Continuous measurement of qubits in a solid-state quantum computer

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Issues to consider:

● Quantum algorithms and error correction when instantaneous projective measurements are not available (*measurement takes time!*)
● Initialization of entangled states
● Measurement of multi-qubit operators
● RF-SET as a detector
● Theoretical modeling of an experiment
Projective vs. continuous measurement of solid-state qubits

All quantum algorithms and error correction procedures assume “orthodox” projective measurements. They are typically not possible in solid-state quantum computers.

Algorithms should be rewritten for realistic case of continuous quantum measurements!

Two possible approaches:
- ensemble-averaged (loss of information, not clear if possible at all)
- Bayesian (selective or conditional)
Status of the Bayesian approach

Continuous measurement of a single qubit – well studied by now (experimental predictions, quantum feedback control, etc.)

Bayesian formalism is ready to be used in design of quantum algorithms and error correction; however, no attempts yet

Continuous measurement of entangled qubits – formalism developed, few examples studied

Bayesian formalism is ready to be used in design of quantum algorithms and error correction; however, no attempts yet
Initialization of entangled qubits

Using a ground state – very slow and not reliable way
⇒ measurements should be used (ON - OFF is simple!)

Two qubits can be made and kept 100% entangled using continuous measurement (Ruskov-Korotkov, PRB 2003)

Can $N$-qubit entangled state be produced by continuous measurement? (Answer not known yet.)
Measurement of multi-qubit operators

Measurement of one qubit – natural
Measurement of a multi-qubit function – not trivial

*Problem:* measurement tends to collapse each qubit separately
*Solution:* not distinguishable states (equal coupling)

1. Measurement of \((\bar{S}_1 + \bar{S}_2)^2\) *(Ruskov-Korotkov, 2002)*

2. Measurement of \(S_{1Z}S_{2Z}\) *(Averin-Fazio, 2002)*
   Quadratic detector, can be used in error correction

3. Continuous measurement by a quadratic detector;
   operator \(S_{1Z}S_{2Z} + S_{1Y}S_{2Y}\)
   *(Mao-Averin-Ruskov-Korotkov, work in progress)*

Which \(N\)-qubit operators can be measured? How?
Quadratic Quantum Detection

Mao, Averin, Ruskov, A.K., 2003

\[ I(\uparrow\uparrow) \]

\[ I(\uparrow\downarrow) = I(\downarrow\uparrow) \]

\[ I(\downarrow\downarrow) \]

Linear detector

Nonlinear detector

\[ I(\uparrow\uparrow) \]

\[ I(\uparrow\downarrow) = I(\downarrow\uparrow) \]

\[ I(\downarrow\downarrow) \]

Quadratic detector

Quadratic detection is useful for quantum error correction (Averin-Fazio, 2002)
Two-qubit detection
(oscillatory subspace)

\[ S_I(\omega) = S_0 + \frac{8}{3} \frac{\Omega^2 (\Delta I)^2 \Gamma}{(\omega^2 - \Omega^2)^2 + \Gamma^2 \omega^2} \]

\[ \Gamma = \eta^{-1} (\Delta I)^2 / 4S_0, \Delta I = I_1 - I_{23} = I_{23} - I_4 \]

Spectral peak at \( \Omega \), peak/noise = \((32/3)\eta\)
(\(\Omega\) is the Rabi frequency)

Extra spectral peaks at \(2\Omega\) and 0

\[ S_I(\omega) = S_0 + \frac{4\Omega^2 (\Delta I)^2 \Gamma}{(\omega^2 - 4\Omega^2)^2 + \Gamma^2 \omega^2} \]

\( (\Delta I = I_{23} - I_{14}, \ I_1 = I_4, \ I_2 = I_3) \)

Peak only at \(2\Omega\), peak/noise = \(4\eta\)

Mao, Averin, Ruskov, A.K., 2003
Two-qubit quadratic detection: scenarios and switching

Three scenarios: (distinguishable by average current)

1) collapse into $|\uparrow\downarrow - \downarrow\uparrow\rangle = |1\bar{E}\rangle$ , current $I_D$, flat spectrum
2) collapse into $|\uparrow\uparrow - \downarrow\downarrow\rangle = |2\bar{E}\rangle$ , current $I_\uparrow$, flat spectrum
3) collapse into remaining subspace $|3\bar{E}\rangle$, current $(I_D + I_\uparrow)/2$, spectral peak at $2\Omega$, peak/pedestal = $4\eta$.

Switching between states due to imperfections

1) Slightly different Rabi frequencies, $\Delta\Omega = \Omega_1 - \Omega_2$
$\Gamma_{1B\rightarrow2B} = \Gamma_{2B\rightarrow1B} = (\Delta\Omega)^2 / 2\Gamma, \Gamma = \eta^{-1}(\Delta I)^2 / 4S_0$

$$S_I(\omega) = S_0 + \frac{(\Delta I)^2\Gamma}{(\Delta\Omega)^2} \frac{1}{1 + \left[\omega\Gamma / (\Delta\Omega)^2\right]^2}$$

2) Slightly nonquadratic detector, $I_1 \neq I_4$

$\Gamma_{2B\rightarrow34B} = [(I_1 - I_4) / \Delta I]^2 \Gamma / 2$

$$S_I(\omega) = S_0 + \frac{2}{3} \frac{4\Omega^2(\Delta I)^2\Gamma}{(\omega^2 - 4\Omega^2)^2 + \Gamma^2\omega^2} + \frac{8(\Delta I)^4}{27\Gamma(I_1 - I_4)^2} \frac{1}{1 + [4\omega(\Delta I)^2 / 3\Gamma(I_1 - I_4)^2]^2}$$

Mao, Averin, Ruskov, Korotkov, 2003

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RF-SET as a detector

SET as a classical detector – well studied
(Korotkov et al. 1992; Korotkov 1994; Hershfield et al. 1993; Galperin et al. 1993; etc.)

Very good detector, sensitivity $\sim 10^{-6} e/\sqrt{\text{Hz}}$

SET as a quantum detector – under active study

SET can be an ideal (100% efficient) quantum detector

RF-SET as a classical detector – studied just a little
(Korotkov-Paalanen 1998; Blencowe-Wybourne 2000; Zhang-Blencowe 2002; Turin-Korotkov 2003)

RF-SET performance is comparable to SET performance

Not studied: high frequency operation, superconducting RF-SET, etc.

RF-SET as a quantum detector – not studied at all

RF SET mixer (Knobel-Yung-Cleland 2002) – not studied theoretically
RF-SET with a large $Q$-factor

(Turin-Korotkov, 2003)

Large $Q$-factor increases RF-SET response, but worsens sensitivity

RF-SET performance is comparable in the proposed regime of resonant overtone

MR – maximum response mode
OS – optimized sensitivity mode
Theoretical modeling of an experiment

Experiment by Pierre Echternach, JPL

Theoretical modeling at UCR

Geometrical modeling using FASTCAP: prediction of parameters, CAD-tool for layout design

Simulation of physical processes: checking and understanding experimental results
Conclusions

- Measurement of solid-state qubits is typically continuous; this requires new quantum algorithms and error correction procedures.
- Initialization of entangled qubits can be done by measurement; only one simple example studied.
- Measurement of multi-qubit operators is important, but not trivial; study just started.
- Surprisingly, the theory of RF-SET is still at initial stage.
- Numerical modeling is important both before and after experiment (FASTCAP + process simulation).