High-Fidelity
Josephson Gates

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Outline

Superconducting and Phase Qubits

Environmental Decoherence
  Dielectric loss and TLS
  T1

Control Decoherence & Gate Fidelity
  98% measured, 99.99% 2 errors
  >99.9% possible for coupled gates
Quantum Computer Architecture

(1) Single qubits
(2) Coupling
(3) Long-range coupling

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Error threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlimited range</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>2D lattice nearest-neighbor</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>1D lattice nearest-neighbor</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>

Superconducting qubits: “Quantum Bus” = Al wire (use IC technology)
Coherence versus Coupling

**Atoms**
- EM modes
  - Photons
  - Ions
  - Neutral Atoms
  - NMR
  - Spin
  - Semiconductor spin
  - Quantum Dot

**Coherence easier**

**Coupling easier**

**SC: unique approach, Strength seen in future**

**microscopic**
- Superconductor SET
- 2-Degenerate SSET
- 3 Junction SQUID
- RF SQUID
- Josephson Junctions
  - (this work)

**mesoscopic**
- Photons
- Superconductor SET
- 2-Degenerate SSET
- 3 Junction SQUID
- RF SQUID
- Josephson Junctions
  - (this work)

**atomic**
- Photons
- Superconductor SET
- 2-Degenerate SSET
- 3 Junction SQUID
- RF SQUID
- Josephson Junctions
  - (this work)
Strategy for Phase Qubits

• Impedance $Z = 1/\omega C \sim 50 \ \Omega$
  More straightforward to couple (direct wiring)
• Gate fidelity through speed
  1 qubit 10 ns
  2 qubit 10-20 ns, > 99.9% intrinsic fidelity
• Improve $T_1$, $T_2$ through materials
• No sensitivity to charge noise
  (Biased transmon)
Environmental Decoherence: Where’s the Problem?

**Inductors & Junctions**

Superconductors:
- Gap protects from dissipation
- X-tal or amorphous metal
- Protected from magnetic defects

**Circuits**

Good circuit design (
wave engineering.)

**Capacitors**

Many low-E states
Only see at low T

2$∆$~4$T_c$
Qubit Improvements: Understanding TLS Defects

- Al₂O₃ wafer
- SiO₂ $\Rightarrow$ SiNx
- Small junction + external Cap.
- $\Delta t_{\text{Rabi}}$[ns]
  - $T_1 = 40\,\text{ns}$
  - $T_1 = 500\,\text{ns}$
  - $T_1 = 470\,\text{ns}$
- $T_\Phi \approx 300\,\text{ns}$
- $I_L \Rightarrow I_R\Rightarrow E$
- Piezoelectric materials

Diagram showing quantum states and energy levels.
TLS Defects and Dielectric Loss

- a-oxides have large loss, $\delta_i \sim 10^{-3}$ – BE CAREFULL
- Statistically avoid TLS with small junctions ($\delta_i \sim 10^{-5}$)
- TLS invisible at high T, power – BE CAREFULL
- Predicted how to improve phase qubits - outsource C
- Explains spectroscopy data (size and density)
- Explains loss of measurement visibility
- Explains loss of Rabi amplitude (coherence)
- Consistent with 30+ years of LT physics

- Lower loss dielectrics: xtal’s or a-Si:H (4-bonds)
  Lossy barriers: a-AlN, MgO (D. Pappas, NIST)
- Understand magnitude of 1/f charge noise $S_Q \sim \delta_i$ (Yu and
- Understand magnitude of 1/f critical-current noise Constantin)
- TLS produces phase noise (C-fluctuations), theory in progress

- New resonator data (J. Gao … Caltech/JPL)
  $\delta_i \sim 10^{-5} – 10^{-6}$ from surface oxide
$T_1$ Decoherence (energy decay)

• 5 different devices give $T_1 \sim 500$ ns
  50 gate op’s – algorithms possible
  Indication that 1-2 $\mu$s possible
  2-3 $\mu$s from loss of a-Si:H (not optimized)
  Radiation possible
  Need to measure $T_1$ of resonator

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\caption{$T_1 = 470$ ns}
\end{figure}
Gate Fidelity and $T_1$-ology

- Often implied: gate fidelity $= T_{\text{op}}/T_{1,2}$

- Incomplete since other errors possible
  Possible to have errors constant with time
  $T_1$ & $T_2$ describe memory operation, not logic (change in state)
Single Qubit Gate Errors: Measurement Errors

Nothing or \( \pi \)-pulse

\[ I_{\mu w} \quad \text{and} \quad I_z \]

8 ns 3 ns

Spectroscopy

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.22 GHz</td>
</tr>
<tr>
<td>6.75 GHz</td>
</tr>
</tbody>
</table>

Tunneling Prob.

\[ I_{\text{meas}} / I_c \]

\( |1> \) (misidentified as \( |0> \))
- 4.5% splitting at 7GHz
- 3-5% other splittings
- 1% \( T_1 \) during measurement

\( |0> \) (misidentified as \( |1> \))
- 3.4% stray tunneling

Error Budget

\[ |1> \]

\[ |0> \]
Single-Qubit Gate Errors: Tomography Check

Goal:
Measure fidelity of pi-pulse (longest single-qubit gate) separately from measurement errors.

Idea:
Two pi-pulses bring state back to |0>, where the only measurement error is stray tunneling. Remaining error is due to pi-pulses only.

Tomography Check:
On resonance, phase of second pulse has no effect, as expected for pi-pulses.
Single-Qubit Gate Errors: Limited by $T_1$

Vary the time between pi pulses to separate gate fidelity from decoherence due to $T_1$ decay.

**double - $\pi$ error:**  
$4\%$

**single-qubit gate fidelity:**  
$98\%$  
*(limited by $T_1$)*

Direct measure of probability  
Checks on measurement & $\pi$-gates
Two State Errors

Gaussian pulses:
Minimum width in
time and frequency

|2> Errors from Fast Pulses

Measure

\( \tau \) (FWHM)

\( \chi_{\pi} \)

\( \omega_{10} \)

\( \omega_{21} \)

Pulse Amplitude [V]

P of Tunneling [%]

Measure Pulse Amplitude [V]

|0> 4ns 5ns 6ns 8ns
**π - π Pulses Give Low Background & Error Filtering**

![Graphical representation of π-π pulses and their effect on background and error filtering.](image)

- **High Power Spectroscopy**
  - |2> Error
  - Two Photon
  - Qubit

- **Ramsey Fringe Filtering of |2> state**
  - Delay time \( \tau_{\text{delay}} \) [ns]

- **Microwave Frequency [GHz]**
  - 6.05
  - 6.15
  - 6.25

- **Graphs showing the distribution of P[|1> [%]] and P[|2> [%]] vs. delay time \( \tau_{\text{delay}} \) [ns] and microwave frequency.**

- **Equations and labels:**
  - \( \pi \)
  - \( \pi \)
  - \( X_\pi \)
  - \( X_\pi \)
  - Microwave Frequency [GHz]
  - \( |1> \)
  - \( |2> \)
  - \( 4P_2\)-error
  - 5 ns
  - 200MHz
Error vs. Gaussian Pulse Width

- S-curve
- $\pi-\pi$
- FT theory
- Spectrum analyzer
- Quantum simulation

$|2\rangle$ error vs. $\tau$ [ns]
GHz DAC Electronics

Old analog system:

14 bits, 2x Gs/s
FPGA memory, ~2k$

measured waveform
Beyond $T_1, T_2$: Gate Performance

“\textbf{It works}” \quad \rightarrow \quad \textbf{Gates (+ fidelity)}
## CNOT gates for capacitively coupled UCSB qubits

<table>
<thead>
<tr>
<th>design</th>
<th>coupling strength g</th>
<th>speed</th>
<th>coupling efficiency $\eta$</th>
<th>average gate fidelity: intrinsic</th>
<th>average gate fidelity: 500ns amplitude damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNOTsqiswSteffen</td>
<td>3MHz</td>
<td>114ns</td>
<td>2.92</td>
<td>97.1%</td>
<td>90.9%</td>
</tr>
<tr>
<td>CNOTsqiswEntangling</td>
<td>3MHz</td>
<td>132ns</td>
<td>2.52</td>
<td>92.1%</td>
<td>85.5%</td>
</tr>
<tr>
<td>CNOTczStrauch</td>
<td>10MHz</td>
<td>98ns</td>
<td>1.02</td>
<td>98.5%</td>
<td>93.1%</td>
</tr>
<tr>
<td>CNOTspectroscopic</td>
<td>50MHz</td>
<td>82ns</td>
<td>0.24</td>
<td>84.7%</td>
<td>81.4%</td>
</tr>
<tr>
<td>CNOTrfCouplingWeyl</td>
<td>10MHz</td>
<td>111ns</td>
<td>0.90</td>
<td>85.7%</td>
<td>80.8%</td>
</tr>
<tr>
<td>CNOTsteeringGaliaudinov</td>
<td>3MHz</td>
<td>106ns</td>
<td>3.14</td>
<td>96.4%</td>
<td>90.8%</td>
</tr>
<tr>
<td>CNOTsqiswSteffen (RWA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>off/on ratio = 1%</td>
<td>50MHz</td>
<td>20ns</td>
<td>1.0</td>
<td>$&gt;99.9%$</td>
<td>$98.7%$</td>
</tr>
<tr>
<td>off/on ratio = 10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Geller et al., to be published
Design Issues for Coupled Qubits

1) Switching by tuning/detuning is limited: \( \text{off/on ratio} = \frac{g}{\Delta} \)

\[
\begin{align*}
|11\rangle & \quad \text{“on”} \\
|10\rangle & \quad \text{coupling} = g \\
|00\rangle & \quad \text{“off”} \\
|01\rangle & \quad \text{coupling} \approx \frac{g^2}{\Delta}
\end{align*}
\]

Effective tuning via \( \mu \)waves gives no further improvement

2) Computational basis used here is the **uncoupled** qubit basis

- **computational basis** vs. **eigenstates**
  - \( \{\langle 00|, \langle 01|, \langle 10|, \langle 11|\} \) vs. \( |\psi_{00}\rangle = |00\rangle + a_1 |01\rangle + a_2 |10\rangle + a_3 |11\rangle \)
  - \( |\psi_{01}\rangle = |01\rangle + b_1 |00\rangle + b_2 |10\rangle + b_3 |11\rangle \)

- **basis choice compatible with scalability**
  - the \( a_i \) and \( b_i \) are of order \( \frac{g}{\Delta} \) (counted as errors)

3) For \( 10^{-4} \) errors, \( \frac{g}{\Delta} \sim 10^{-2} \)

- With \( g = 100 \text{ MHz} – 10 \text{ GHz} \) is a difficult frequency detuning.

**Can achieve with adjustable coupling (ie Berkeley, NEC)**
Conclusions

Coherence is key issue with superconducting qubits

TLS & dielectric loss THE important decoherence mechanism
  Basic understanding of physics
  Know how to improve (materials take time)

Gate Fidelity is additional important measure
  98% single-qubit gate (limited by $T_1$)
  99.99% 2 errors
  >99.9% possible for coupled gates

$T_2$ and dephasing – Optimistic, see R. McDermott’s talk
Beyond 2 Qubits: Planning for Scalability

**Custom electronics**
- Cost effective: $2,000 / Qubit
- Scalable: Rack mount design
- Flexible, yet powerful: FPGAs

**Custom software**
- Modular ⇒ “Easy complexity”
- Cross language ⇒ efficient
- Distributed ⇒ many PCs
- Open Source ⇒ maintainable

**Custom DR**
- There’s plenty of room at the bottom: 200 coax’s

**UCSB Qubit Fab**
- Robust, multi-layer process
- Engineered materials
- Everyone makes qubits!