Exploring parasitic Material Defects with superconducting Qubits

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

Utilizing qubits to study individual TLS:
- TLS tuning by mechanical strain, strain spectroscopy
- mutual TLS interactions:
  - origin of time-dependent fluctuations
- noise spectroscopy
- TLS-quasiparticle interactions
Two-Level-Systems: Tunneling Atom Model \(^{[1,2]}\)

- In amorphous materials, atoms may tunnel between two positions:

- These "tunneling systems" couple via:
  - Electric dipole moment
  - Mechanical strain

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

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**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**

- **dangling bonds**

- **electrons trapped at interfaces:**
  - Kondo- / Andreev Fluctuators
  - PRL 95, 046805 (2005)
  - PRB 84, 235102 (2011)

- **phononically dressed electrons**
  - PRB 87, 144201 (2013)

- **tunneling atoms**
  - Phys. Rev. Lett. 95, 210503 (2005)
The Phase Qubit


- **complete circuit**

- **Hamilton-Operator**

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

\[
\Phi_{ext} \approx 0.9 \Phi_0 \quad \quad E_J / E_C \approx 10^4
\]

- **Potential for** $E_J >> E_C$

\[
E \uparrow
\]

qubit manipulation
via Rabi oscillation

\[
|1\rangle
\]

\[
|0\rangle
\]

\[
\Phi
\]

\[
\phi_{ext}
\]

\[
E_J
\]

\[
-2\pi \quad 0 \quad 2\pi \quad 4\pi
\]

\[
\phi
\]

\[
Energie
\]

\[
\Phi_{ext} \approx 0.9 \Phi_0
\]
Phase Qubit sample used in this work

- fabricated at UCSB & CNF
  Al/AlOx JJ, SiN capacitor
- large junction $\sim 1 \mu m^2$
  - contains many TLS
  - short coherence time: $T_1 \sim 100$ ns, $T_2 \sim 100$ ns

Defect-Qubit - interaction

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

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

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

Dipole interaction:
\[
\text{for } \vec{p} = 2 \cdot D = 2 \cdot 0.2 \text{ eÅ}
\]
\[
\Rightarrow g = \vec{p} |\vec{E}| \approx h \cdot 10 \text{ MHz}
\]
qubit-TLS coupling strength
Defect – Qubit - Interaction

**Frequency Domain:**
defects cause avoided level crossings

**Time Domain:**
qubit decays due to energy relaxation

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**Graphical Elements:**
- Frequency domain: Peaks at 10 MHz and 8.1 GHz, labeled with $2g$.
- Time domain: $T_1 \approx 100$ ns.

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**References:**
**Defect – Qubit - Interaction**

**Frequency Domain:**
defects cause avoided level crossings

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

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**Time Domain Diagram:**
- Energy oscillates between qubit and defects over time.
- Frequency domain shows avoided level crossings.

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**References:**
Defect – Qubit - Interaction

**Frequency Domain:**
defects cause avoided level crossings

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

$$\delta P : \text{qubit population loss } \Leftrightarrow \text{TLS signal}$$

Defect – Qubit - Interaction

0.3

$P(|1\rangle)$

3.9

$10 \text{ MHz}$

0

$f (\text{GHz})$

8.1

8

7.9

0

$\Phi$

0

flux bias

0.5

0.2

0

$P(|1\rangle)$

0

$\Delta t (\text{ns})$

0

100

200

385

$\delta P$

0

0.9

$P(|1\rangle)$

0

$\Delta t (\text{ns})$

0

40

-0.3

0

$\pi$

$\Phi$

readout

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

**TLS strain tuning** by deforming the sample using a piezo

- tiny deformations
  \[
  \frac{\Delta L}{L} \approx 10^{-7} /V
  \]
  (compress 1 nm by $10^{-16}$ m)

change TLS asymmetry:

\[
\epsilon \approx 200 \text{MHz/V}
\]

By deforming the sample using a piezo (qubit chip), tiny deformations can change the TLS asymmetry. This method, called TLS strain tuning, allows for the study of material defects using superconducting qubits.

- **electrical** dipole moment
- **mechanical** strain
TLS Strain Spectroscopy

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

TLS strain tuning by deforming the sample using a piezo

- tiny deformations
\[ \frac{\Delta L}{L} \approx 10^{-7} /V \]
(compress 1 nm by \(10^{-16} \text{ m}\))

change TLS asymmetry:
\[ \epsilon \approx 200 \text{ MHz/V} \]

TLS Strain Spectroscopy


TLS Strain Spectroscopy


- avoided level-crossings
- time-dependent frequency fluctuations

frequency (GHz)

strain / piezo voltage (V)
Two coherently coupled TLS

telegraphic switching

irreversible shift
**signature in defect spectroscopy**

- **coherently interacting defects**


**simulated spectrum of 2 coupled TLSs**
coherently interacting defects

interaction Hamiltonian:

\[ H_{\text{int}} = g \sigma_z \sigma_z \]

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

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

\[ \hat{H}_{\text{int}} = g \cos \theta \sigma_z \sigma_z + g \sin \theta \sigma_x \sigma_x + \propto (\sigma_x \sigma_z + \sigma_y \sigma_y) \]

minor contributions

coherently interacting defects

coherently interacting defects

TLS interactions: source of fluctuations in qubits


- fluctuations in energy relaxation rate
e.g. 3D-Transmon (IBM)

- fluctuations in TLS resonance frequency

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<tr>
<th>TLS interactions: source of fluctuations in qubits</th>
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NHM: coupling between high-frequency TLS and thermal TLS

results in fluctuations of qubit’s noise density

fluctuations in TLS resonance frequency

coupling between high-frequency TLS and thermal TLS

origin:

results in fluctuations of qubit’s noise density
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

- $\Delta t$
- $P(|1\rangle)$
- 0.5
- 0

frequency [GHz]

8.0

TLS excitation

swap pulse

readout pulse

bias flux [arb. units]

7.8

Rabi oscillation

Ramsey fringes

spin-echo

energy relaxation

Noise Spectroscopy using single TLS as Quantum Spectrum Analyzers

- rotate TLS eigenbasis by strain $\gamma$, which depends linearly on applied piezo Voltage

\[
\Rightarrow \text{matrix elements: } \langle 1 | \sigma_z | 0 \rangle = \frac{\Delta}{\omega_{10}}, \quad \langle 1 | \sigma_z | 1 \rangle = \frac{\varepsilon(\gamma)}{\omega_{10}}
\]

- measure decoherence rates with different protocols

\[
\Delta \propto \Gamma
\]

energy relaxation $\omega_S \approx 6 - 10 \text{GHz}$

Ramsey $\omega_S \approx 0 - 0.5 \text{ MHz}$

Spin-echo $\omega_S \approx 1 - 5 \text{ MHz}$

\[
\Gamma_1 \propto \left( \frac{\Delta}{\omega_{10}} \right)^2 \cdot S_\gamma(\omega_S) \quad \text{energy relaxation} \quad \omega_S \approx 6 - 10 \text{GHz}
\]

\[
\Gamma_\varphi \propto \left( \frac{\varepsilon}{\omega_{10}} \right)^2 \cdot S_\gamma(\omega_S) \quad \text{dephasing} \quad \omega_S \approx 0 - 5 \text{ MHz}
\]

obtain noise spectral density $S_\gamma(\omega_S)$ at different frequencies $\omega_S$
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

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?

\[ T_1 \text{ excited state life time} \]

\[ \text{test :} \]

1) generate quasiparticles by injection or by raising the sample temperature
2) calibrate QP density using the qubit
3) measure TLS coherence times

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injection of quasiparticles cf. M. Lenander et al., PRB 84, 024501 (2011)

- drive 2\textsuperscript{nd} 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
Quasiparticle density calibration

A. Bilmes, J. Lisenfeld, M. Marthaler, A.V. Ustinov et al., to be published (2016)

- Use the qubit as a QP-detector\(^\text{[1,2]}\)
- the local superconducting gap shrinks: \(\Delta s \approx \Delta_0 \left(1 - \frac{n_{qp}}{n_{cp}}\right)\)

\(\Delta f \propto \frac{n_{qp}}{n_{cp}}\)

- Qubit resonance shift
- increased energy relaxation \(\Gamma_1 \propto \frac{n_{qp}}{n_{cp}}\)

- pulsed QP injection, time domain

\(V_{\text{inj}}\)

\(\tau_{\text{tot}}\)

\(\tau_{\text{inj}}\)

\(\Delta f = 10^7\)

\(\Gamma_1 = 10^7\)

\(\Delta n_{qp}/n_{cp}\)

\(\Delta n_{qp}/n_{cp}\)

\(|V_{\text{inj}}| = 1\text{V}\)

\(|V_{\text{inj}}| = 0.75\text{V}\)

\(|V_{\text{inj}}| = 0.5\text{V}\)

\(\frac{n_{qp}}{n_{cp}}\)

\(x 10^6\)

\(x 10^{-5}\)

\(x 10^{-4}\)


QP-induced decoherence of Two-Level Systems

A. Bilmes, J. Lisenfeld, G. Weiss, A.V. Ustinov et al., to be published (2016)

- Korringa-like QP-TLS-interaction:
  \[ \Gamma_1 = S x_{qp} + \Gamma^{(0)}_1 \]

- 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

- we observe:
  \[ \Gamma_{1\text{therm}} > \Gamma_{1\text{inject}} \]

Summary: Exploring TLS with superconducting Qubits

- TLS are an important decoherence source for various microfabricated devices
  - fluctuating qubit relaxation
  - frequency-dependent $\Gamma_1$

- Superconducting qubits are ideal tools to study single TLS:
  - TLS strain spectroscopy
  - Coherently coupled TLS
  - Noise spectroscopy

R. Barends et al., PRL 111, 080502 (2013)