Loss Mechanisms on Superconducting Quantum Devices and Microwave Microscopy for Probing Superconducting Devices Metrology

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Classical vs. Quantum computing

- Classical computing utilizes two voltage levels for computations (bits)

- Quantum superpositions can be used to speed up certain computations

\[ \Psi = \alpha |0\rangle + \beta |1\rangle \]

Superconducting quantum systems

IBM chip

Google
Different Types of Superconducting Qubit

Remarkable improvement in $T_1$ and $T_2$

--- Materials

--- Design

--- Fabrication

Coherence time $t_{coh}$: The qubit's lifetime

![Diagram showing quantum state, state decaying, and state lost over time with environmental disruptions]

\[
\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}
\]

Moore's law for $T_2$

![Graph showing lifetime $T_1$, $T_2$, and $T_1$ over years with different types of qubits and their lifetimes]

Kjaergaard et al, arXiv:1905.13641v1

M. Kjaergaard, WDO, et al., arXiv:1905.13641
WDO & Welander, MRS Bulletin (2013)
Harmonic Resonators

3D types of Cavities

\[ E_n = (n + \frac{1}{2})\hbar\omega \]

Planar types of Cavities

Resonator Design and Fabrication

\[
\frac{\lambda}{2}
\]
λ/2 Resonator Design and Fabrication

Resonator Design and Fabrication
λ/2 Resonator Design and Fabrication

- 280 µm
- 10 µm
- 10 µm
- Frequency (Hz) × 10^9
- |S_{21}| (dBm)

Graph showing frequencies range from 5 to 15 GHz with |S_{21}| values ranging from -100 to 20 dBm.
Two Level System Losses

Packaging and System Setup

\[ S_{21}(f) = \left| S_{21,\text{in}}S_{21,\text{out}} \right| \left( \frac{Q_L/Q_c}{1 + 2iQ_L\left(\frac{f - f_r}{f_r}\right)} + c_0 \right) \]

\[ \Rightarrow Q_L \text{ and } Q_c \]

\[ \frac{1}{Q_L} = \frac{1}{Q_i} + \frac{1}{Q_c} \]

\( Q_c \sim 7e5 \)
\( Q_L \sim Q_i \)
$$\langle n \rangle \equiv \frac{4Q_L^2 P_{in}}{Q_c \omega_0^2}$$
Two Level System Losses

$E_\pm = \pm \frac{1}{2} \sqrt{\Delta^2 + \Delta_0^2} = \pm \frac{1}{2} \varepsilon$,

$H_{TLS} = \begin{pmatrix} -\Delta & \Delta_0 \\ \Delta_0 & \Delta \end{pmatrix}$

- **Sources of TLS**
  1. Defects present in dielectrics at the metal/substrate/vacuum interface
  2. Primarily associated with oxide layer/OH- groups/chemical residues
Contribution of TLS and Thermal Quasi Particles

\[
\frac{f-f_n}{f_n} = F \cdot \frac{\tan \delta}{\pi} \left\{ \text{Re} \left[ \Psi \left( 0.5 - \frac{hf}{2\pi j k_b T} \right) \right] - \ln \left( \frac{hf}{k_b T} \right) \right\} - \frac{\alpha}{2} \sqrt{\frac{\pi \Delta s_0}{2k_b T}} \exp \left( - \frac{\Delta s_0}{k_b T} \right)
\]

\[\alpha = \frac{L_k}{L_k + L_{geo}}\]

<table>
<thead>
<tr>
<th>Fitting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta s_0) ((\mu eV))</td>
<td>174.03 (\mu) eV</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>0.0185</td>
</tr>
<tr>
<td>(F)</td>
<td>0.32</td>
</tr>
<tr>
<td>(\tan \delta)</td>
<td>2e-5 (sapphire)</td>
</tr>
<tr>
<td>(f_n) (GHz)</td>
<td>3.644</td>
</tr>
</tbody>
</table>
Contribution of Nonequilibrium Quasiparticles and Others

$\Delta$ - superconducting energy gap

$E > 2\Delta$ breaks a Cooper pair forming 2 quasiparticles giving dissipation

Multi photon $h\nu < 2\Delta$ also generate quasiparticles

\[
\frac{1}{Q_i} = \frac{1}{Q_{TLS}(T, E)} + \frac{1}{Q_{QP}(T, E)} + \frac{1}{Q_{vortices}(B)} + \frac{1}{Q_{rad}(w)}
\]
Temperature Dependent $Q_i$

\[
\frac{1}{Q_i} = \frac{1}{Q_{TLS}(T, E)} + \frac{1}{Q_{QP}(T, E)} + \frac{1}{Q_{other}}
\]

\[
\delta_{TLS} = \frac{\delta^0_{TLS} \tanh \left( \frac{\varepsilon}{2k_B T} \right)}{\sqrt{1 + \frac{A}{T} \tanh \left( \frac{\varepsilon}{2k_B T} \right)}}
\]

\[
T_1 \sim \tanh \left( \frac{\varepsilon}{2k_B T} \right)
\]

\[
T_2 \sim \frac{1}{T}
\]
\[
\delta_{TLS} = \frac{\delta^0_{TLS} \tanh \left( \frac{\varepsilon}{2k_B T} \right)}{\sqrt{1 + \frac{A}{T} \tanh \left( \frac{\varepsilon}{2k_B T} \right)}}
\]

\[
A = \frac{2d_0^2}{3} \left( \frac{1}{\Delta_0^2} \right) \left[ \frac{r^2_L}{V^5_L} + \frac{r^2_T}{V^5_T} \right]^{-1} \ast \frac{2\pi \hbar^2}{\varepsilon} \ast \frac{\pi \hbar \rho^2 v^2}{C \gamma \rho \Delta} E^2
\]
Qubit Readout

Dispersive Jaynes-Cummings Hamiltonian

\[ H_{JC}^{(\text{disp})} = \hbar (\tilde{\omega}_r + \chi \sigma_z) a^\dagger a + \frac{1}{2} \hbar \tilde{\omega}_q \sigma_z \]

|g4⟩ ——— |e3⟩
|g3⟩ ——— |e2⟩
|g2⟩ \[ \omega_q + 4\chi \] ——— |e1⟩
|g1⟩ \[ \omega_q + 2\chi \] ——— \[ \tilde{\omega}_r + \chi \] ——— |e0⟩
|g0⟩ \[ \omega_q \] ———

cavity
transmon qubit

Magnetic field
Driving a qubit on resonance at frequency $\omega_{ge}$
Driving the Qubit & Rabi Oscillations

Driving a qubit on resonance at frequency $\omega_{ge}$

Transmon in 3D Cylindrical Cavities

Qubit Power=-20 dBm
Qubit Relaxation Measurement

1. TLS Loss?

2. Imbalanced Nonequilibrium Quasiparticles at two different SC gaps?

\[
n_{1L} \approx n_{th,1} + \frac{n_{ne,1L}}{1 + \frac{\Omega_{2L}}{\Omega_{1L}} \sqrt{\frac{\Delta_2}{\Delta_1}} \exp\left(\frac{\Delta_1 - \Delta_2}{K_BT}\right)}
\]
\[
\frac{1}{Q_i} = \frac{1}{Q_{TLS}(T,E)} + \frac{1}{Q_{QP}(T,E)} + \frac{1}{Q_{rad}(W,\text{geometry})} + \frac{1}{Q_{vortices}(B)} + \ldots
\]

Develop a microscopy which can microscopically locate the place of loss at devices/cavities operating condition and identify the loss mechanism.

Superconducting circuits

de Leon et al., Science 372, eabh2823 (2021) 16 April 2021
1. Reflectance mode to generate a conventional image

- Laser
- Collimating lens
- Movable Galvano-mirrors
- Beam splitter
- Converging lens
- F-θ Objective Lens
- Photodiode
- Lock-in Amplifier
- 10 KHz modulation
- LNA
- Window
- Z
Laser Scanning Microwave Microscopy

2. Photoresponse mode to image the current density

\[ |S_{21}(f_0)| \]

\[ f_0 \]

\[ z \]

\[ |S_{21}|^2 \sim A [ J_{RF}(x,y)]^2 \]
Nonlinear Measurement and Modeling

General curve of $P_{3f} (P_f)$

$\text{Effective } P_{3f}$ at $T=9K$

$Tamin Tai \ et \ al., \ PRB \ 92, \ 134513 \ (2015)$

Bakhron Oripov \ et \ al.

$\text{Third-harmonic response } V_{3f}$

$PHYSICAL \ REVIEW \ APPLIED \ 11, \ 064030 \ (2019)$
Conclusions

- **Superconducting Quantum Computing**
  - In aluminum resonator, an unusual increase of Qi with decreasing temperature is observed, which is due to the increase of TLS coherence time (T2) in ultra-low temperature and power.

  - Temperature dependent of T1 on transmon qubits is also affected by many loss issues. In addition to TLS loss issue, two gaps model also can interpret the T1 temperature dependent behavior.

- **Microscopy**
  - **Laser Scanning Microscopy**
    A clear photo response with the capability of phase-sensitive measurement of local microwave properties on YBCO resonators are obtained by LSM with ~ µm length resolution.

  - **Near-field Scanning Microwave Microscopy**
    This microscopy achieved local harmonic generation from bulk Nb surfaces from sub-micron scale length and the measured nonlinearity is interpreted by the model of weak-link Josephson junctions.