Quantum Computing and the Technical Vitality of Materials Physics

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SSSC, 4/2008
Physical systems actively considered for quantum computer implementation

- Liquid-state NMR
- NMR spin lattices
- Linear ion-trap spectroscopy
- Neutral-atom optical lattices
- Cavity QED + atoms
- Linear optics with single photons
- Nitrogen vacancies in diamond
- Electrons on liquid He
- Small Josephson junctions
  - “charge” qubits
  - “flux” qubits
- Spin spectroscopies, impurities in semiconductors & fullerines
- Coupled quantum dots
  - Qubits: spin, charge, excitons
  - Exchange coupled, cavity coupled

(list almost unchanged for some years)
Electron spins in quantum dots

Top-Gated Quantum Dots

- Spin up and spin down are qubit 1 and 0.
- One electron per dot
- Qubit rotations using ESR
- Exchange enables swap operations

Details of Marcus-group structures and measurements
-- full electric circuit, pulsed operation
-- charging honeycomb, termination at empty dots
Cartoon of double quantum dot

Electrons coupled,
Exchange coupled to thousands of nuclear spins.
Spin echo experiment

Fig. 5. (A) Spin-echo pulse sequence. The system is initialized in (0,2)S and transferred to S by rapid adiabatic passage. After a time \( \tau_E \) at large negative detuning, S has dephased into a mixture of S and \( T_0 \) due to hyperfine interactions. A z-axis \( \pi \) pulse is performed by making detuning less negative, moving to a region with sizable \( \langle \epsilon \rangle \) for a time \( \tau_E \). Pulsing back to negative detunings for a time \( \tau_S = \tau_S' \) refocuses the spin singlet. (B) \( P_S \) as a function of detuning and \( \tau_E \). The z-axis rotation angle \( \phi = \langle \epsilon \rangle \tau_E / \hbar \) results in oscillations in \( P_S \) as a function of both \( \epsilon \) and \( \tau_E \). (Inset) Model of \( P_S \) using \( \langle \epsilon \rangle \) extracted from the S-T, resonance condition, assuming \( g^* = -0.44 \) and ideal measurement contrast (from 0.5 to 1). (C) Echo recovery amplitude \( P_S \) plotted as a function of \( \tau_S - \tau_S' \) for increasing \( \tau_S + \tau_S' \) (red points), along with fits to a Gaussian with adjustable height and width. The best-fit width gives \( T_2^* = 9 \) ns, which is consistent with the value \( T_2^* = 10 \) ns obtained from singlet decay measurements (Fig. 3B). Best-fit heights (black points) along with the exponential fit to the peak-height decay (black curve) give a lower bound on the coherence time \( T_1 \) of 12 \( \mu s \).
Si/SiGe Heterostructures

Schematic

<table>
<thead>
<tr>
<th>Layer</th>
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<tbody>
<tr>
<td>Strained Silicon Cap Layer</td>
</tr>
<tr>
<td>Relaxed Si$<em>{0.7}$Ge$</em>{0.3}$</td>
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<tr>
<td>n-type Dopants</td>
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<tr>
<td>2D Electron Gas (2DEG)</td>
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<tr>
<td>Strained Silicon</td>
</tr>
<tr>
<td>Virtual Substrate Si$_{1-x}$Ge$_x$</td>
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Conduction Band

Heterostructures grown by Don Savage
Coulomb blockade in Schottky-gated Si/SiGe quantum dots

Ohmic Contacts: Au/Sb(1%)
Schottky Top Gates: Pd
Other routes to spin-based solid state qubits

P in Si
Electrons on He surface
Carbon CNTs
II-VI semiconductors (nuclear spin story much more varied)
“Yale” Josephson junction qubit

Nature, 2004

Coherence time again c. 0.5 $\lambda$ s (in Ramsey fringe experiment)
But fringe visibility $> 90\%$!
Excess noise – Where from?

Co-Planar Waveguide Geometry

Most of the EM field resides in the CPW slots

Resonator Geometry

HFSS- FEM Simulation


• Crystalline substrate – thin native oxide layer
• Oxidised metal surface
• TLS in glassy layer @ interface interact with E field cause phase noise! (Gao et. al. 2007, Martinis et. al. 2005)
Excess Phase Noise

- Device performance limited by resonator intrinsic noise
- Intrinsic noise of the device >> G-R noise Device (Day et. al., Nature 2004)
- Noise primarily in phase direction - frequency jitter (Gao et. al., APL 2007)

- Floor set by HEMT noise – amplitude direction
- Phase noise > Amplitude noise
- Rolls of with device bandwidth

\[
S_{21} (\delta x) = G \left[ \frac{S_{21\text{min}} + 2jQ_r\delta x}{1 + 2jQ_r\delta x} \right], \delta x = \frac{f - f_r}{f_r}
\]

\[
S_{21\text{min}} = 1 - \frac{Q_r}{Q_c}, Q_r^{-1} = Q_i^{-1} + Q_c^{-1}
\]
Q – factor vs Temperature

- Loss increases with temperature

Physical picture
- Temperature increases - population of higher energy state increases
- More loss to phonon bath
- Power dependence – saturation of TLS effects?

$f_r = 4.35 \text{ GHz}, Q_c = 496,000$

Shwetank Kumar, IBM
High-Fidelity Josephson Qubits

UC Santa Barbara

John Martinis
Andrew Cleland
Ken Cooper (JPL)
Robert McDermott (UW)
Matthias Steffen (IBM)
Eva Weig (LMU)
Nadav Katz (HU)
Haohua Wang
Max Hofheinz

Markus Ansmann
Matthew Neeley
Radek Bialczak
Erik Lucero
Aaron O’connell
James Wenner
Daniel Sank

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Abraham Kofman (VS)

UCI
C. Yu, Magdalena Constantin (PD)

UG
M. Geller, Emily Pritchett (GS),
(Andrei Galiautdinov (PD))

NIST
D. Pappas, Jeff Kline
Physical 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
  - (μ-wave engineering.)

**Capacitors**
- Many low-E states
  - Only see at low T
Qubit Improvements: Understanding Atomic TLS’s

$Al_2O_3$ wafer $SiO_2 \Rightarrow SiN_x$

Small junction + external Cap.

$90\%$ $P_{1\rangle}$ $T_1 = 470$ ns  $T_f \sim 300$ ns

$60\%$ $P_{1\rangle}$ $T_1 = 500$ ns

$40\%$ $P_{1\rangle}$ $T_1 = 40$ ns
TLS Defects and Dielectric Loss

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

- Lower loss dielectrics: xtal’s or a-Si:H
  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
Dielectric Loss in CVD SiO$_2$

\[ \text{HUGE Dissipation} \]

\[ \text{Im}\{\varepsilon\}/\text{Re}\{\varepsilon\} = \delta = 1/Q \]

\[ P_{in} \text{ lowering} \]

\[ P_{out} \quad f \ [\text{GHz}] \]

\[ T = 25 \text{ mK} \]
Theory of Dielectric Loss

Two-level (TLS) bath: saturates at high power, decreasing loss

von Schickfus and Hunklinger, 1977

\[
\text{Im}\{\varepsilon\}/\text{Re}\{\varepsilon\} = \delta = 1/Q
\]
Junction Resonances:
Dielectric Loss at the Nanoscale

New theory (Martin et al, Martinis et al):

\[
\frac{d^2 N}{dE dS} = \sigma A \frac{[1 - (S / S_{\text{max}})^2]^{1/2}}{S}
\]

\[
S_{\text{max}} = \frac{d}{1.5 \text{nm}} \frac{2 \sqrt{E_0 e^2 / 2C}}{1.5 \text{nm}}
\]

Explains sharp cutoff
d=0.13 nm (bond size of OH defect!)

\[S_{\text{max}}\text{ in good agreement with TLS dipole moment:}
\]
Charge fluctuators at \(\sim 10\ \text{GHz}\) explain resonances
Wineland group, NIST boulder
Errors and error correction in trapped ion systems

D. J. Wineland, Dec. ’07
Fig. 1. (A) The energy level structure of the NV center

Fig. 3. (A) Spin-echo revival frequency as a function of magnetic field amplitude

Magnetism in SQUIDs at Millikelvin Temperatures

S. Sendelbach\textsuperscript{1}, D. Hover\textsuperscript{1}, A. Kittel\textsuperscript{2}, M. Mück\textsuperscript{3}, John M. Martinis\textsuperscript{4}, and R. McDermott\textsuperscript{1,*}

This observation points to a microscopic explanation for the excess $1/f$ flux noise in Josephson circuits, a dominant source of dephasing in superconducting qubits and an open question for more than 20 years. We observe
MRS Symposium J: Material Science for Quantum Information Processing Technologies

Over the past decade there has been enormous progress in the fields of quantum information. It is now clear that one of the main challenges facing the field is the development of materials that meet the stringent requirements of quantum computing and quantum communication. This symposium will bring together scientists addressing materials issues in quantum information, including semiconductor heterostructures, semiconductor dopants, superconducting devices, diamond, graphene, $C_{60}$, carbon nanotubes, and low-noise dielectrics. Issues to be addressed include decoherence from traps and two-level system, fabrication techniques, dielectric deposition, growth and characterization, electronic-to-optical interconversion, ion implantation, semiconductor heteroepitaxy, and characterization at the atomic scale.