Spectroscopy and coherent Control of Defects in superconducting Films and Qubits

Jürgen Lisenfeld, Alexander Bilmes, Jan Brehm, Georg Weiss, and A.V. Ustinov

Two-Level-Systems (TLS): a major source of noise in quantum devices

Using superconducting Quantum Bits to study single TLS

- TLS spectroscopy and mechanical strain tuning
- mutual TLS interactions, noise spectroscopy
- TLS - electron interaction
Two-Level-Systems (TLS)

measurements on glasses revealed several peculiarities:

- specific heat disagrees with Debye model (Zeller & Pohl 1971)

- common signatures in amorphous materials
  - ultrasound attenuation
  - electric field response
  - microwave response
  - thermal conductivity
  - heat capacity …

conclusion: glasses must contain intrinsic states having excitation energies < 1 K and which couple to both electric fields and phonons.
Two-Level-Systems: Tunneling Atom Model\textsuperscript{[1,2]}

- in amorphous materials, atoms may tunnel between two positions:
  - these "tunneling systems" couple via

  \begin{itemize}
  \item electric dipole moment
  \item mechanical strain
  \end{itemize}

- classical
- quantum

\[
\Delta E = \sqrt{\varepsilon^2 + \Delta^2}
\]

\begin{itemize}
\item energy
\item coordinate
\end{itemize}

\textsuperscript{[1]} W.A. Phillips, J. Low Temp. Phys. 7 351 (1972)
\textsuperscript{[2]} Anderson, Halperin, and Varma, Philosophical Mag. 25, 1 (1972)
TLS in microfabricated circuits and Josephson junctions

- **TLS are found**
  - in surface oxides
  - in / on the substrate
  - at interfaces
  - in tunnel junctions

- **TLS generate noise & dissipation in**
  - MOSFETs & single-electron transistors
  - micro-mechanical resonators
  - single-photon detectors, nanowires
  - superconducting resonators and qubits
  - ...

in Josephson junctions:

- hydroxide defects: \[ \text{Appl. Phys. Lett. 97, 252501 (2010)} \]
- dangling bonds
- electrons trapped at interfaces: \[ \text{Kondo- / Andreev Fluctuators} \]
- phononically dressed electrons: \[ \text{PRB 87, 144201 (2013)} \]
- tunneling atoms: \[ \text{Phys. Rev. Lett. 95, 210503 (2005)} \]
The Phase Qubit


- **Complete circuit**

- **Hamilton-Operator**

  \[
  \hat{H} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L} - E_J \cos \hat{\phi}
  \]

- **Potential for** $E_J \gg \frac{Q^2}{2C}$:

  \[
  \Phi_{\text{ext}} \approx 0.9 \Phi_0
  \]
Defect-Qubit - interaction

Qubit-TLS interaction: via TLS electrical dipole moment \( \vec{p} \)

**Qubit:**
\[
\hat{H} = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{\mathcal{Q}}^2}{2C} + E_j
\]

**el. Field:**
\[
\vec{E} = \frac{\hat{\mathcal{Q}}}{t C} \approx 1000 \text{ V/m}
\]

**Dipole interaction:**
\[
\vec{p} \approx \frac{2 \cdot 0.2 \text{ eÅ}}{2} \approx 10 \text{ MHz}
\]

qubit-TLS coupling strength
Defect – Qubit - Interaction

Frequency Domain:
defects cause avoided level crossings

Qubit-TLS interaction: via TLS electrical dipole moment $\vec{p}$

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Dipole interaction:
for $p = 2 D = 2 \cdot 0.2 \text{ eÅ}$
$$\Rightarrow g = p|\vec{E}| \approx \hbar \cdot 10 \text{ MHz}$$
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\Rightarrow g = \vec{p} \left| \vec{E} \right| \approx h \cdot 10 \text{ MHz}
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qubit-TLS coupling strength

Defect – Qubit - Interaction

Frequency Domain:
defects cause avoided level crossings

Time Domain:
qubit decays due to energy relaxation

Defect – Qubit - Interaction

Frequency Domain:
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Time Domain:
energy oscillates between qubit and defects

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Defect – Qubit - Interaction

Frequency Domain:
defects cause avoided level crossings

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$P(\ket{1})$
0.3
0
8.1
8
7.9
f (GHz)

$\delta P$ : qubit population loss $\Leftrightarrow$ TLS signal

$\Phi$

Readout

t

TLS signals for fixed $\Delta t = 40$ ns
TLS Strain Spectroscopy

**TLS strain tuning** by deforming the sample using a piezo
- tiny deformations
  \[
  \frac{\Delta L}{L} \approx 10^{-7} \text{ /V}
  \]
  (compress 1 nm by 10^{-16} m)
change TLS asymmetry:
\[
\varepsilon \approx 200 \text{ MHz/V}
\]

\[
\omega_{10} = \sqrt{\varepsilon^2 + \Delta^2}
\]

TLS asymmetry \( \varepsilon \), strain

\[
\Phi \leftrightarrow \pi \leftrightarrow \Delta t \leftrightarrow \delta \Phi
\]

TLS signals for fixed \( \Delta t = 40 \text{ ns} \)

piezo voltage \( V \) / strain \( \varepsilon \)

\[
\delta P
\]

frequency (GHz)

\[
0 \quad 40 \Delta t (\text{ns})
\]

\[
0 \quad -0.3
\]
TLS Strain Spectroscopy


**TLS Strain Spectroscopy**


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Two coherently coupled TLS telegraphic switching.

Irreversible shift.

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**Graphical Elements**

- **Frequency (GHz)**
- **Piezo Voltage (V)**
- **Color Scale:**
  - $\delta P$
  - 0
  - -0.2
  - -0.4

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**Figure Notes**

- **Frequency (GHz):**
  - 7
  - 8
  - 9

- **Piezo Voltage (V):**
  - -20
  - 0
  - 20
  - 40
  - 60
  - 80
coherently interacting defects


signature in defect spectroscopy

simulated spectrum of 2 coupled TLSs
coherently interacting defects


interaction Hamiltonian:

\[ H_{\text{int}} = g \sigma_{z_1} \sigma_{z_2} \]

rotate to eigenbasis by angle \( \theta \), where

\[ \cos \theta = \frac{\varepsilon}{E}, \quad \sin \theta = \frac{\Delta}{E} \]

\[ \hat{H}_{\text{int}} = g \cos \theta_1 \cos \theta_2 \hat{\sigma}_{z_1} \hat{\sigma}_{z_2} + g \sin \theta_1 \sin \theta_2 \hat{\sigma}_{x_1} \hat{\sigma}_{x_2} + \propto \left( \hat{\sigma}_x \hat{\sigma}_z + \hat{\sigma}_z \hat{\sigma}_x \right) \]

minor contributions

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**Plot:**

- Plot of frequency (GHz) vs. strain / piezo voltage (V)
  - Two distinct regions labeled TLS1 and TLS2
  - Peaks at 6.8, 6.4, and 6.0 GHz
  - Graph with labeled \( g_{\parallel} \) and \( g_{\perp} \)
coherent control of individual TLS

- TLS resonantly absorbs photons via a Raman transition involving a virtual qubit excitation
- Full NMR-like TLS control via microwave pulse sequences
- TLS operation not degraded by qubit decoherence

8.0

7.8

frequency [GHz]
bias flux [arb. units]
Strain-dependence of TLS coherence times

Strain-dependence of TLS coherence times


- Symmetric pattern in $\Gamma_1$ can not originate in mutual TLS interactions.

- Golden rule: $\Gamma_1 \propto \left( \frac{\Delta}{\sqrt{\Delta^2 + \epsilon^2}} \right)^2 \cdot S(\omega_{10})$

- Several TLS have a common maximum in $\Gamma_1$ around 7.4 GHz.

- Possibly coupling to same phonon mode.
Strain-dependence of TLS coherence times

Strain-dependence of TLS coherence times

Temperature dependence of TLS coherence

- TLS energy relaxation rate exceeds phonon contribution

\[ \Gamma_1 \propto \coth(\Delta E/2k_B T) \]

- TLS decay at higher temperatures \[^{[1]}\] caused by quasiparticles?

\[ T_1 \]

excited state
life time

\[ T \propto E/2k_B \coth(\Delta E/2k_B T) \]

- TLS decay at higher temperatures \[^{[1]}\] caused by quasiparticles?

\[ \text{c.f. J. L. Black, Glassy Metals I, Topics in Applied Physics 46, 167 (1981).} \]

- Test:
  1) generate quasiparticles by injection or by raising the sample temperature
  2) calibrate QP density using the qubit
  3) measure TLS coherence times
injection of quasiparticles  cf. M. Lenander et al., PRB 84, 024501 (2011)

- drive 2nd on-chip DC-SQUID with current $I_b > I_C$
- generated QPs diffuse to qubit’s Josephson junction where they interact with TLS
- we expect a difference in QP density on the two JJ electrodes because of the sample layout


QP-induced decoherence of Two-Level Systems

- **Korringa-like QP-TLS-interaction:**
  \[ \Gamma_1 = S x_{qp} + \Gamma_1^{(0)} \]

- **QP-TLS coupling depends on TLS location**

- **QP densities differ in injection experiment:**
  \[ x_{qp}^{(L)} \approx x_{qp}^{(R)}/2 \]

- **Estimation of TLS location**

- **QP-induced decoherence of Two-Level Systems**

- **We observe:**
  \[ \Gamma_{\text{therm}} > \Gamma_{\text{inj}} \]
coupling TLS to a transmission-line resonator

J. Brehm, A. Bilmes, J. Lisenfeld, to be published (2016)

- AIOx fabricated using anodization
  $t = 50 \text{ nm}$, area $10 \mu m \times (5/10/15) \mu m$

- choose a dielectric volume to have
  $\sim 1$ TLS within 1-MHz-window
  $\rho \approx 100$ TLS/$(\mu m^3 \cdot GHz) \Rightarrow V \approx 10 \mu m^3$

- coupling strength resonator-TLS $g$:
  \[
  hg = p_{\parallel}|\bar{E}| \approx \frac{p_{\parallel}}{t} \sqrt{\frac{hf_{res}}{2(C_{res} + C_{cap})}}
  \]
  \[
  C_{res} \approx 1.4 \ pF, \quad C_{cap} \approx 0.2 \ pF
  \]
TLS coupled to a resonator: strain-spectroscopy
J. Brehm, A. Bilmes, J. Lisenfeld, to be published (2016)

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- individual TLS are resolved
double-peaks in resonance with strongly coupled TLS

- fit to model provides TLS parameters [1]:
  example: • $T_1 = 1.6 \, \mu s$, energy relaxation rate
  • $g = 540 \, \text{kHz}$, coupling strength
  • $p_{||} = 1.0 \, \text{eÅ}$, dipole moment

mechanical-strain tuning of TLS: setup

1. IR-filters
2. RF-chokes
3. low-pass filters
4. isolators
5. Mu-metal box lid
6. steel-powder filters
7. piezo housing
8. sample box

Summary: exploring TLS with superconducting Qubits

- **TLS** are a major decoherence source which affects various microfabricated devices.
  - It is vitally important to understand emergence of TLS in fabrication.
- It is now possible to **address single TLS coherently** with superconducting circuits.

**TLS strain spectroscopy**

**coherently coupled TLS**

**TLS quantum dynamics**

Superconducting qubits (and resonators) are **ideal tools** for the characterization of materials and defect properties.