Continuous measurement of qubits in a solid-state quantum computer

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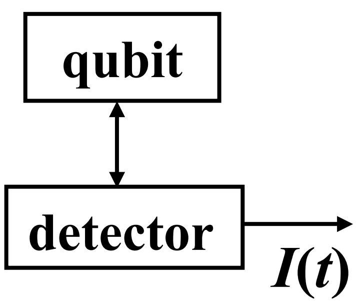
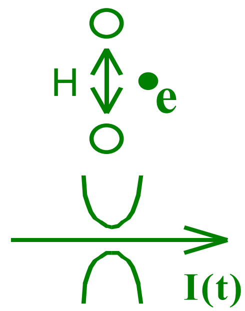
Issues to consider:

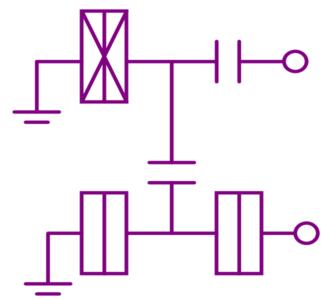
- **Quantum algorithms and error correction when instantaneous projective measurements are not available (*measurement takes time*!)**
- **Initialization of entangled states**
- **Measurement of multi-qubit operators**
- **RF-SET as a detector**
- **Theoretical modeling of an experiment**

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.







$$\tau_m = \frac{2S_I}{(\Delta I)^2}$$

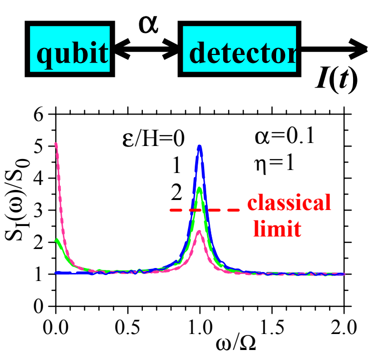
Algorithms should be rewritten for realistic case of continuous quantum measurements!

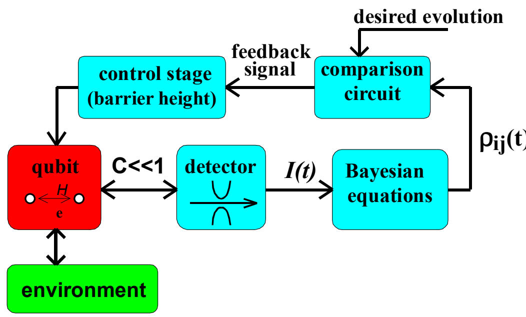
Two possible approaches:

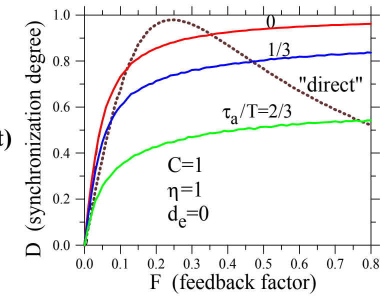
- ensemble-averaged (loss of information, not clear if possible at all)
- Bayesian (selective or conditional)

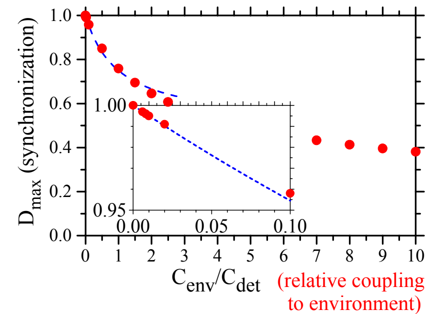
Status of the Bayesian approach

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

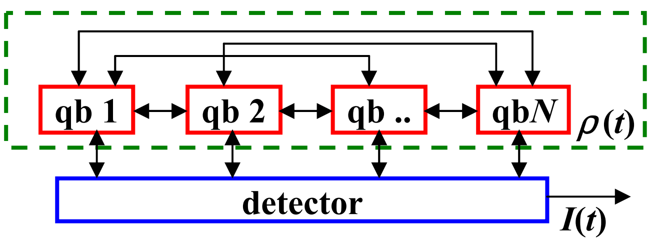


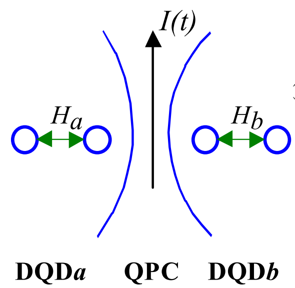


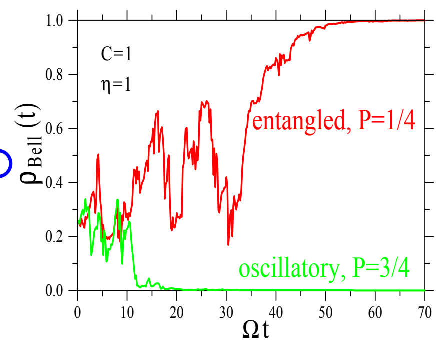


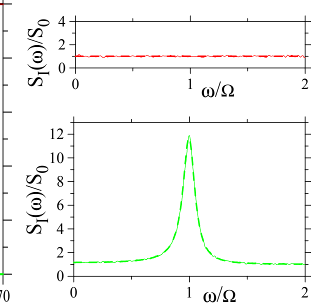


Continuous measurement of entangled qubits – formalism developed, few examples studied









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

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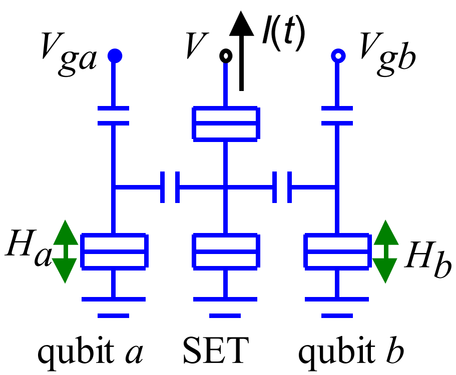
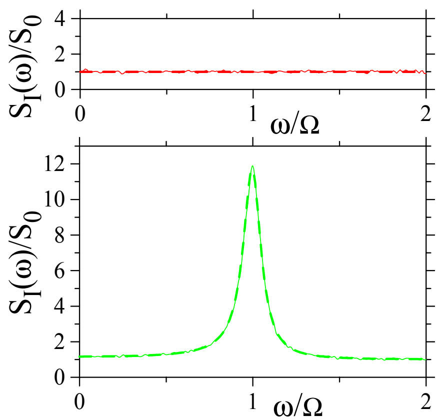
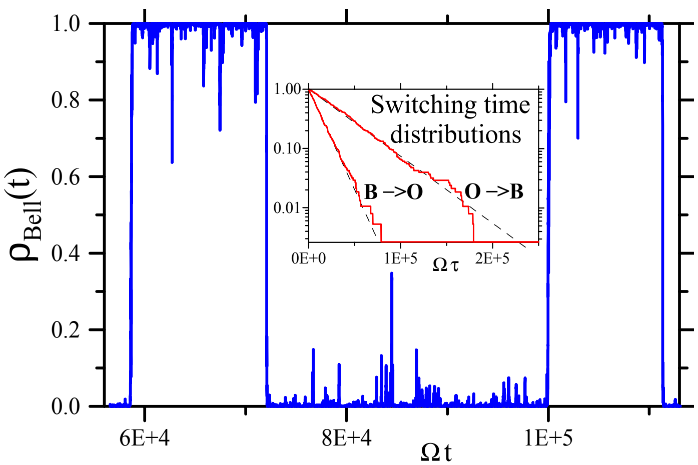
Initialization of entangled qubits

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 $(\vec{S}_1 + \vec{S}_2)^2$ ***(Ruskov-Korotkov, 2002)***

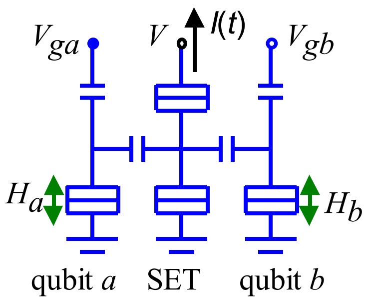
2. Measurement of $S_{1Z}S_{2Z}$ ***(Averin-Fazio, 2002)***
Quadratic detector, can be used in error correction

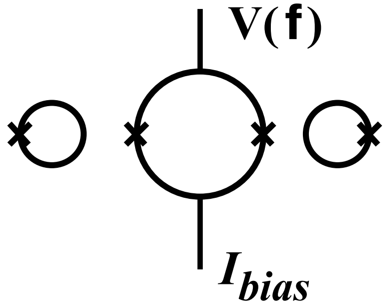
3. Continuous measurement by a quadratic detector;
operator $S_{1Z}S_{2Z} + S_{1Y}S_{2Y}$
(*Mao-Averin-Ruskov-Korotkov*, work in progress)

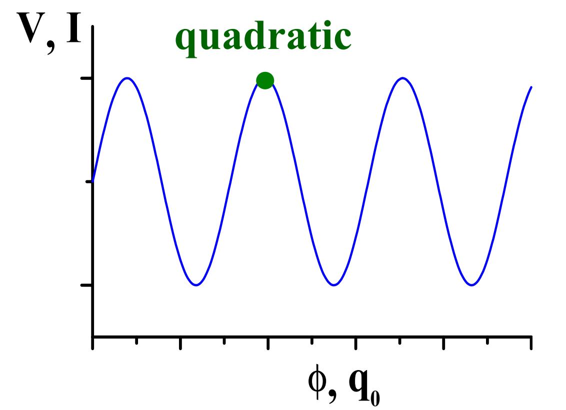
Which *N*-qubit operators can be measured? How?

Quadratic Quantum Detection

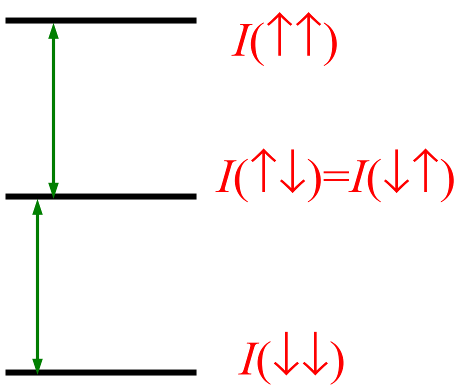
Mao, Averin, Ruskov, A.K., 2003



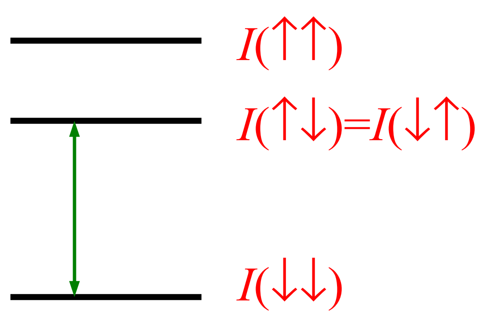




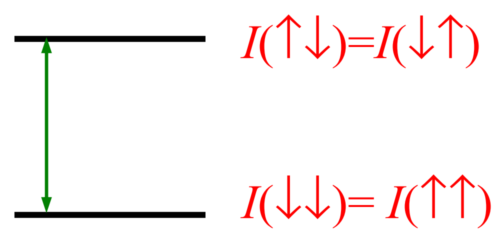
Linear detector



Noninear detector



Quadratic detector

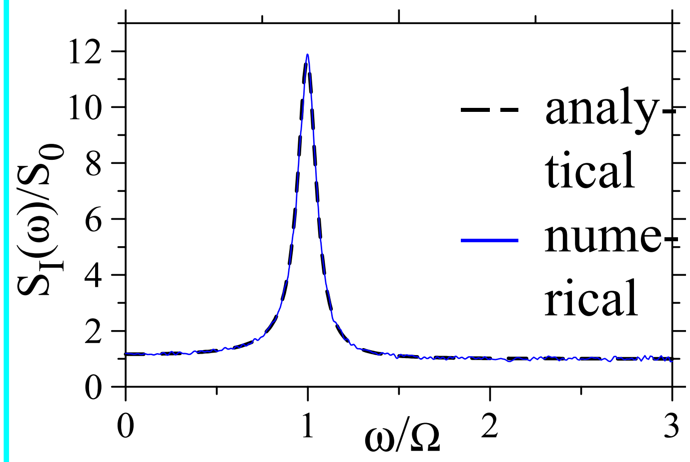


Quadratic detection is useful for quantum error correction (Averin-Fazio, 2002)

Two-qubit detection

(oscillatory subspace)

Linear detector



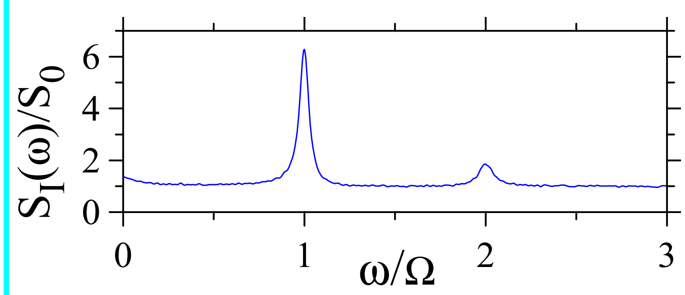
$$S_I(\omega) = S_0 + \frac{8}{3}\frac{\Omega^2(\Delta I)^2\Gamma}{(\omega^2-\Omega^2)^2+\Gamma^2\omega^2}$$

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

Spectral peak at Ω, peak/noise = (32/3)η

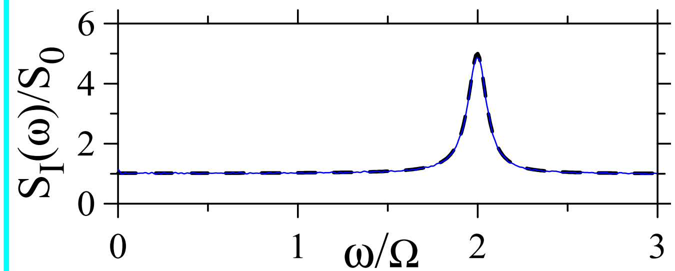
(Ω is the Rabi frequency)

Nonlinear detector



Extra spectral peaks at 2Ω and 0

Quadratic detector



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

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

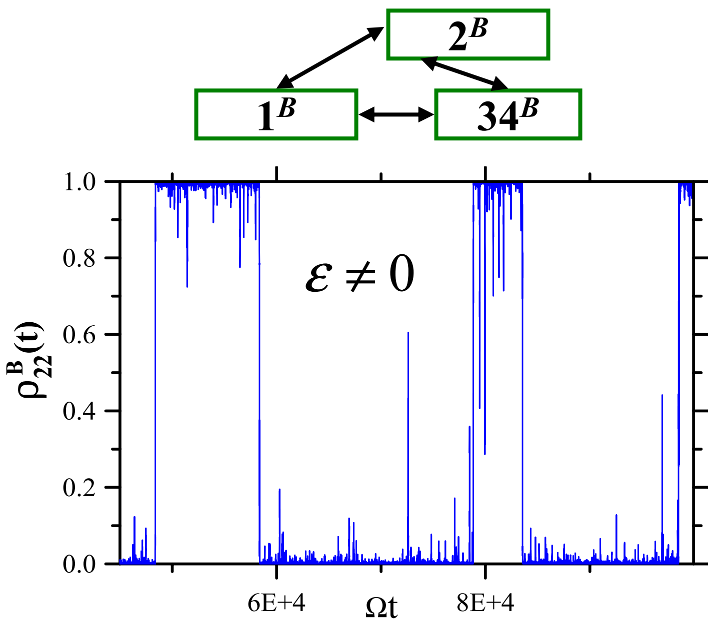
Peak only at 2Ω, peak/noise = 4η

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

Two-qubit quadratic detection: scenarios and switching

Three scenarios:
(distinguishable by average current)

1) collapse into $|\uparrow\downarrow - \downarrow\uparrow\acute{U} = |1\acute{U}^{B}$, current $I_{Æ\infty}$, flat spectrum
2) collapse into $|\uparrow\uparrow - \downarrow\downarrow\acute{U} = |2\acute{U}^{B}$, current $I_{ÆÆ}$, flat spectrum
3) collapse into remaining subspace $|34\acute{U}^{B}$, current $(I_{Æ\infty}+I_{ÆÆ})/2$, spectral peak at 2Ω, peak/pedestal = 4η.



3) Slightly asymmetric qubits, **ε≠0**

$$\Gamma_{2B\to 34B} = 2\varepsilon^2\Gamma/\Omega^2$$

Switching between states due to imperfections

1) Slightly different Rabi frequencies, $\boldsymbol{\Delta\Omega=\Omega_1-\Omega_2}$

$$\Gamma_{1B\to 2B} = \Gamma_{2B\to 1B} = (\Delta\Omega)^2/2\Gamma, \quad \Gamma = \eta^{-1}(\Delta I)^2/4S_0$$

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

2) Slightly nonquadratic detector, $\boldsymbol{I_1 \neq I_4}$

$$\Gamma_{2B\to 34B} = [(I_1-I_4)/\Delta I]^2\,\Gamma/2$$

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

Mao, Averin, Ruskov, Korotkov, 2003

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 ~ 10^{-6} $e/\sqrt{\text{Hz}}$

SET as a quantum detector – under active study

(Shnirman-Schőn 1998; Korotkov 2000; Devoret-Schoelkopf 2000; Averin 2000; van den Brink 2000; Zorin 1996; Clerk et al. 2002; Johansson et al. 2003)

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

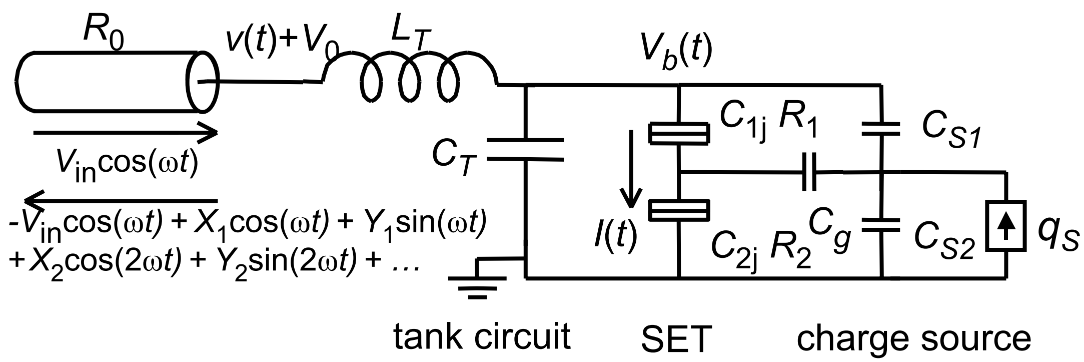
Not studied: high frequency operation, superconducting RF-SET, etc.

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

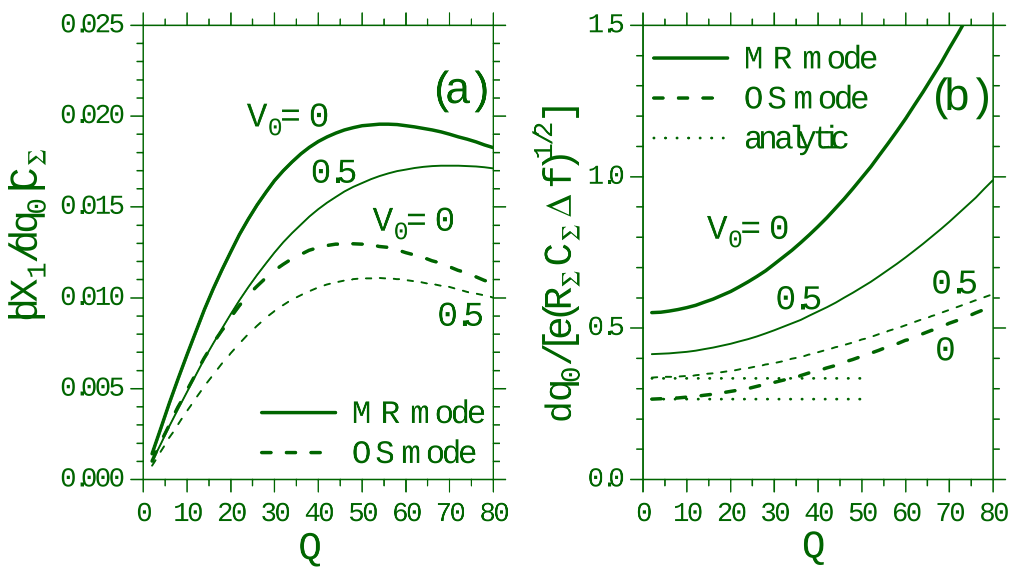
(Turin-Korotkov, 2003)



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

response

sensitivity



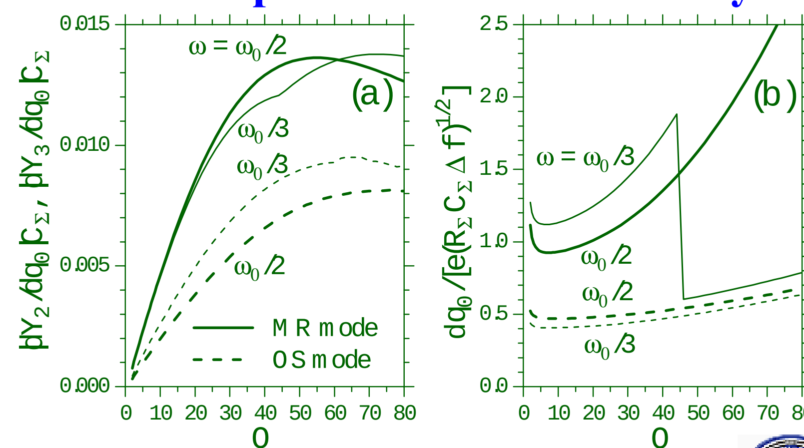
MR – maximum response mode

OS – optimized sensitivity mode

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

response

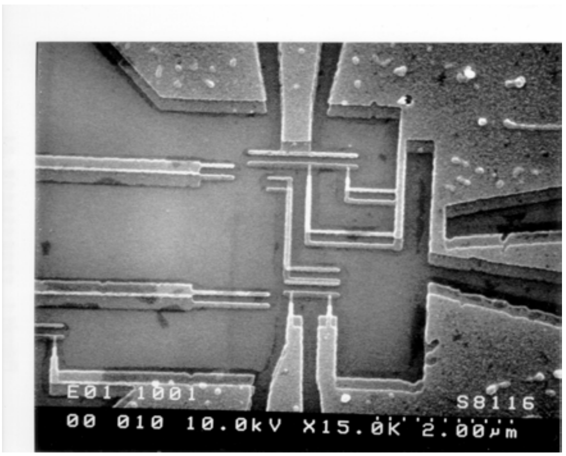
sensitivity



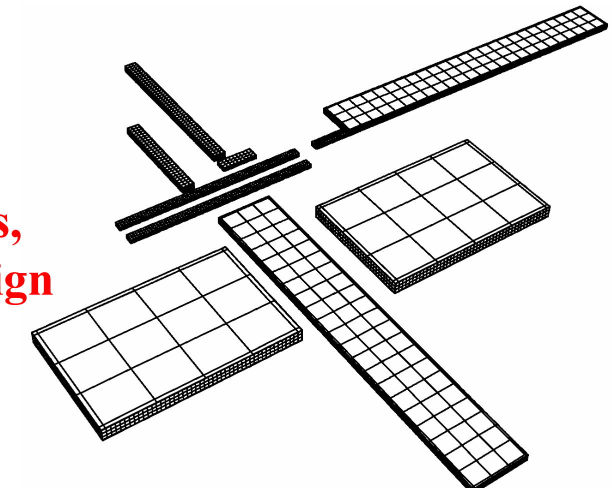
Theoretical modeling of an experiment

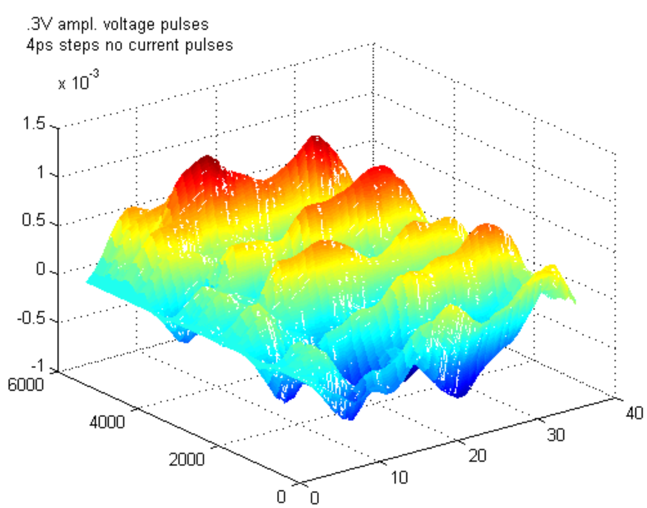
Experiment by Pierre Echternach, JPL

Theoretical modeling at UCR

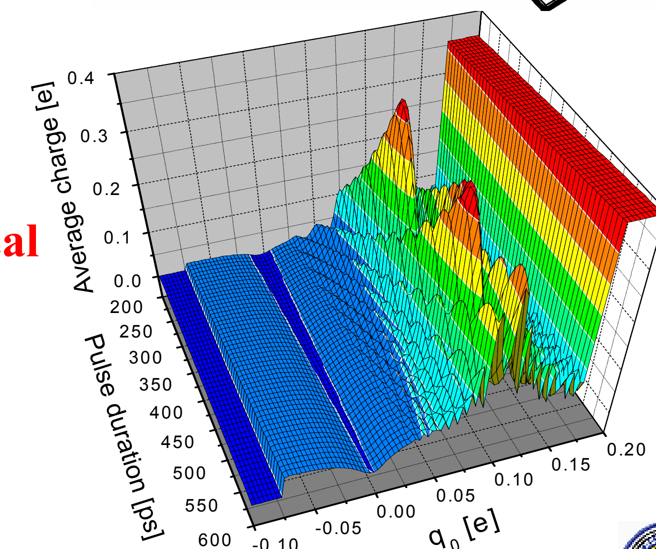


Geometrical modeling using FASTCAP: prediction of parameters, CAD-tool for layout design





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)