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

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Outline:

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

\[ T_1 = \text{Relaxation time} \]

\[ \frac{1}{T_1} - \text{radiation to the environment} \]

\[ T_2 = \text{Dephasing time} \]

\[ \frac{1}{T_2} - \text{parameter fluctuations} \]

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

Interlayer Dielectric
(stores energy, 250 nm thick, a-Si is also used)

AIO_x Josephson Junction Barrier
(thermally grown, in almost all qubits, 2 nm thick)

Interfaces/Surfaces*

Trialayer JJ
~ µm

Sapphire
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.

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

$$\Delta = \sqrt{\Delta^2 + \Delta_0^2}.$$
**TLS contribution to the dielectric function**

Hamiltonian of TLS in the electric problem

\[ H = H_0 + H_{\text{int}} \]

\[ H = -\hbar \gamma \vec{B} \cdot \vec{S} = -\hbar \gamma (\vec{B}_0 \cdot \vec{S}) - \hbar \gamma (\vec{B}' \cdot \vec{S}) \]

Hamiltonian of a spin 1/2 system in a magnetic field

Correspondence between TLS and spin system:

\[ \vec{d}' = 2d_0 \frac{\Delta}{\varepsilon} \quad \vec{d} = \frac{\Delta_0}{\varepsilon} \]

Resonant TLS contribution to the (isotropic) dielectric function:

\[ \varepsilon_{\text{TLS}}(\omega) = \int \int \left[ \varepsilon \cdot \chi_{\text{res}}(\omega) \cdot \varepsilon \right] \frac{P}{\Delta_0} d\Delta d\Delta_0 d\varepsilon = \varepsilon_{\text{TLS}}(\omega) - j\varepsilon''_{\text{TLS}}(\omega) \]

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

**Weak fields**  \( \Omega^2T_1T_2 \ll 1 \)

**Strong fields**  \( \Omega^2T_1T_2 \gg 1 \)

\[ \frac{\Omega}{\Delta_0} = \frac{2d_0|\vec{E}|}{\sqrt{3}h} \frac{\Delta_0}{\varepsilon} \]

Rabi frequency
Approximations of strong and weak fields

Weak field

\[
\delta_{\text{TLS}} = \frac{\epsilon'_{\text{TLS}}(\omega)}{\epsilon} = \delta_{\text{TLS}}^0 \tanh \left( \frac{\hbar \omega}{2k_B T} \right)
\]

\[
\frac{\epsilon'_{\text{TLS}}(\omega)}{\epsilon} = -\frac{2\delta_{\text{TLS}}^0}{\pi} \left[ \text{Re}\Psi \left( \frac{1}{2} - \frac{\hbar \omega}{2j\pi k_B T} \right) - \log \frac{\varepsilon_{\text{max}}}{2\pi k_B T} \right]
\]

Field Dependence of TLS Loss

\[
\frac{1}{\sqrt{1 + \Omega^2 T_1 T_2}} \times \text{Im} \left[ \frac{1}{\omega - \omega + jT_2^{-1}} \right] = \frac{-T_2^{-1}}{T_2^{-1} \sqrt{1 + \Omega^2 T_1 T_2} + (\omega - \omega)^2}
\]

\[
\delta_{\text{TLS}} = \delta_{\text{TLS}}^0 \frac{\tanh \left( \frac{\hbar \omega}{2k_B T} \right)}{\sqrt{1 + \Omega^2 T_1 T_2}}
\]

\[
E_c = \frac{\sqrt{3} \hbar}{2d_0 |\tilde{E}| \sqrt{T_{1,\text{min}} T_2}}
\]

\[
\delta_{\text{TLS}}(|\tilde{E}|) = \frac{\delta_{\text{TLS}}(|\tilde{E}| = 0)}{\sqrt{1 + |\tilde{E}|/E_c}}^2
\]

\[
x = \frac{E}{E_c}
\]
Experimental setup

Dilution Refrigerator

\[ T = 4\,\text{K} \]
\[ 1.4\,\text{K} \]
\[ 30\,\text{mK} \]

RF setup for |\( S_{12} \)| measurement

- RF Source
- RF Analyzer

\[ T = 300\,\text{K} \]
\[ 4\,\text{K} \]
\[ 1.4\,\text{K} \]
\[ 30\,\text{mK} \]

\[ P_{\text{in}} \]
\[ Z_0 \]
\[ P_{\text{out}} \]
Resonance dielectric studies

Quasi-lumped element coplanar resonators

Lumped element resonators with parallel plate capacitor
Equivalent model of the experimental device

Voltage wave amplitudes:

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

Obtain internal quality \( Q_i \equiv R / (\omega_0 L) \) with fit parameters : \( Q_i^{-1} = Q^{-1} - \text{Re}(\tilde{Q}_e^{-1}) \)

\[
\omega_0 L(R_T^{-1} + i\omega_0 C_C \frac{M}{L} \frac{Z_b - Z_a}{Z_b + Z_a} + ...)
\]

\[
\text{FWHM} = 1/Q \\
Q^{-1} = (R^{-1} + R_T^{-1})\omega_0 L \\
i\omega \text{ Im}[\hat{C}] = \frac{Z_a Z_b}{Z_a + Z_b} (\omega C_C)^2 + \frac{(M/L)^2}{Z_a + Z_b}
\]

Norton Equivalent

Resonance Lineshape

\[
I_N \frac{L}{\hat{C}} \frac{1}{C_T} \frac{R_T}{V}
\]
Coplanar resonators

\[ \left| \frac{V_0^+}{V_i^+} \right|^2 = c^2 \left[ 1 - \frac{Q/\tilde{Q}_e}{1 + i2Q(\omega - \omega_0)/\omega_0} \right]^2 \]
ALD dielectric research with coplanar resonators

Process sequence during one ALD cycle

- Initial surface
- Metal precursor
- Purge

Monolayer growth
Simulation of electric field distribution

Coplanar Strip (CPS)

\[ \frac{1}{Q_s} = F \tan \delta_s \]

\[ F = \frac{\int_{V_h} \varepsilon_h \overline{E(r)^2} \, dr}{\int_{V_h} \varepsilon \overline{E(r)^2} \, dr} = \frac{w^e_h}{w^e} = \frac{\text{Energy Stored in Lossy Volume}}{\text{Total Energy Stored in Resonator}} \]

Electric Energy Density Distribution

- Vacuum
- CPS
- 50 nm thick ALD AlOx film
- Sapphire substrate
Loss tangent of ALD AlOx

\[
\frac{1}{Q_i} = \frac{\int_{\text{Lossy}} \varepsilon(r)E^2 \tan \delta(r, E) \, d^3r}{\int_{\text{Total}} \varepsilon(r)E^2 \, d^3r} \]

![Graphs showing loss tangent and 1/Qi against RMS voltage](image)
Fabrication of the parallel plate capacitor superconducting resonator
Fabrication of the superconducting resonator

- Capacitor
- Waveguide
- Inductor
- Plane
- 20 μm
Coupling strength of the microwave resonators

$Q_e$ 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$_x$

“Classic” TLS model: OH rotor (point defect)

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

3 SiH$_4$ + 4 NH$_3$ → Si$_3$N$_4$ + 12 H$_2$

Oxygen concentration is correlated with loss.
UCSB α-Si has similar O concentration as Si-rich SiNx.
Raw experimental data

T=100 mK

T=40 mK

Pin, dBm

$S_{21}$

$\text{f (GHz)}$
Dielectric loss versus microwave voltage

Sample #1

\[
\delta_{TLS} = \frac{\varepsilon''_{TLS}(\omega)}{\varepsilon}
\]

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

\[
\Omega = 2d \cdot \bar{E}/\hbar
\]

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

\[
T_2^{-1} = C \frac{2\gamma^2 P kT^\alpha \Delta}{\pi \hbar \rho \nu^2} \frac{\varepsilon}{\varepsilon} \quad 1 \leq \alpha \leq 2
\]


\[\alpha = 1.8\]
Dielectric loss versus temperature

Crossover temperature:
T(SiO$_2$) $\sim$ 30mK
T(SiO$_x$) $\sim$ 100mK

Sample #1
Sample #2

\[ V_{\text{RMS}} = 2 \times 10^{-7} \text{V} \]

\[ \varepsilon''_{\text{TLS}} \approx \frac{\pi P d^2_0}{3} \tan \left( \frac{\hbar \omega}{2kT} \right) \frac{\tanh \left( \frac{\hbar \omega}{2kT} \right)}{\sqrt{1 + \left( \frac{\hbar \omega}{2kT} \right)^2}} \]

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.

Fluctuation of the dielectric loss in non-saturated TLS regime

Sample #2

Measurements of conductance fluctuations in amorphous metals indicate that TLS interact.

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.

\[ \delta\varepsilon_{ad} = \frac{4\pi p_0^2 P_0}{3} \left( \phi_0/4T \right) \log(\tau_{\text{max}}/t) \]

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

\[ \delta \tan(\delta)(t) = \frac{\pi P_0}{6k_0 t} \left\langle \mu^2 \left[ \tanh \left( \frac{|F_0\mu|}{2T} \right) - \tanh \left( \frac{n_0}{2T} \right) \right] \right\rangle \]

No resonance contribution to dielectric susceptibility has been found
Superconducting resonator with DC bias
Response of resonance absorption of SiN\textsubscript{x} in the presence of swept DC field

<table>
<thead>
<tr>
<th>Time, s</th>
<th>Freq., GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
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</tbody>
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U\textsubscript{DC}, V

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 $\tau \sim 1/t^{2}$.

Logarithmic relaxation caused by relaxation of non-resonant TLSs. This law can be explained by logarithmically uniform distribution of TLS tunneling amplitudes $\Delta_0$.

Response of resonance absorption of SiN\textsubscript{x} in the presence of swept DC field
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 ($\sim f^2$) changes instantaneously to the steady state value, which is shown to the left, after the step.

\[
\begin{align*}
\delta\varepsilon'(t) &= \frac{4\pi^2}{9} (P_0 P_0^2) (P_0 U_0) \log(\phi/T) \log(\tau T^2 \phi/\omega) \log(\tau_{\max}/t), \\
\delta\varepsilon''(t) &= \frac{2\pi^3}{9} (P_0 P_0^2) (P_0 U_0) \log(\phi/T) \log(\tau_{\max}/t),
\end{align*}
\]

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

\[ L = L_0 + L_{ki} \approx L_m + L_{ki} \]

\[ L_K = \mu_0 \lambda^2 / d_i \]

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

\[ \xi_0 >> d, l \]

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

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

\[ l \] – mean free path

\[ d \] – thickness

Superconductor loss

Effective penetration depth

sputtered and evaporated films

Compact LC sputtered
CPS sputtered
Compact C - CPS sputtered
Compact L - CPS sputtered
Compact LC evaporated
CPS evaporated
Compact C - CPS evaporated
Compact L - CPS evaporated

6.59%
6.59%
5.65%
6.05%
6.05%
6.4%
6.4%
Effect of TLS-TLS interaction

\[ H(t) = \sum_i \varepsilon_i S_i^z + 2 \frac{\hbar}{\varepsilon_i} \Delta_i \cos(\omega t) S_i^+ + 2 \frac{\hbar}{\varepsilon_i} \Delta_i \cos(\omega t) S_i^- + \sum_{j \neq i} J_{ij} \vec{S}_i \cdot \vec{S}_j \]

TLSs interacting with the electric field

TLS-TLS interaction

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

\[ \alpha \ln x^2 \]

\[ \alpha \frac{1}{\sqrt{1 + x^2}} \]

Electric field strength dependence of \( \frac{1}{Q_i} \)