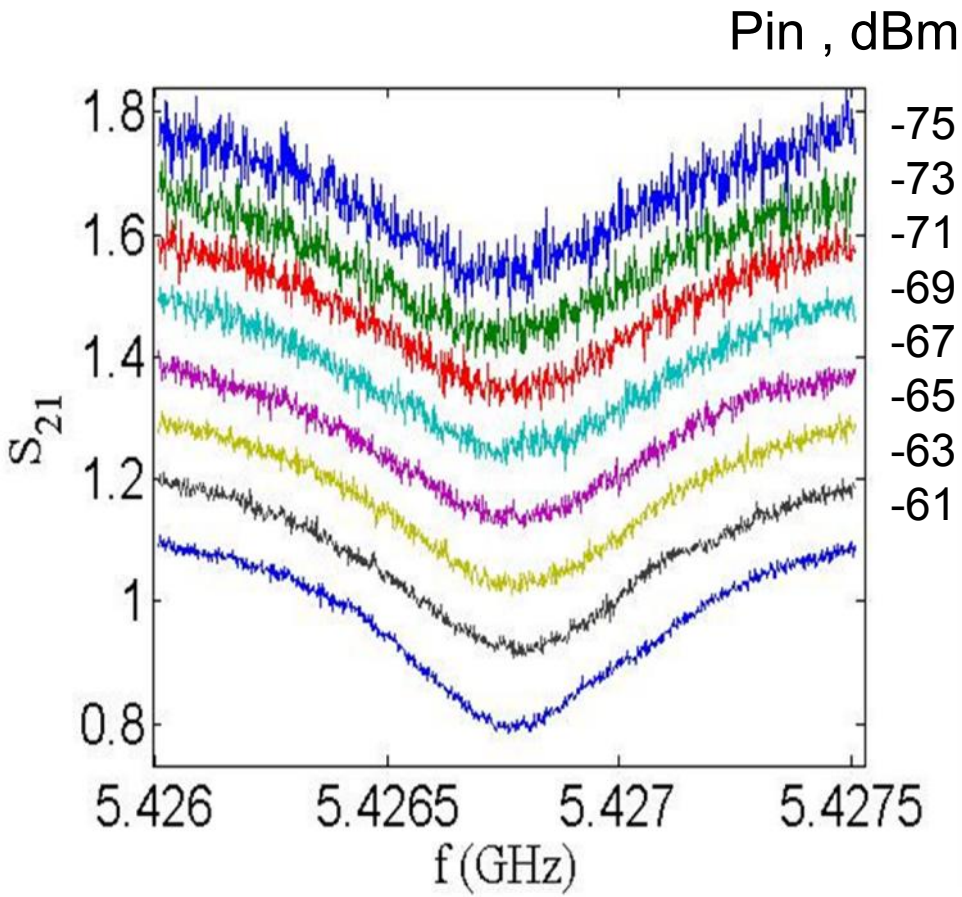
C. Musgrave (CU): similar to a $Al(OH)_3$ defect model for AlO_x:H



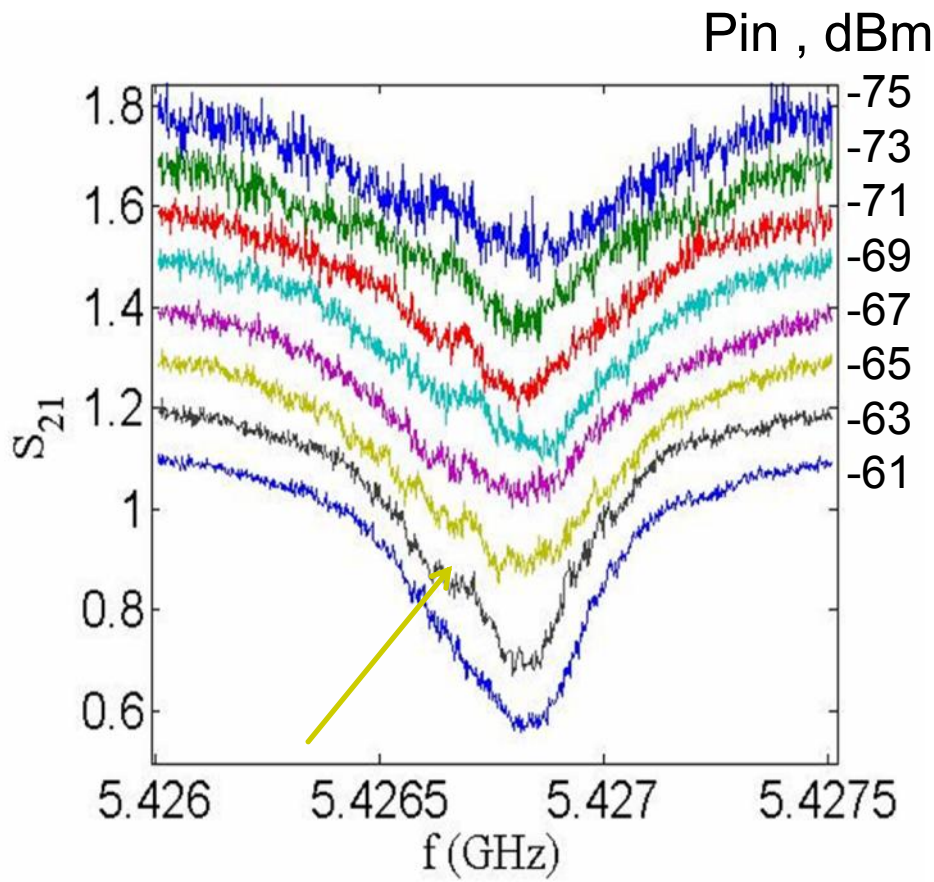
Oxygen concentration is correlated with loss.
UCSB a-Si has similar O concentration as Si-rich SiNx.

Raw experimental data

T=100 mK

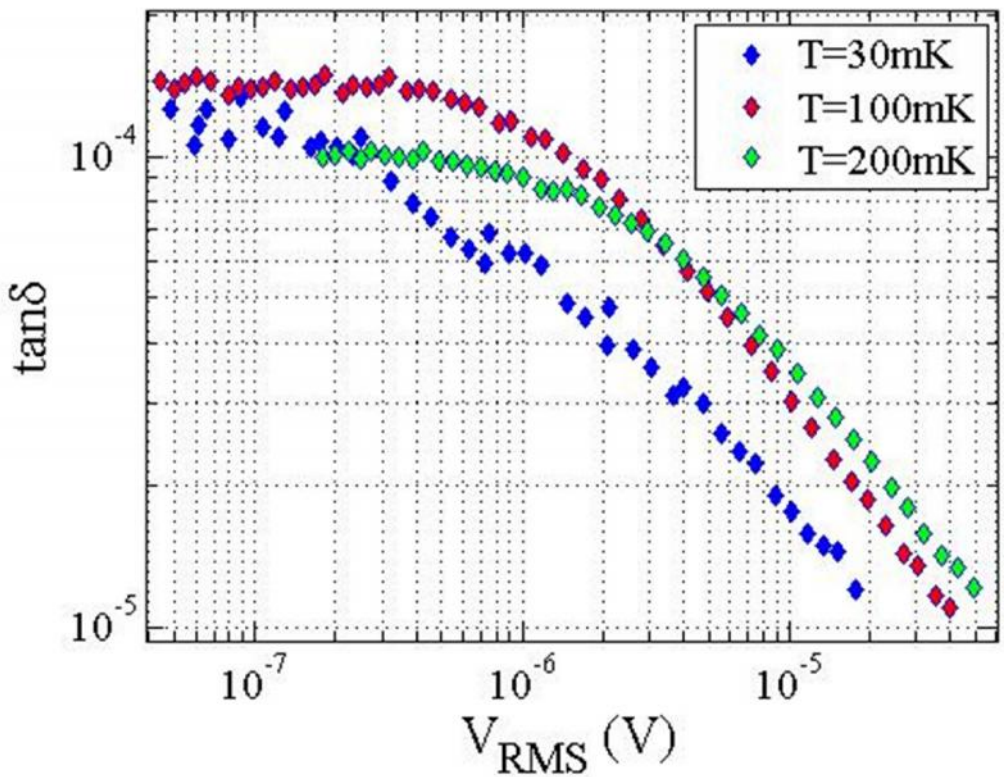


T=40 mK



Dielectric loss versus microwave voltage

Sample #1



$$\delta_{\mathrm{TLS}} = \frac{\epsilon''_{\mathrm{TLS}}(\omega)}{\epsilon}$$

$$\epsilon''_{TLS}(\omega) \approx \frac{\pi P d_0^2}{3} \frac{tanh\left(\frac{\hbar\omega}{2kT}\right)}{\sqrt{(1+\Omega^2 \mathrm{T}_1 \mathrm{T}_2)^{\beta}}}$$

$$\Omega = 2\vec{d} \cdot \vec{E}/\hbar$$

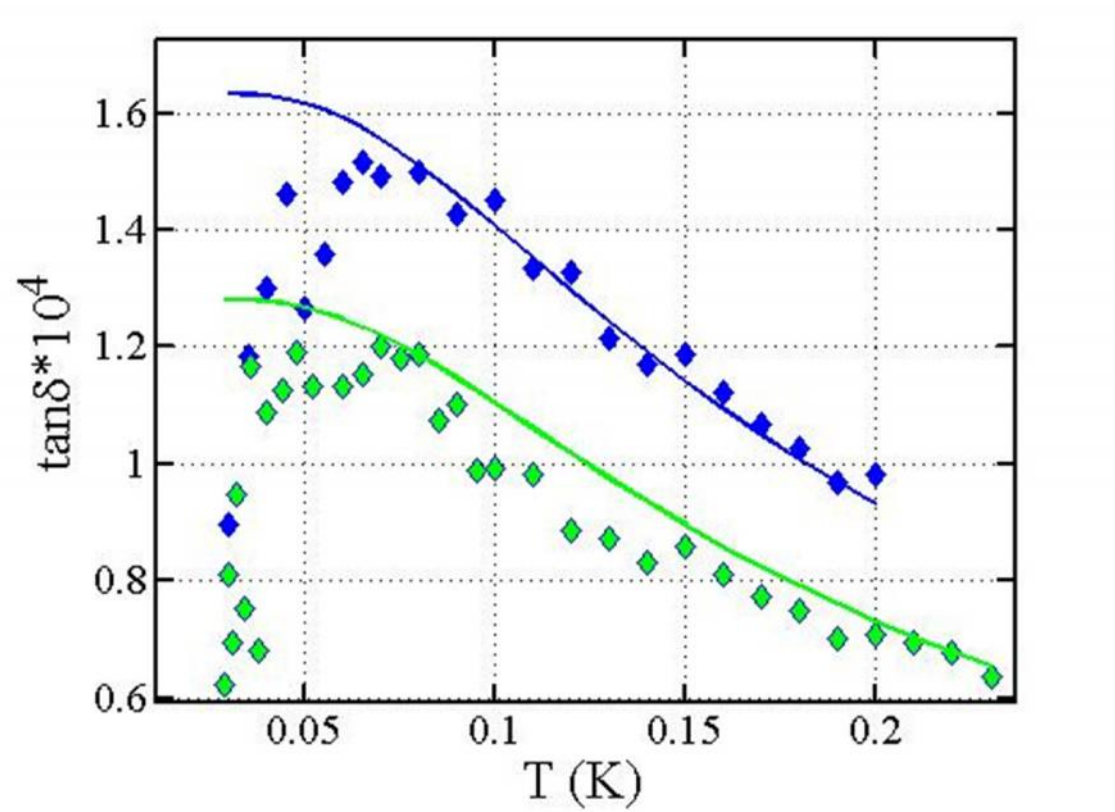
$$T_1^{-1} = \left(\frac{\Delta_0}{\varepsilon}\right)^2 \left[\frac{\gamma_L^2}{v_L^5} + \frac{\gamma_T^2}{v_T^5}\right] \frac{\varepsilon^3}{2\pi\rho\hbar^4} coth\left(\frac{\varepsilon}{2kT}\right)$$

$$T_2^{-1} = C \frac{2\gamma^2 PkT^{\alpha}}{\pi\hbar\rho v^2} \frac{\Delta}{\varepsilon} \qquad 1 \leq \alpha \leq 2$$

Lyo S.K: Phys.Rev.Lett. 48, 688 (1982)

$\alpha = 1.8$

Dielectric loss versus temperature



- Sample #1
- Sample #2

$V_{RMS} = 2*10^{-7}V$

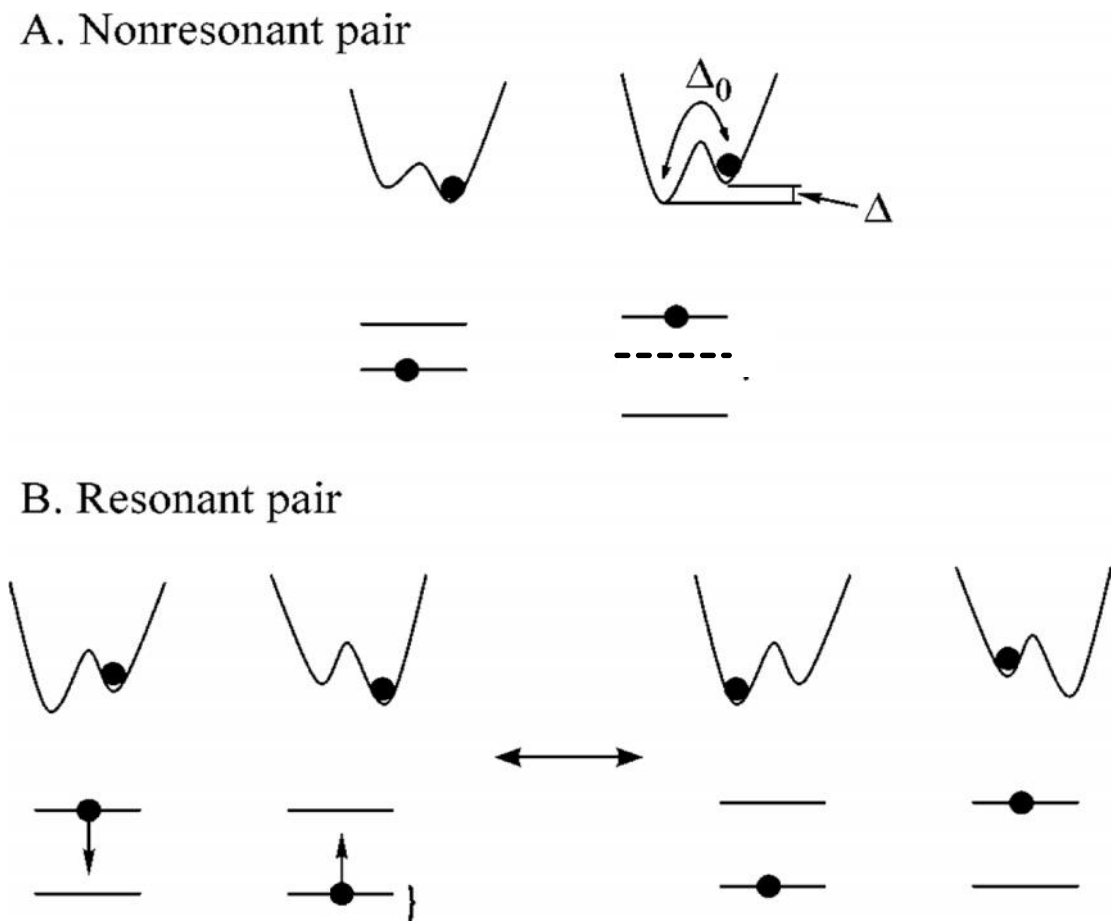
$1 >> \Omega^2 T_1 T_2$

$$\epsilon''_{TLS} \approx \frac{\pi P d_0^2}{3} \frac{\tanh\left(\frac{\hbar\omega}{2kT}\right)}{\sqrt{1+\Omega^2 T_1 T_2}}$$

Crossover temperature:
$T(SiO_2) \sim 30mK$
$T(SiO_x) \sim 100mK$

A.L.Burin JLTP 100, 309 (1995)

Delocalized collective excitation

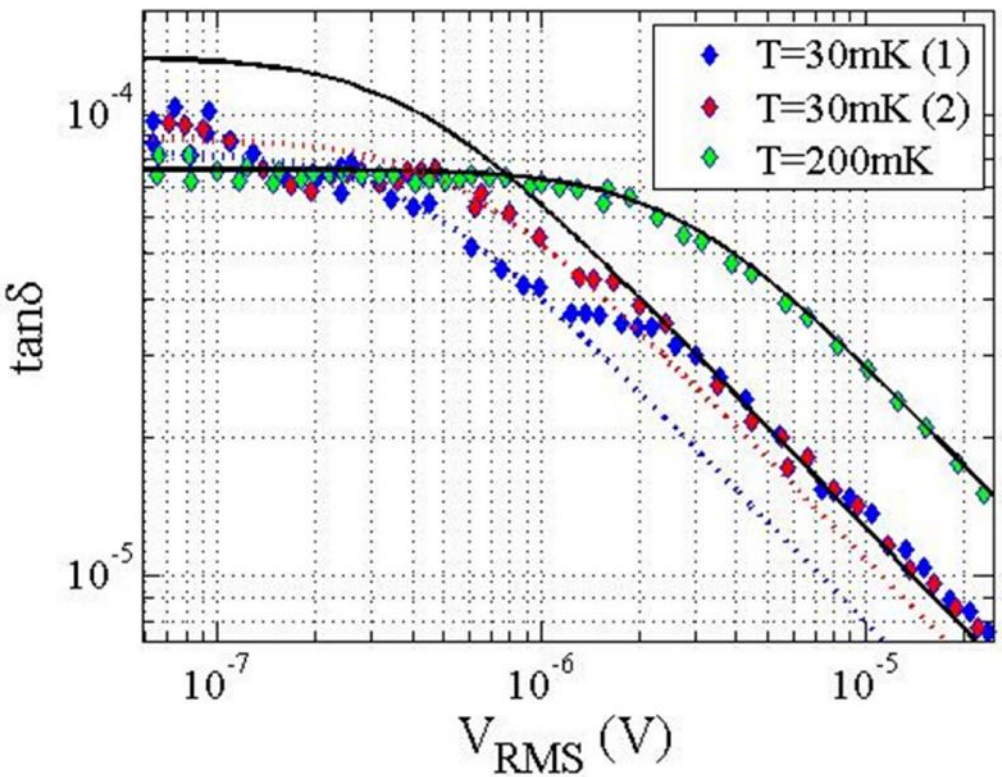


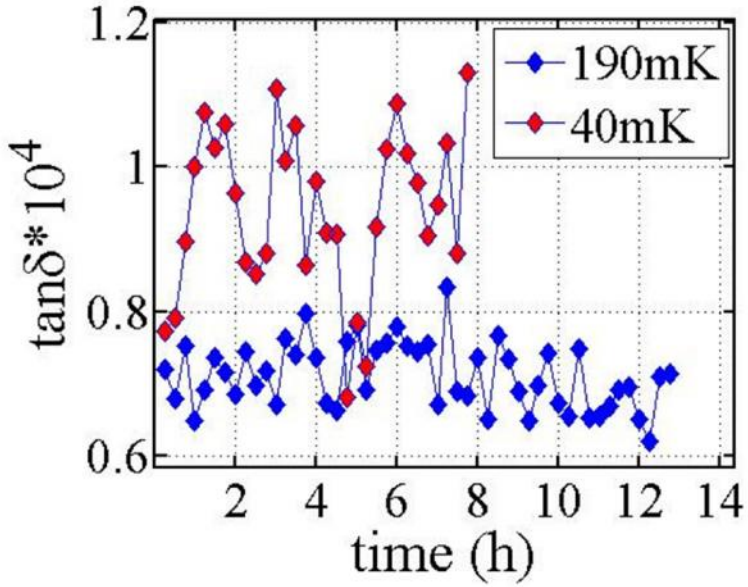
Energy transport is not efficient in the off resonance (A) case where the energy Level mismatch exceeds the resonant interval. For resonant pair (B) interaction induce flip-flop transition.

A.L.Burin, L.A.Maksimov, and I.Ya. Polischuk JETP Lett.80, 513 (2004)

Fluctuation of the dielectric loss in non-saturated TLS regime

Sample #2

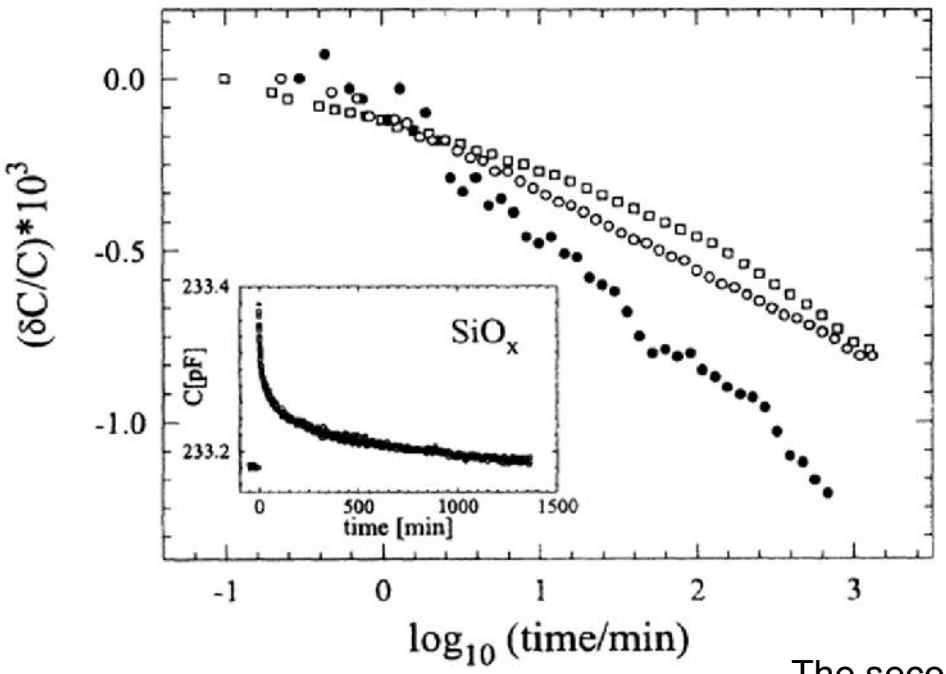




Measurements of conductance fluctuations in amorphous metals Indicate that TLS interact

G.A.Garfunkel et al. Phys. Rev. B 40, 8049 (1989)

Low temperature dielectric response of glasses to DC electric field



The relaxation and resonance response of dielectric susceptibility expected

Instantaneous rise with log relaxation of the density of states insures the same behavior for AC dielectric constant. The logarithmic character of relaxation contribution described by logarithm spectrum of TLS relaxation times.

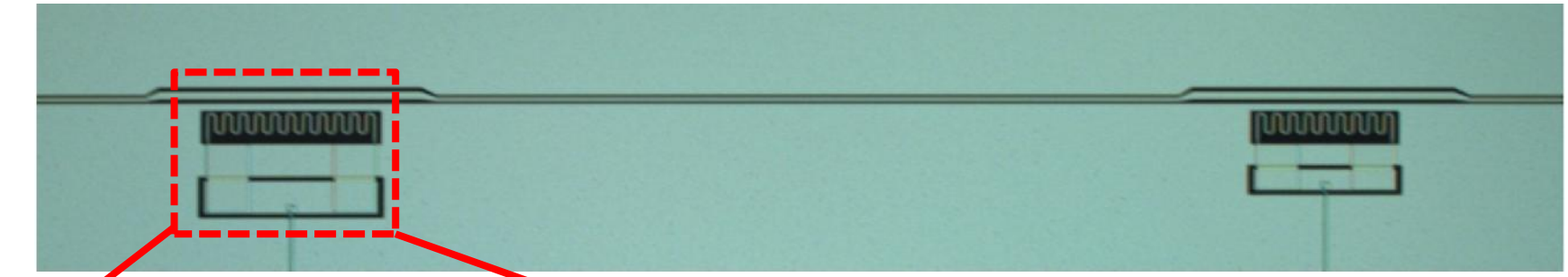
$$\delta\varepsilon_{\mathrm{ad}} = \frac{4\pi p_0^2 P_0}{3}(\phi_0/4T)\log(\tau_{\max}/t)$$

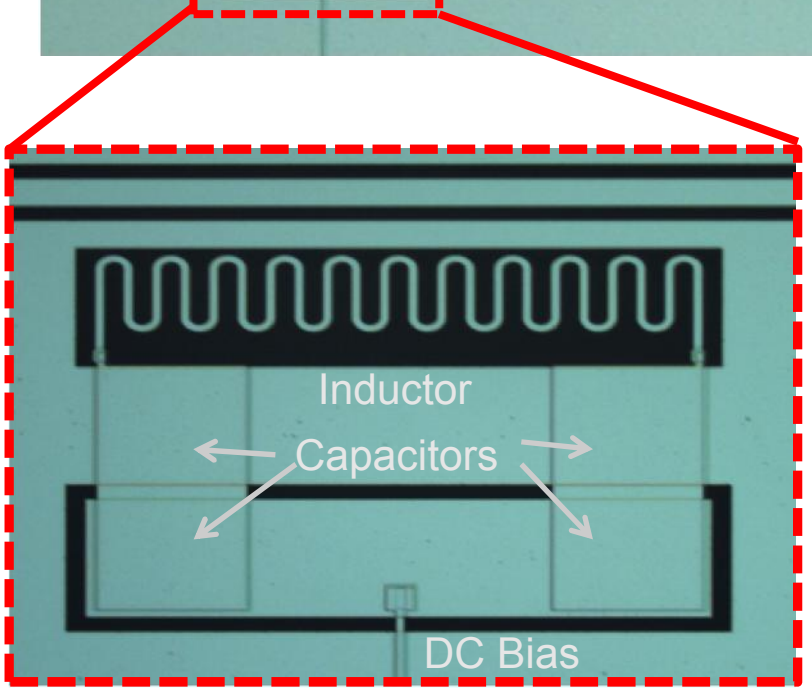
The second contribution caused by relaxation of TLS population differences, there is a resonance component with relaxation time proportional to 1/t.

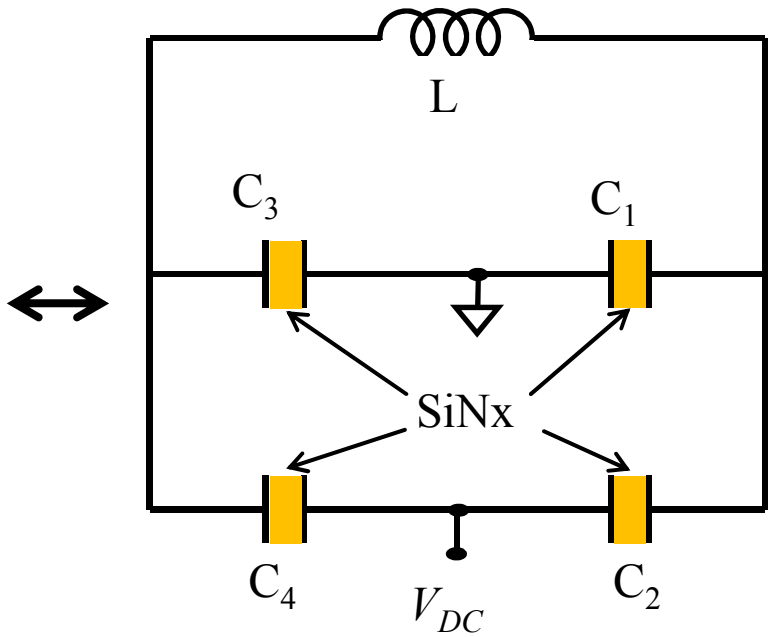
No resonance contribution to dielectric susceptibility has been found

$$\delta\tan(\delta)(t) = \frac{\pi P_0}{6k_\omega t}\left\langle \mu^2\left[\tanh\left(\frac{|\boldsymbol{F}_0\boldsymbol{\mu}|}{2T}\right) - \tanh\left(\frac{\hbar\omega}{2T}\right)\right]\right\rangle$$

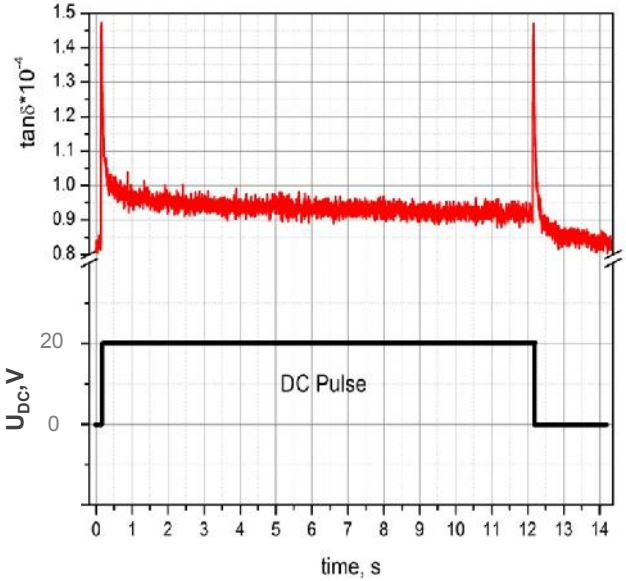
Superconducting resonator with DC bias







Response of resonance absorption of SiN_x in the presence of swept DC field

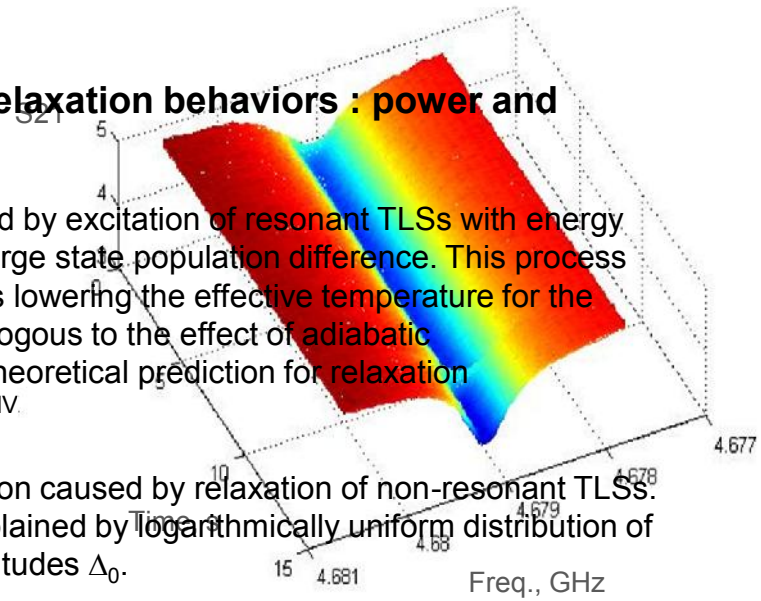


DC pulse amplitude = 20V ~ 40MV

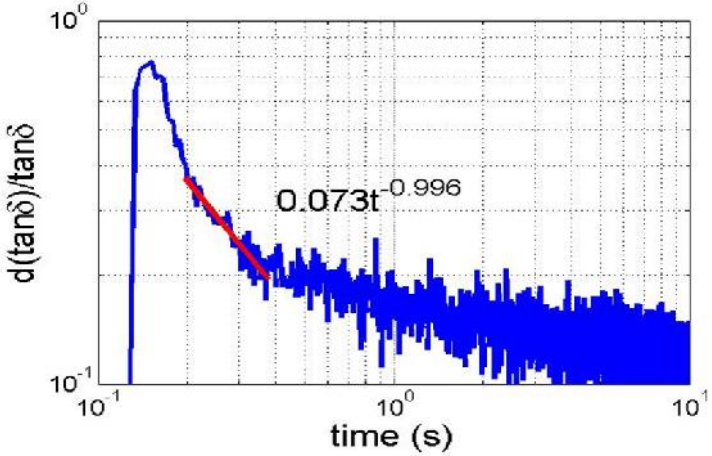
Two observed relaxation behaviors : power and logarithmic.

First process caused by excitation of resonant TLSs with energy $\varepsilon \sim \Delta_0$ leading to a large state population difference. This process can be described as lowering the effective temperature for the resonant TLSs analogous to the effect of adiabatic demagnetization. Theoretical prediction for relaxation time is t^{-1} [2].

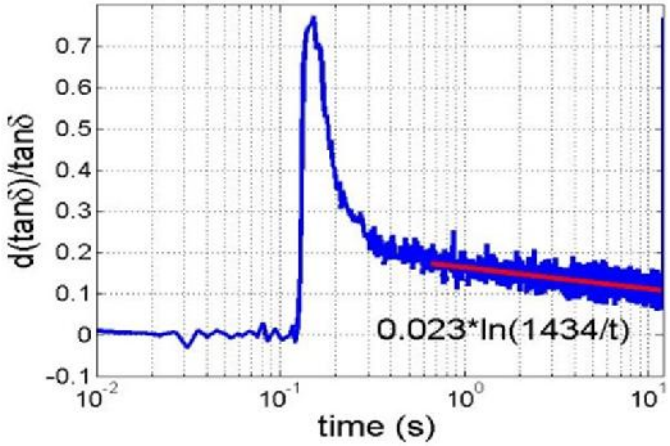
Logarithmic relaxation caused by relaxation of non-resonant TLSs. This law can be explained by logarithmically uniform distribution of TLS tunneling amplitudes Δ_0.



Resonant relaxation

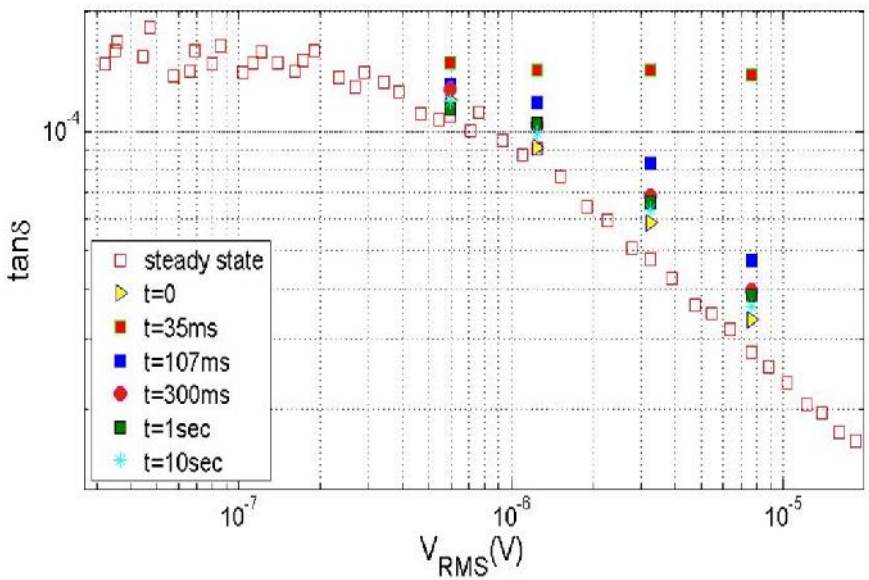


Non-resonant relaxation

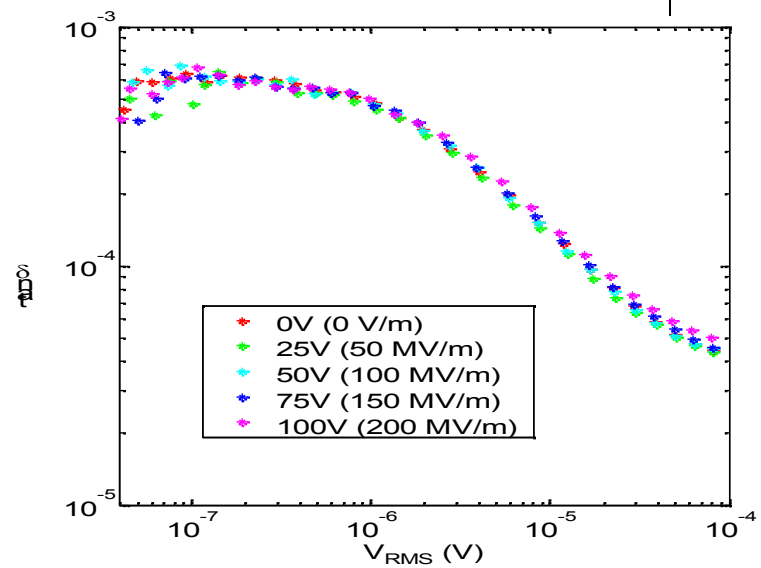


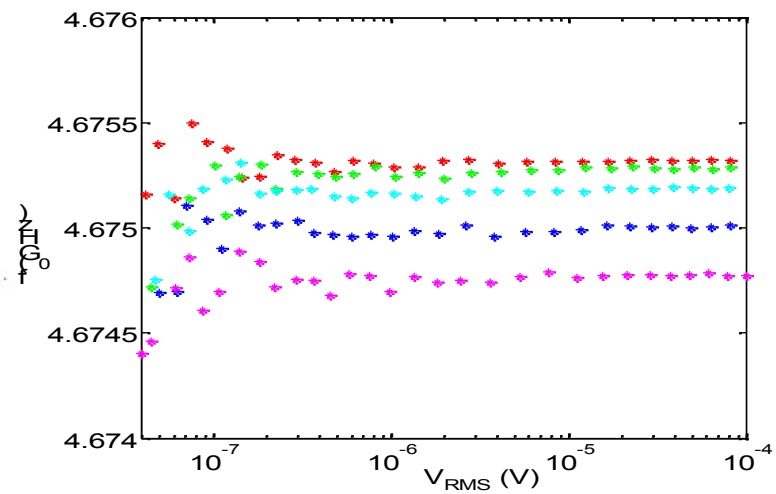
Dielectric loss for different delay time after DC pulse application

Pulse turned on at t=0 (rise time~20ms)



Steady state measurement





Loss tangent increases at sudden DC voltage step then decays as 1/t and logarithmically. The dielectric permittivity (~ f^{-2}) changes instantaneously to the steady state value, which is shown to the left, after the step.

$$\delta\varepsilon'(t) = \frac{4\pi^2}{9}(P_0 p_0^2)(P_0 U_0)\log(\phi/T)\,\underline{\log(\alpha T^2\phi/\omega)}\,\log(\tau_{max}/t),$$

$$\delta\varepsilon''(t) = \frac{2\pi^3}{9}(P_0 p_0^2)(P_0 U_0)\log(\phi/T)\log(\tau_{max}/t),$$

[1] H. Paik and K. D. Osborn, Appl. Phys. Lett. 96, 072505 (2010).
[2] A.L.Burin JLTP 100, 309 (1995)

Summary

- We studied sources of decoherence in the superconducting qubits mainly focusing on the two level defect states in amorphous dielectrics.

1. *We measured the dielectric loss of ALD deposited AlOx. That is the same order of magnitude as the loss found for another amorphous oxides.*
2. *The dominant contribution of the native oxide loss has been found for the coplanar resonator deposited on the crystalline sapphire.*
3. *We have demonstrated that the OH rotor is the main source of loss in amorphous SiNx.*
4. *We found evidence of interaction between two-level defects states in amorphous SiNx. We suppose this interactions can lead to delocalized collective excitation at sufficiently low energy.*
5. *We measured AC susceptibility response on the DC field and found the clear proof of the both relaxation and resonant TLSs contribution to dielectric function.*
6. *The discrepancy between theory and experiment found in the behavior of real component of dielectric function.*

Superconductor loss

$$L = L_0 + L_{ki} \approx L_m + L_{ki}.$$

$$L_K = \mu_0 \lambda^2 / d,$$

$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

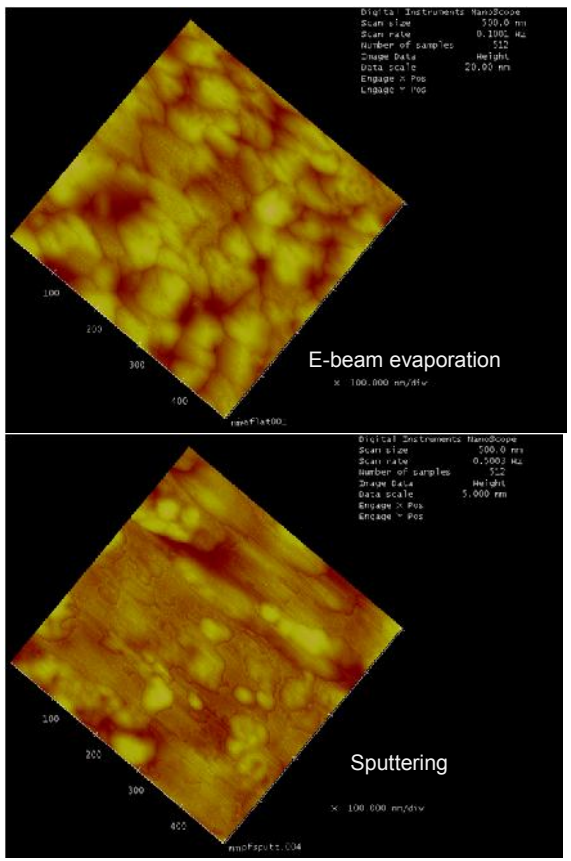
ξ_0 >> *d,l*

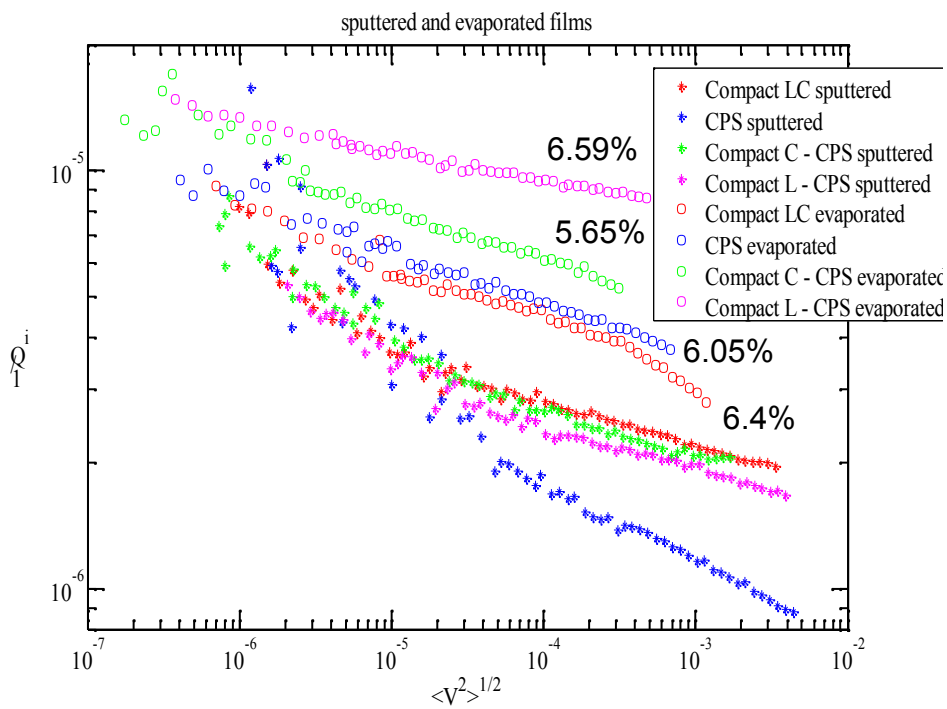
Effective penetration depth

$$\lambda_{eff}(l,T) = \lambda_L(T)\left(\frac{\xi_0}{l}\right)^{1/2}[J(0,T)]^{-1/2}$$

$$\lambda_{eff}(l,T) = \lambda_L(T)\left(\frac{\xi_0}{d}\right)^{1/2}[J(0,T)]^{-1/2}$$

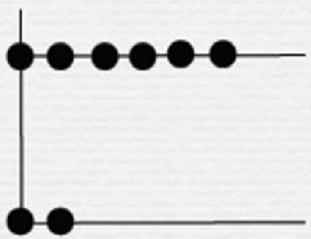
l – mean free path
d - thickness





Effect of TLS-TLS interaction

independent TLSs

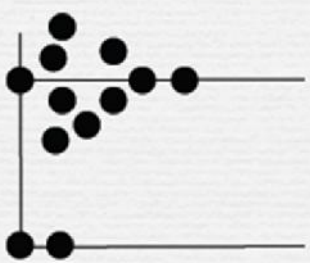


high power - TLSs saturation
small absorption

$$H(t) = \sum_i \varepsilon_i S_z^i + 2\frac{\vec{d}_0^i \cdot \vec{E}}{\varepsilon_i}\Delta_0^i \cos(\omega t) S_x^i + 2\frac{\vec{d}_0^i \cdot \vec{E}}{\varepsilon_i}\Delta_i \cos(\omega t) S_z^i + \sum_{j \neq i} J_{ij}\vec{S}_i \cdot \vec{S}_j$$

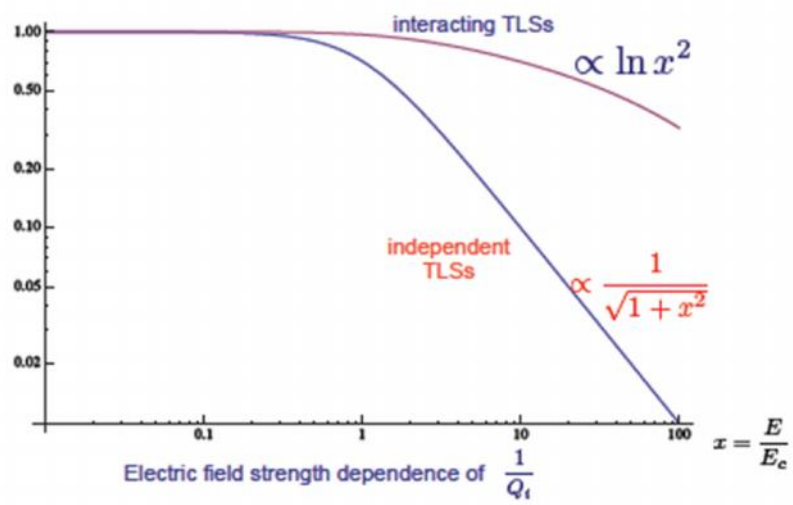
TLSs interacting with the electric field — TLS-TLS interaction

interacting TLSs



high power - dispersion -
with a given frequency it is very difficult
to saturate them

$$\frac{1}{Q_i} = F\delta_{TLS}^0 \tanh\left(\frac{\omega}{2KT}\right) T\nu_0 \int \frac{d\gamma}{\gamma} \frac{1}{\sqrt{1 + \frac{T_1 T_2 \Omega^2}{1+\gamma T_1}}}$$



Electric field strength dependence of $\frac{1}{Q_i}$