Quantum Computing and the Technical Vitality of Materials Physics

David DiVincenzo, IBM

SSSC, 4/2008

(list almost unchanged for some years)

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**

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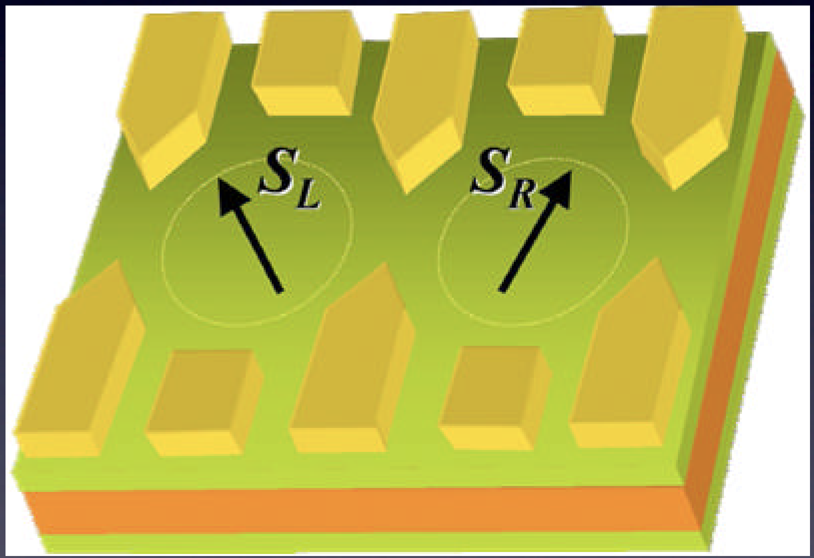
Electron spins in quantum dots

Top-Gated Quantum Dots



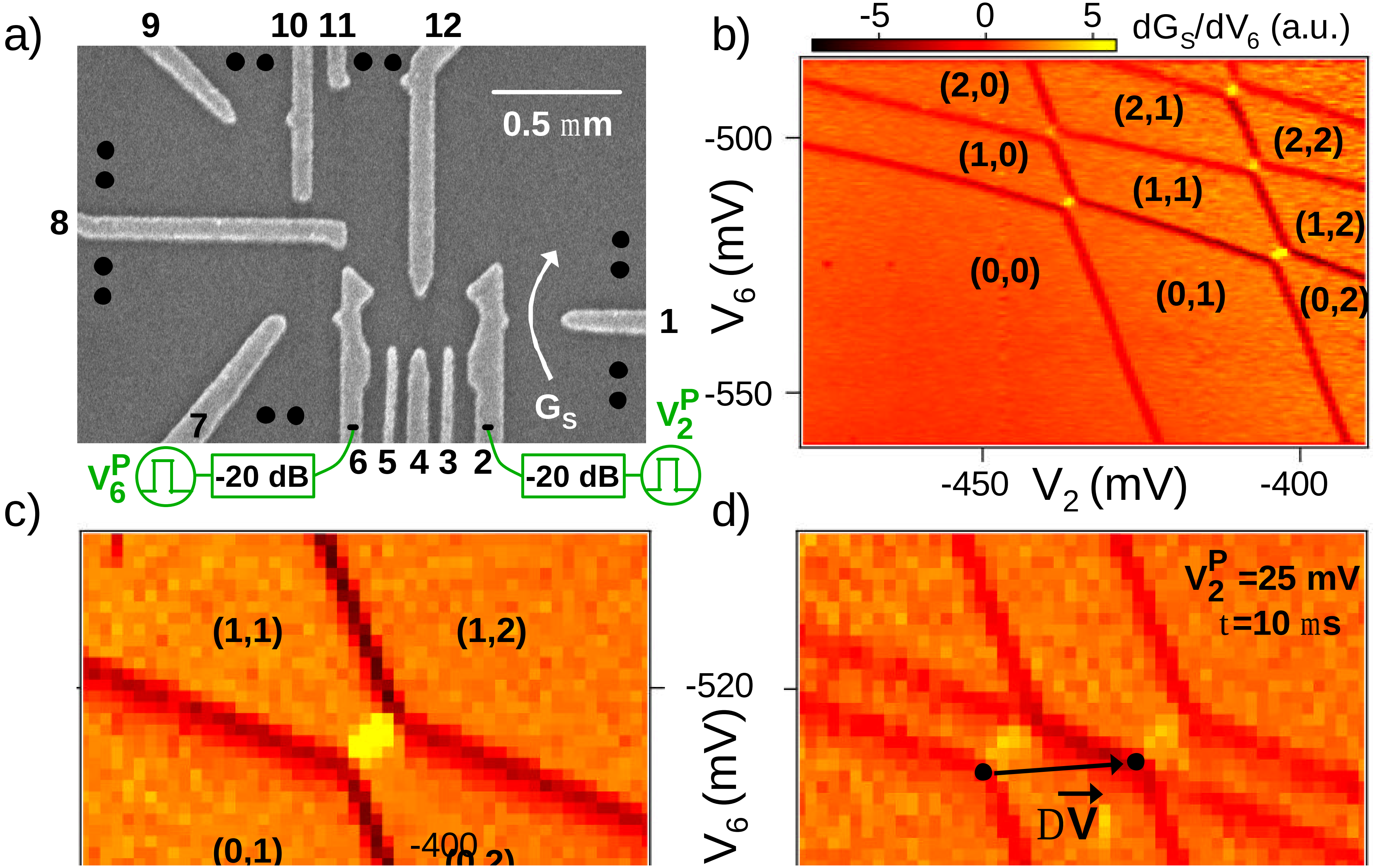
- Spin up and spin down are qubit 1 and 0.
- One electron per dot
- Qubit rotations using ESR
- Exchange enables swap operations

D. Loss and D.P. DiVincenzo, Phys. Rev. A **57**, 120 (1998)

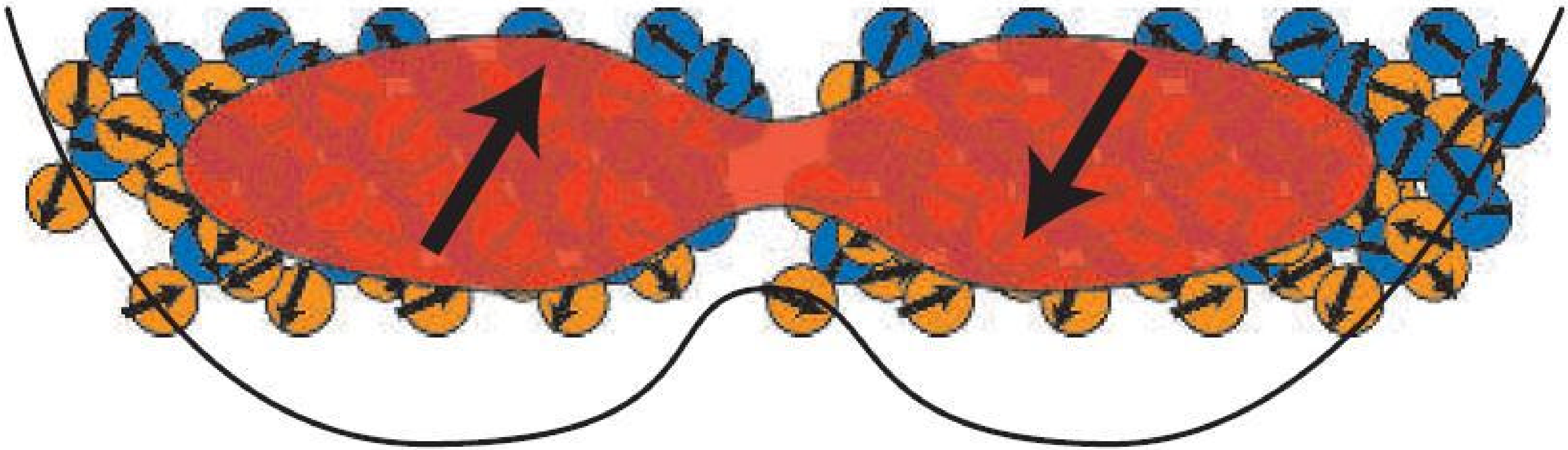
Details of Marcus-group structures and measurements

-- 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

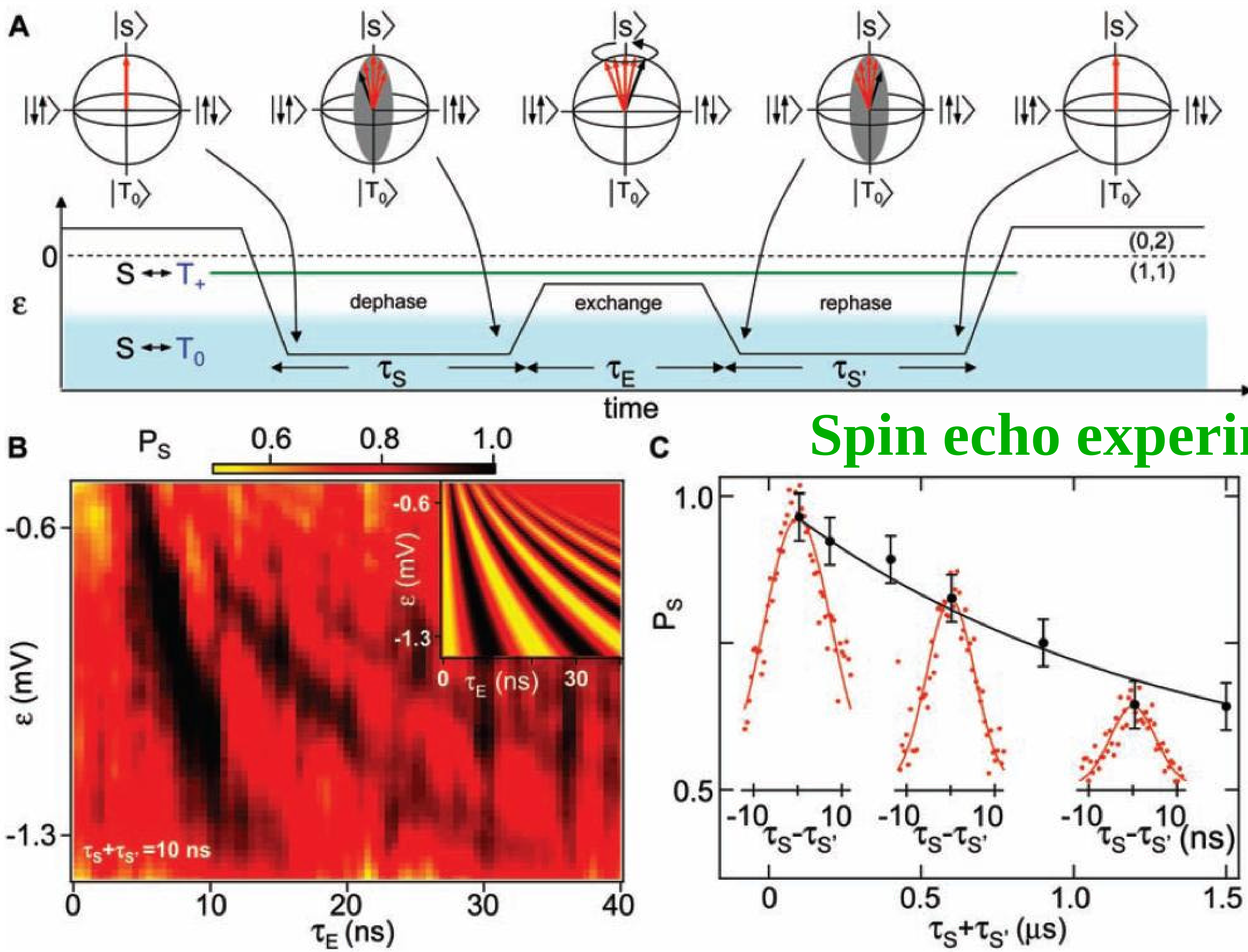


Fig. 5. (**A**) Spin-echo pulse sequence. The system is initialized in (0,2)S and transferred to S by rapid adiabatic passage. After a time τ_S at large negative detuning, S has dephased into a mixture of S and T_0 due to hyperfine interactions. A *z*-axis π pulse is performed by making detuning less negative, moving to a region with sizable $J(\varepsilon)$ for a time τ_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 τ_E. The *z*-axis rotation angle $\phi = J(\varepsilon)\tau_E/\hbar$ results in oscillations in P_S as a function of both ε and τ_E. (Inset) Model of P_S using $J(\varepsilon)$ 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_2 of 1.2 μs.

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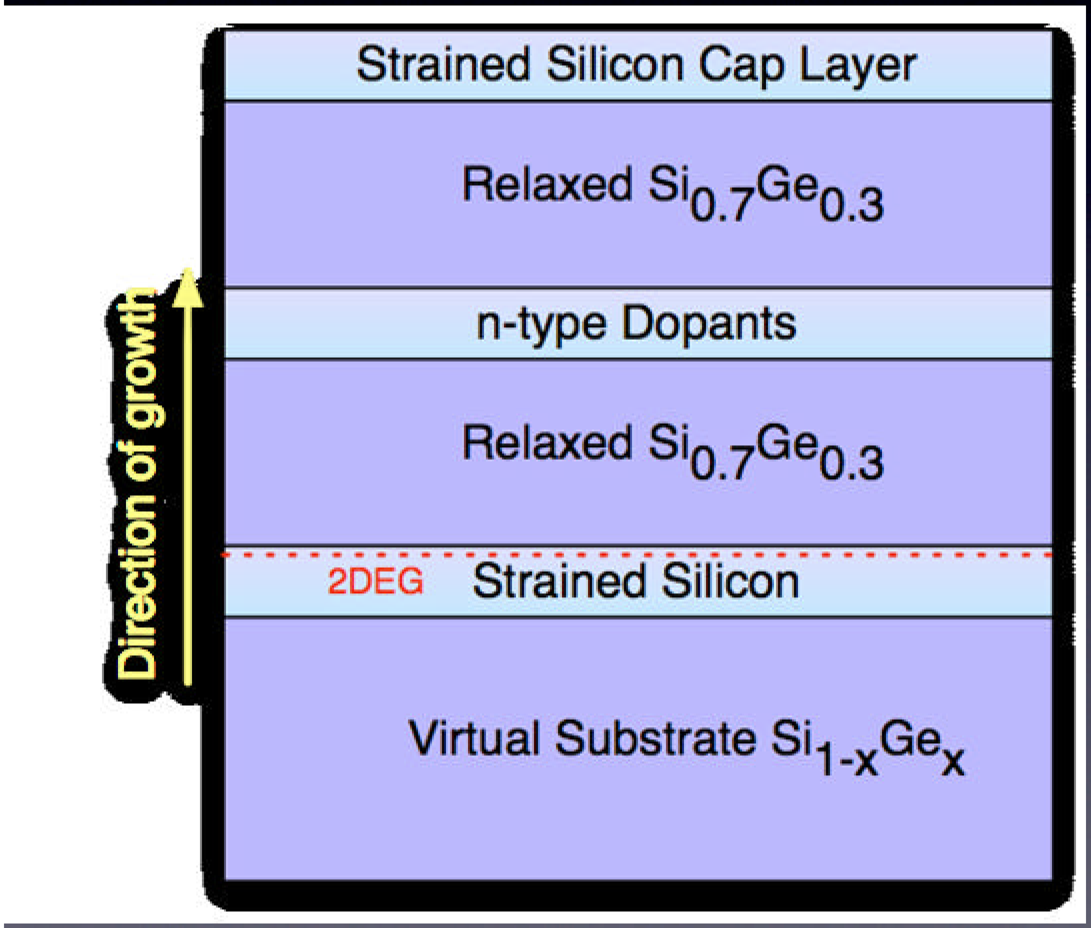
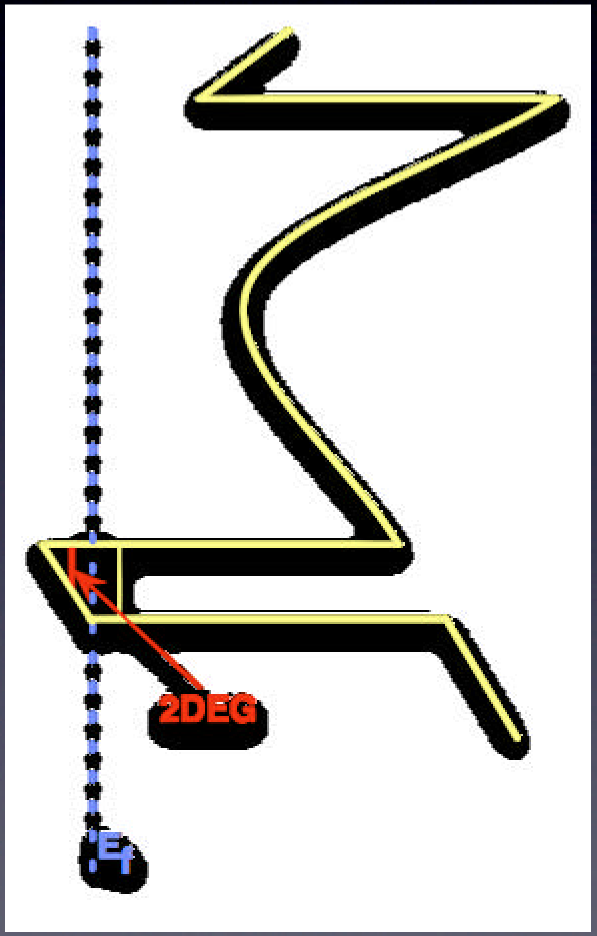
Si/SiGe Heterostructures

Schematic



Heterostructures grown by Don Savage

Conduction Band



Coulomb blockade in Schottky-gated Si/SiGe quantum dots

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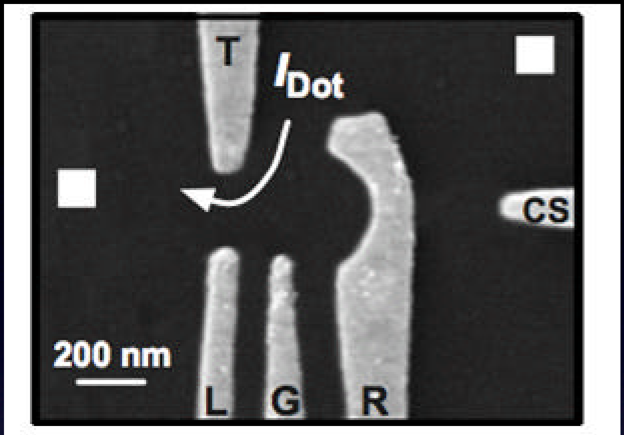
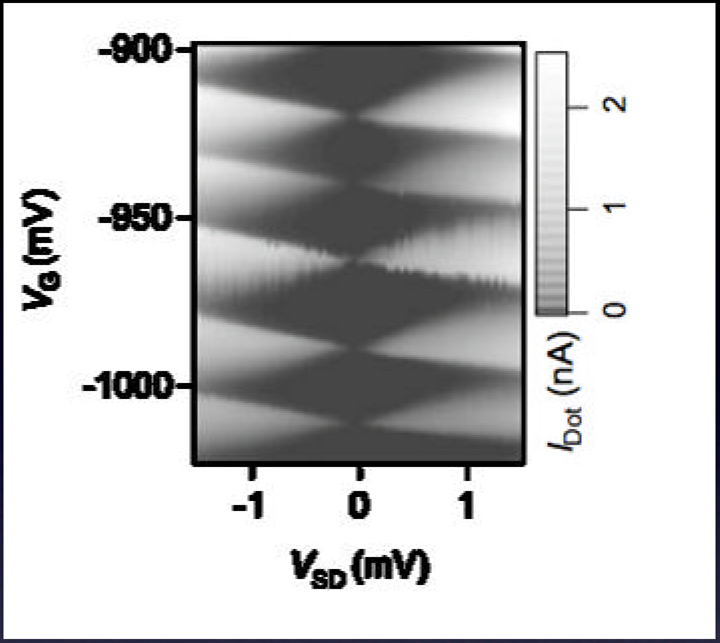
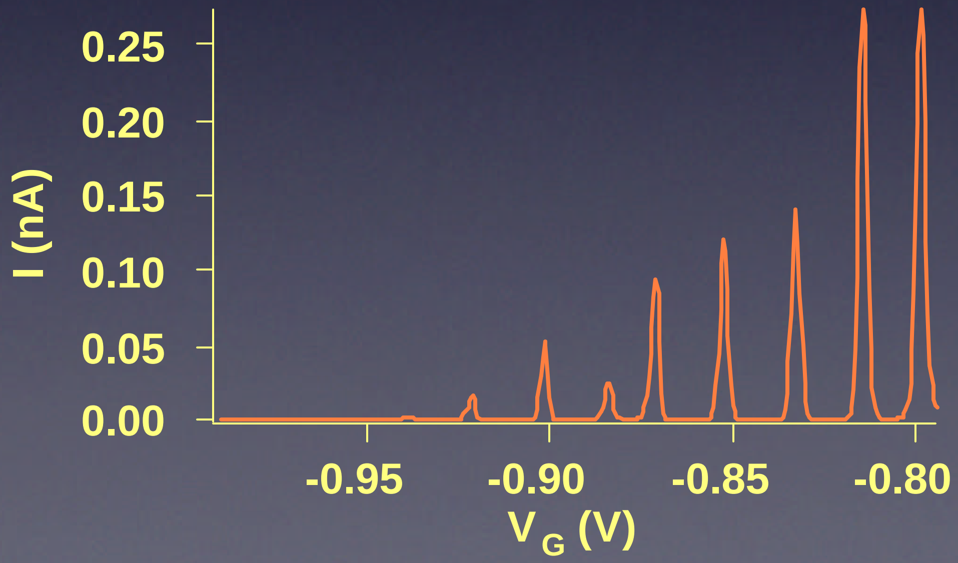


Ohmic Contacts: Au/Sb(1%)

Schottky Top Gates: Pd



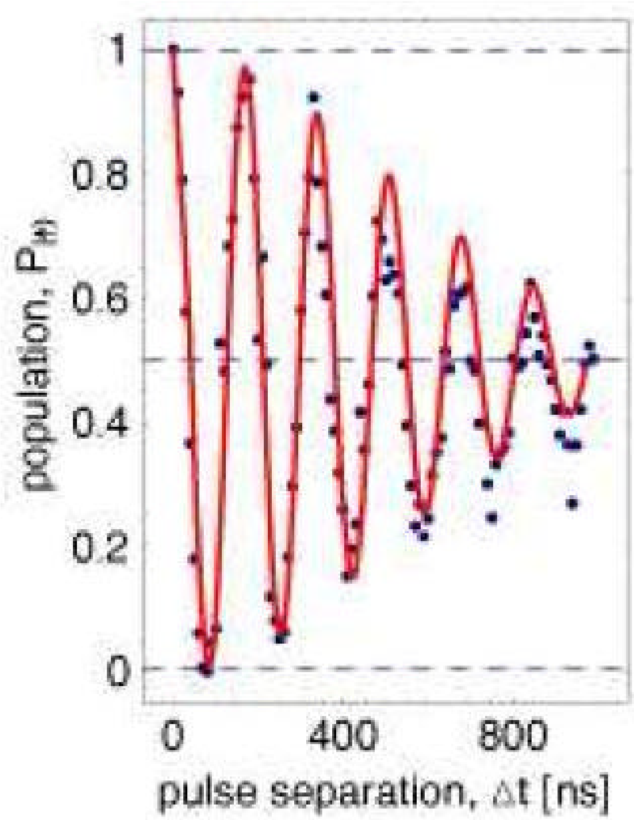


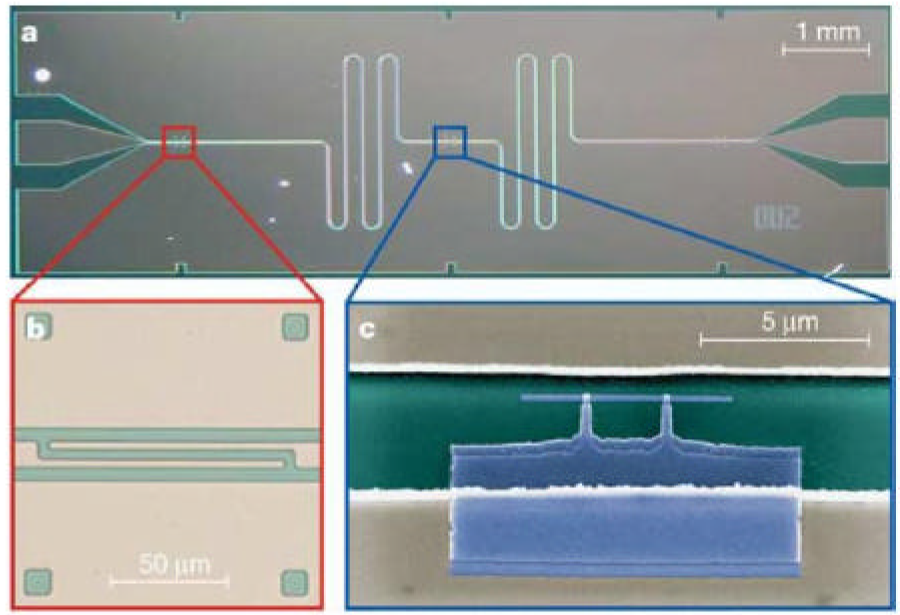
Other routes to spin-based solid state qubits

P in Si
Electrons on He surface
Carbon CNTs
II-VI semiconductors (nuclear spin story much more varied)

"Yale" Josephson junction qubit

Nature, 2004





Approaching Unit Visibility for Control of a Superconducting Qubit with Dispersive Readout

A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, J. Majer, S. M. Girvin, and R. J. Schoelkopf

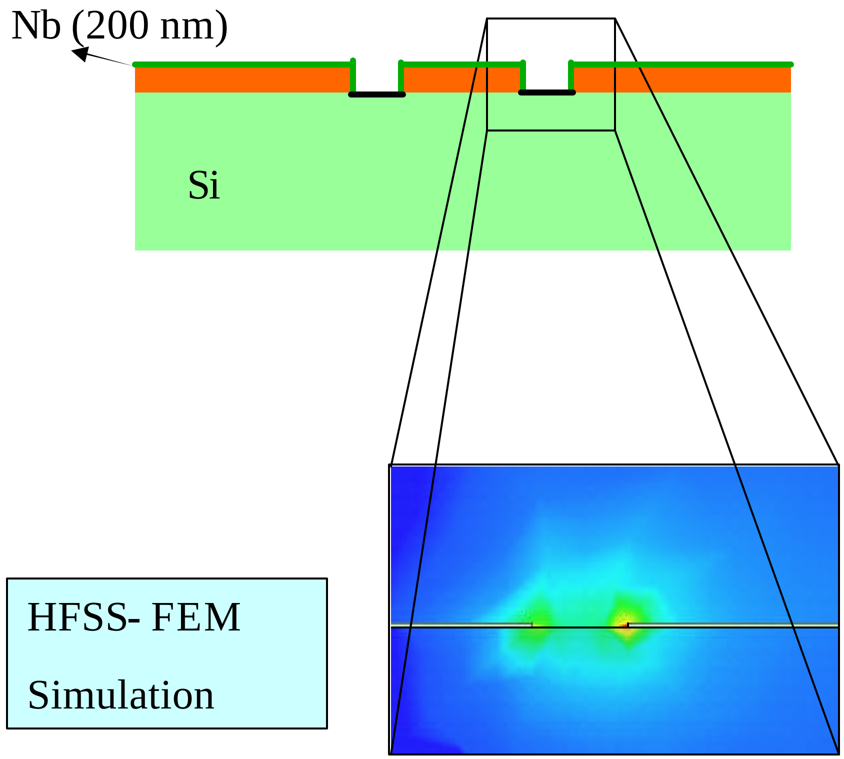
arXiv:cond-mat/0502645 v1 27 Feb 2005

Coherence time again c. 0.5 λs (in Ramsey fringe experiment)
But fringe visibility > 90% !

Shwetank Kumar, IBM

Excess noise – Where from?

Co-Planar Waveguide Geometry

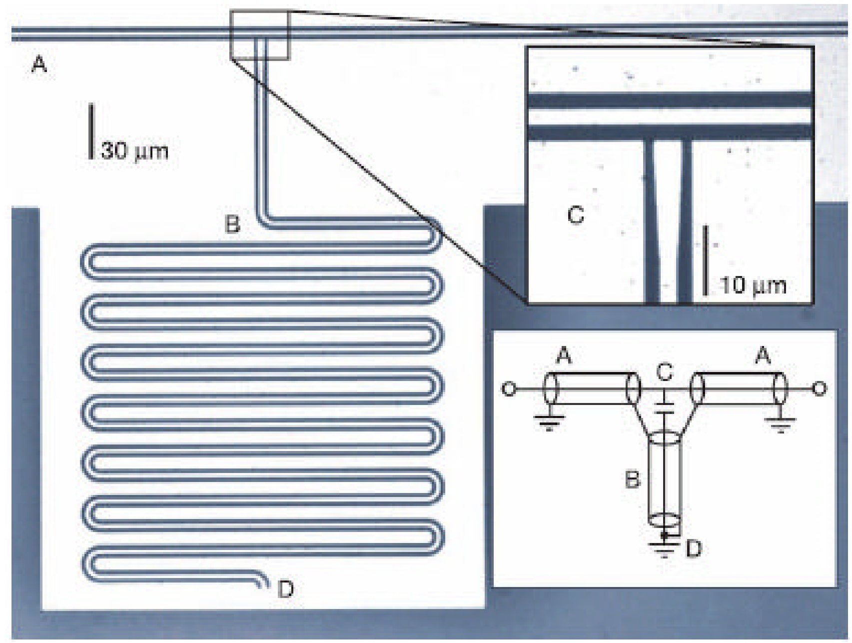


HFSS- FEM

Simulation

Most of the EM field resides in the CPW slots

Resonator Geometry



Day et. al (Nature, 2003)

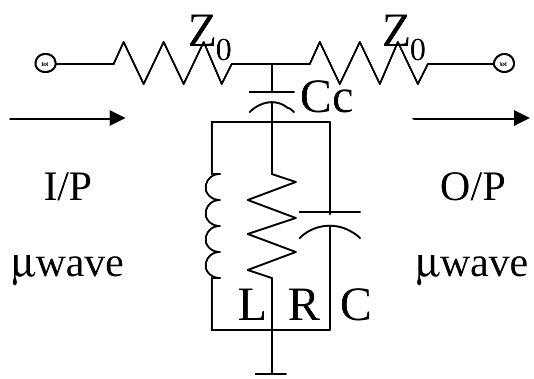
- Crystalline substrate – thin native oxide layer
- Oxidised metal surface
- TLS in glassy layer @ interface interact with E field cause phase noise! (Gao et. al. 2007, Martinis et. al. 2005)

Shwetank Kumar, IBM

Excess Phase Noise

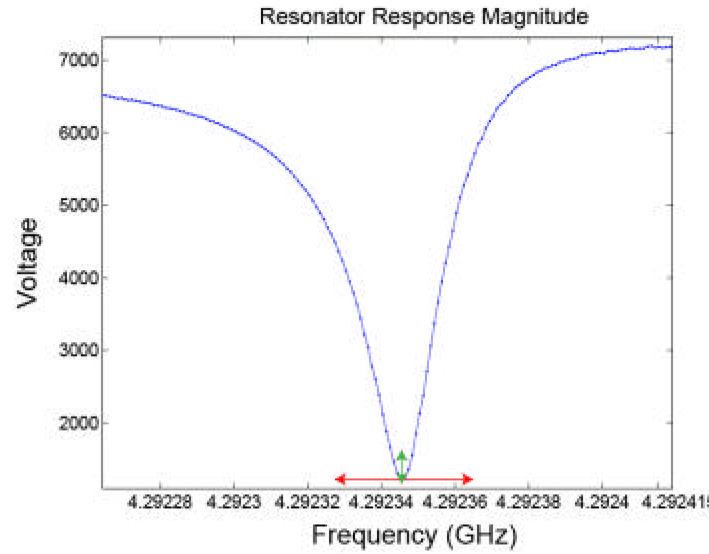
- Device performance limited by resonator intrinsic noise
- Intrinsic noise of the device >> G-R noise Device (Day et. al., Nature 2004)
- Noise primarily in phase direction - frequency jitter (Gao et. al., APL 2007)

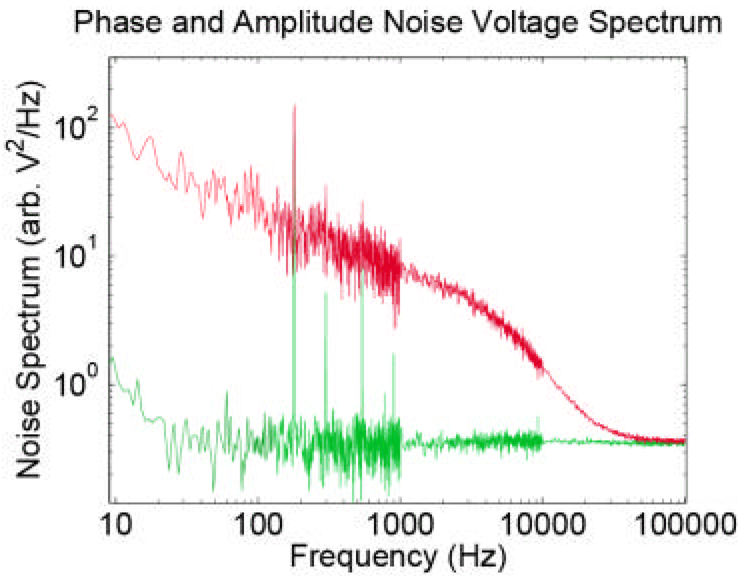
- Floor set by HEMT noise – amplitude direction
- Phase noise > Amplitude noise
- Rolls of with device bandwidth



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

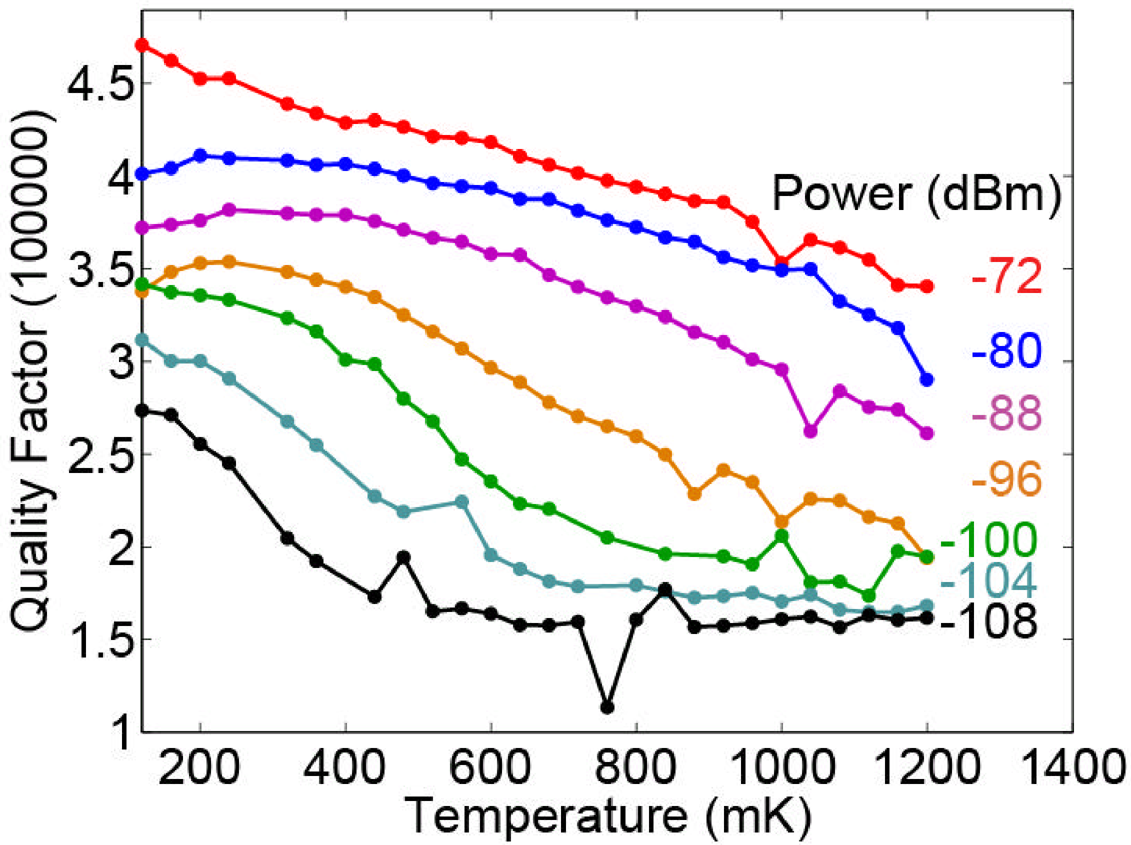
$$S_{21\,\min} = 1 - Q_r / Q_c, Q_r^{-1} = Q_i^{-1} + Q_c^{-1}$$





Shwetank Kumar, IBM

Q – factor vs Temperature



f_r = 4.35 GHz, Q_c = 496,000

• Loss increases with temperature

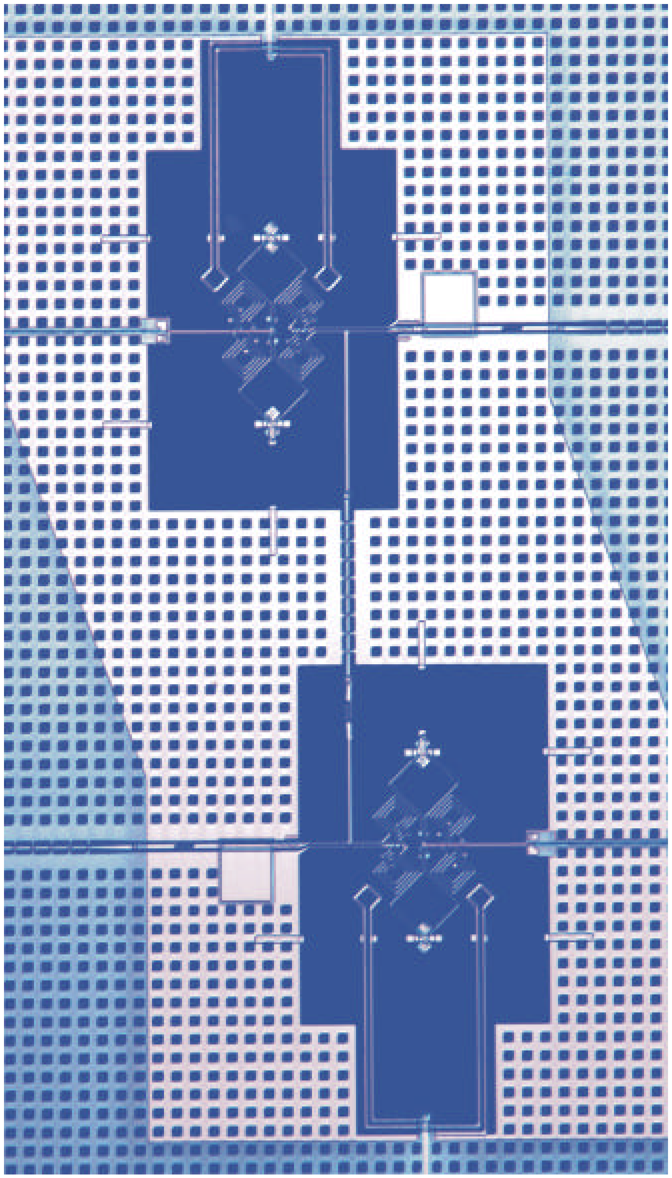
Physical picture

• Temperature increases - population of higher energy state increases

• More loss to phonon bath

• Power dependence – saturation of TLS effects?

High-Fidelity Josephson Qubits



UC Santa Barbara

John Martinis
Andrew Cleland

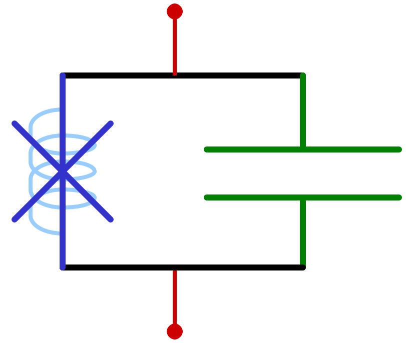
PD
Ken Cooper (JPL)
Robert McDermott (UW)
Matthias Steffen (IBM)
Eva Weig (LMU)
Nadav Katz (HU)
Haohua Wang
Max Hofheinz

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

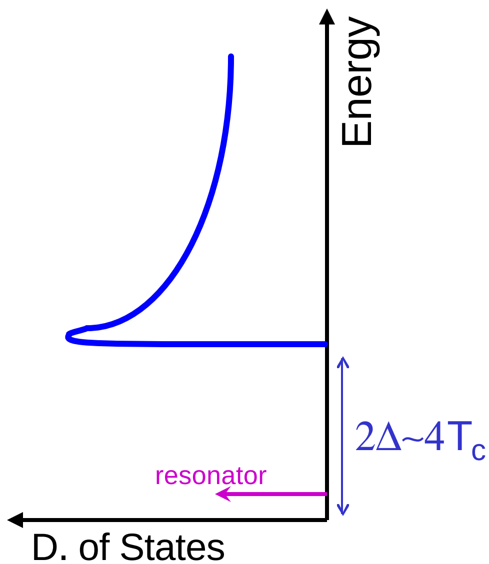
UCR **A. Korotkov**, Qin Zhang (GS),
Abraham Kofman (VS)
UCI **C. Yu**, Magdalena Constantin (PD)
UG **M. Geller**, Emily Pritchett (GS),
(Andrei Galiautdinov (PD))

NIST D. Pappas, Jeff Kline

Physical Decoherence: Where's the Problem?

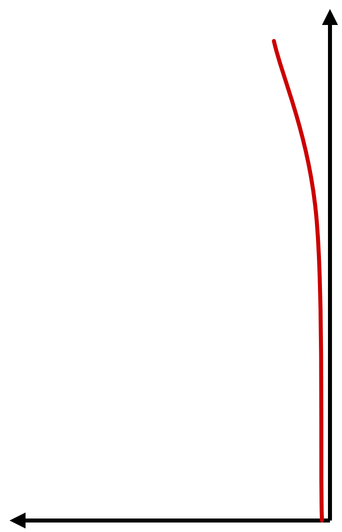


Inductors & Junctions



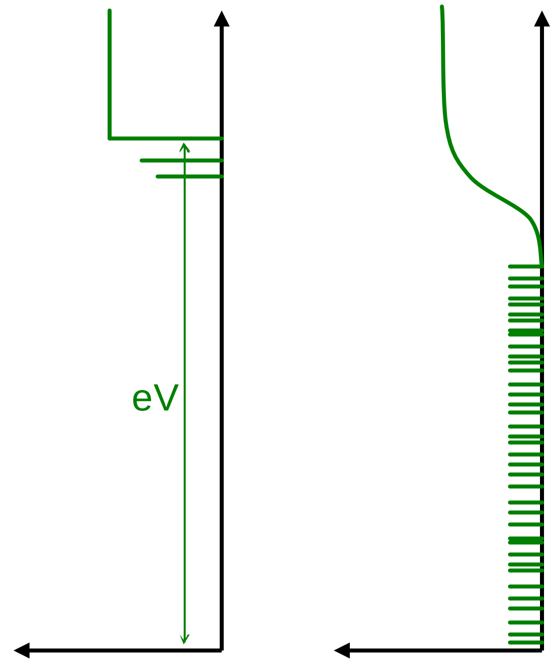
Superconductors:
- Gap protects from dissipation
- X-tal or amorphous metal
- Protected from magnetic defects

Circuits



Good circuit design
(μwave engineering.)

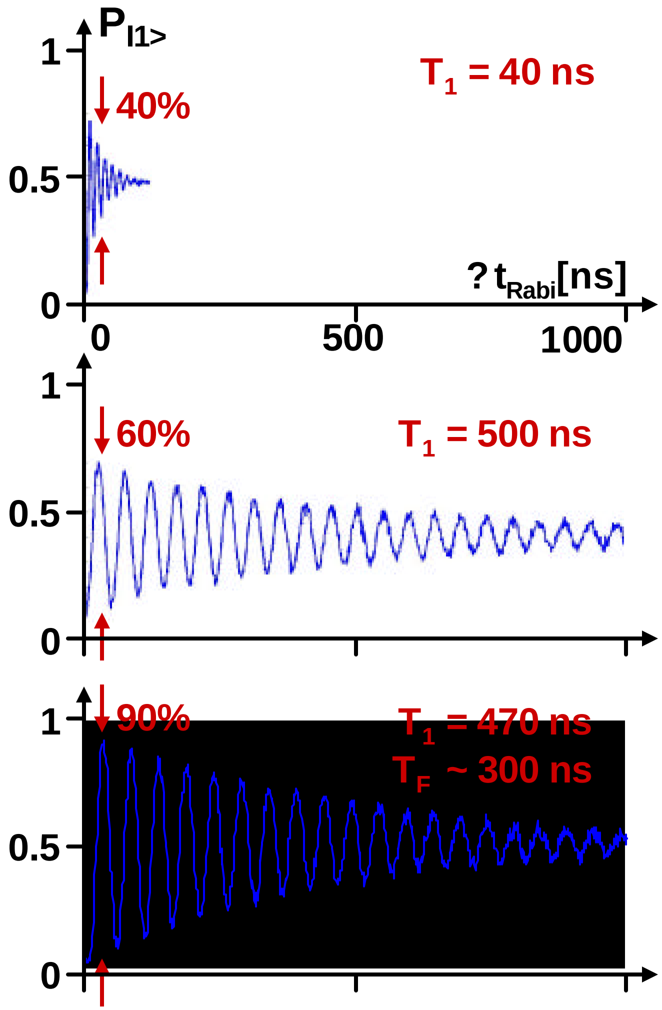
Capacitors



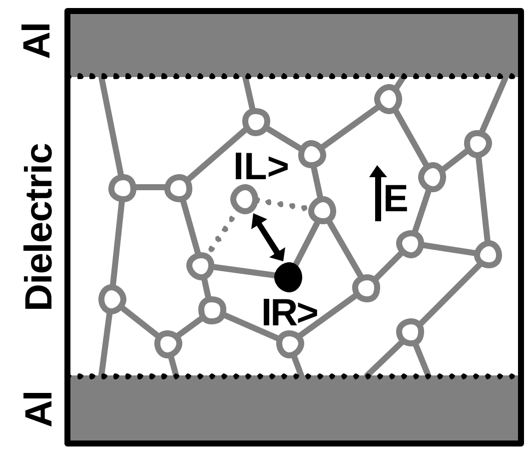
(X-tal) (amorphous)

Many low-E states
Only see at low T

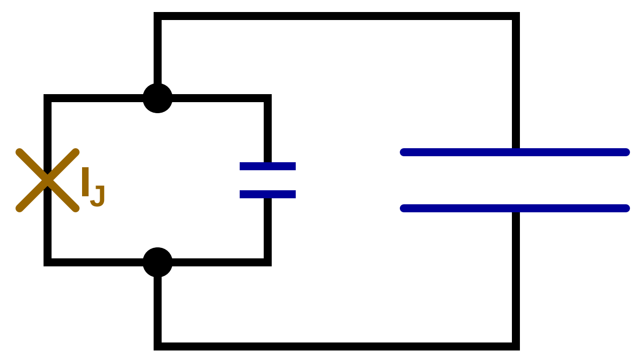
Qubit Improvements: Understanding Atomic TLS's



Al_2O_3 wafer
SiO_2 ⇨ SiN_x



Small junction
+ external Cap.



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

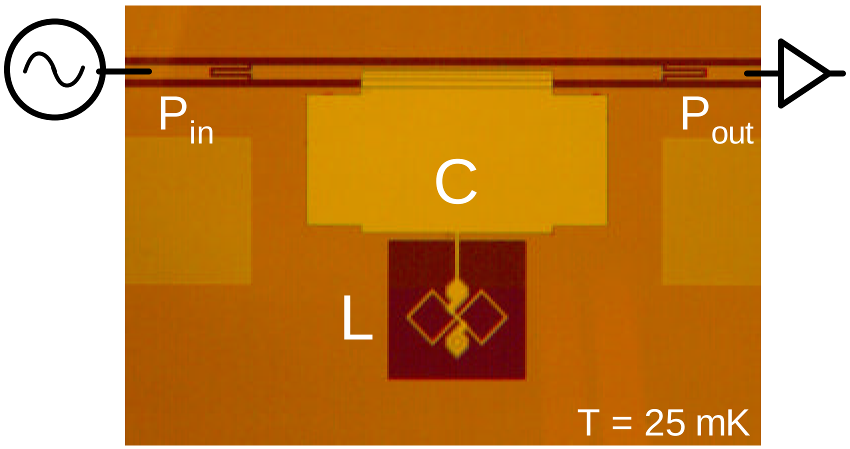
- Lower loss dielectrics: xtal's or a-Si:H

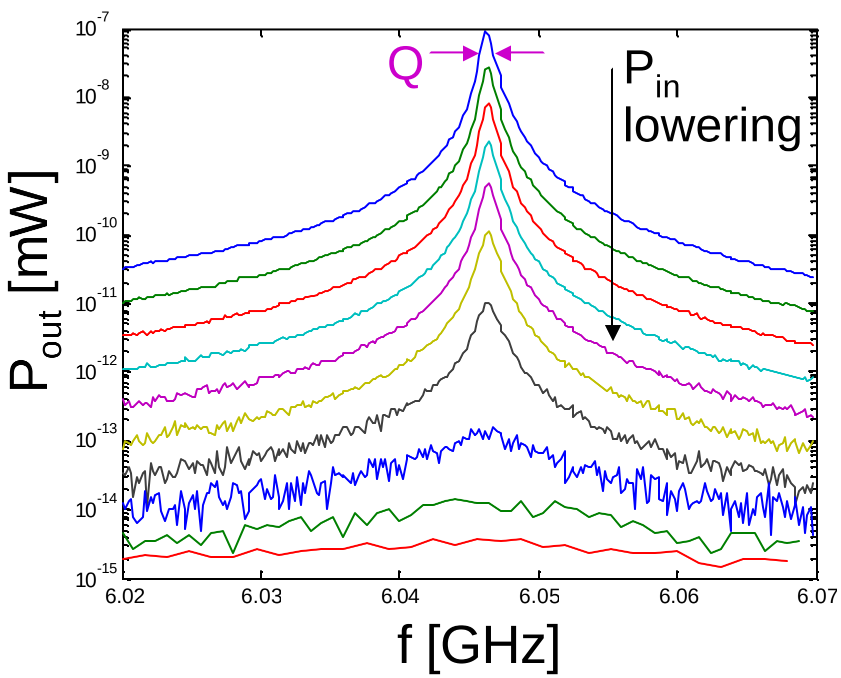
  Lossy barriers: a-AlN, MgO (D. Pappas, NIST)
- Understand magnitude of 1/f charge noise $S_Q \sim \delta_i$ (Yu and
- Understand magnitude of 1/f critical-current noise Constantin)
- TLS produces phase noise (C-fluctuations), theory in progress

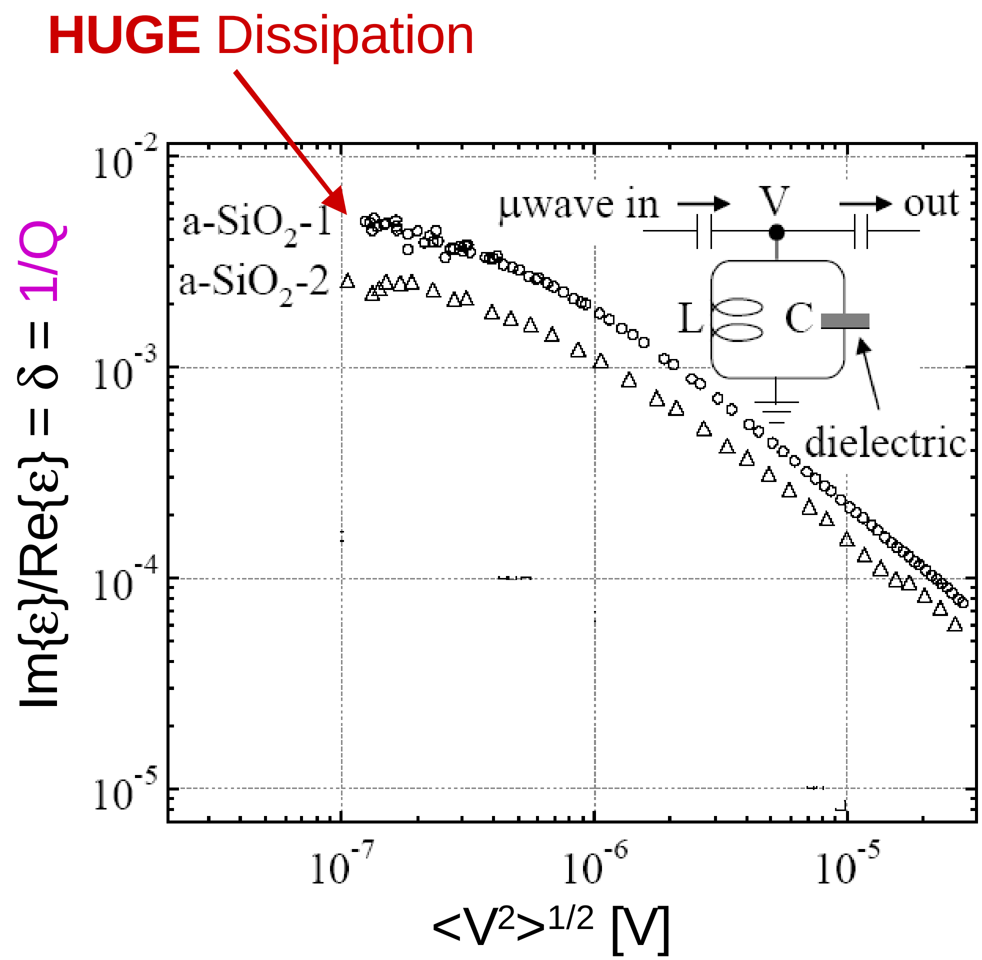
- New resonator data (J. Gao … Caltech/JPL)

  $\delta_i \sim 10^{-5} – 10^{-6}$ from surface oxide

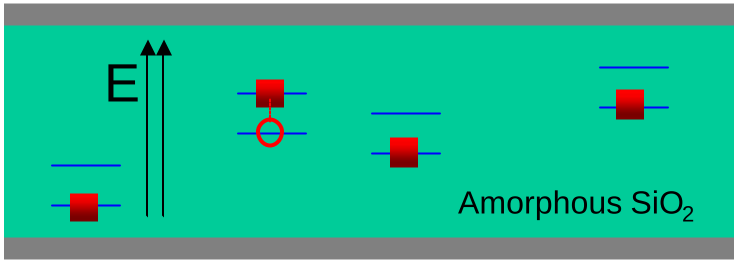
Dielectric Loss in CVD SiO_2



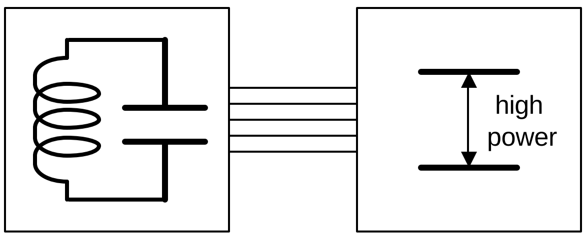




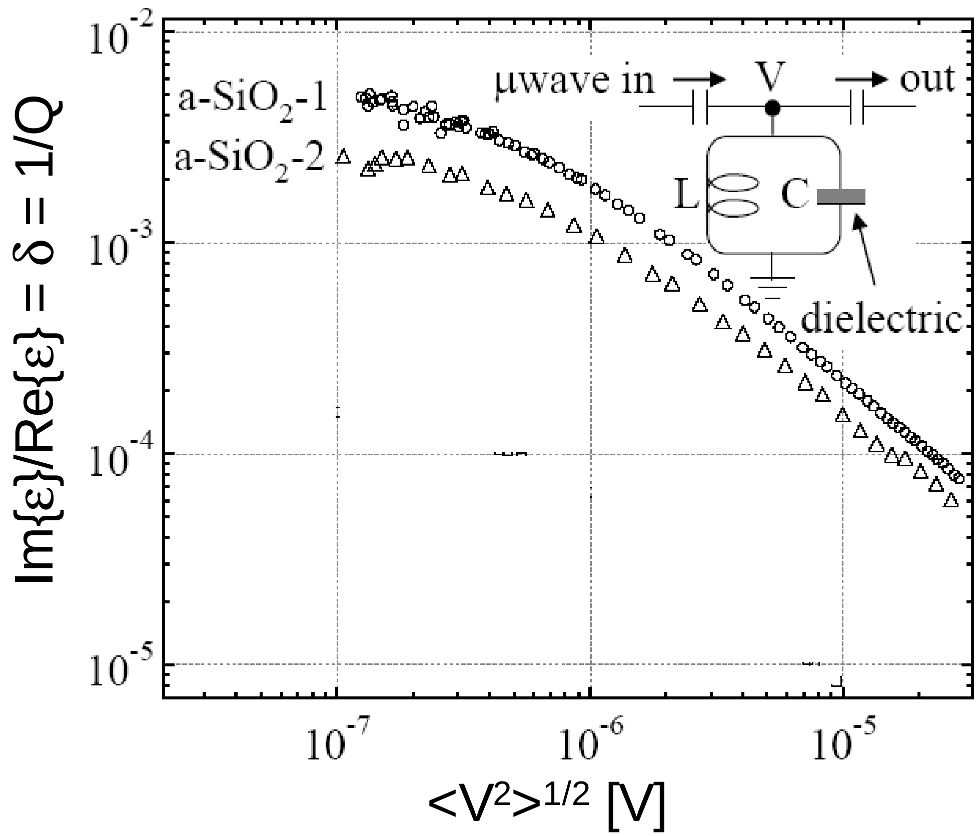
Theory of Dielectric Loss



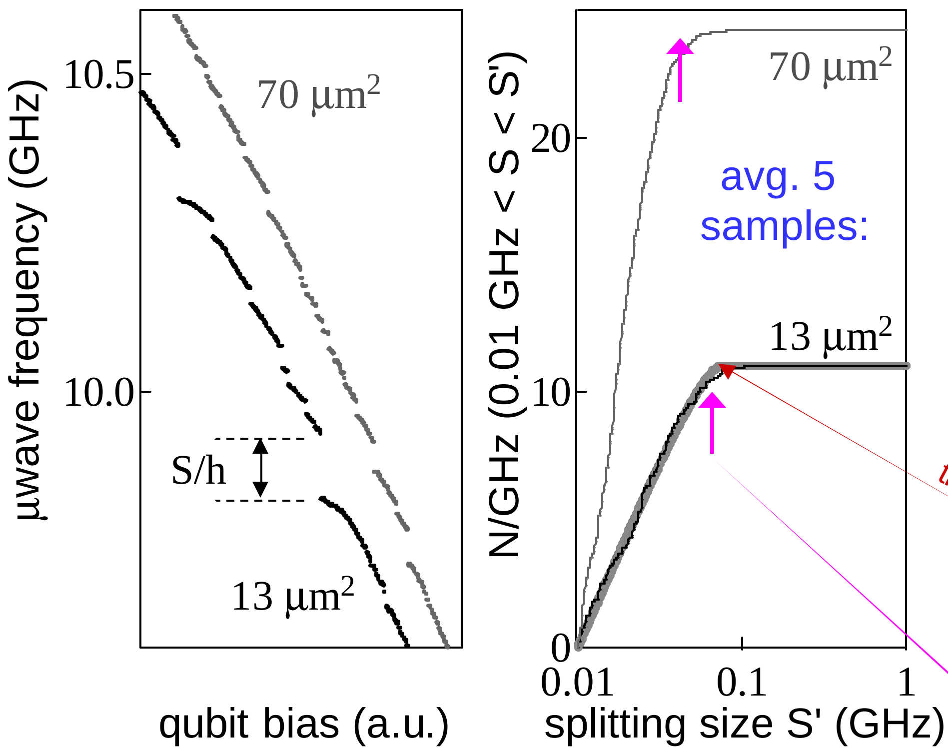
Two-level (TLS) bath: saturates at high power, decreasing loss



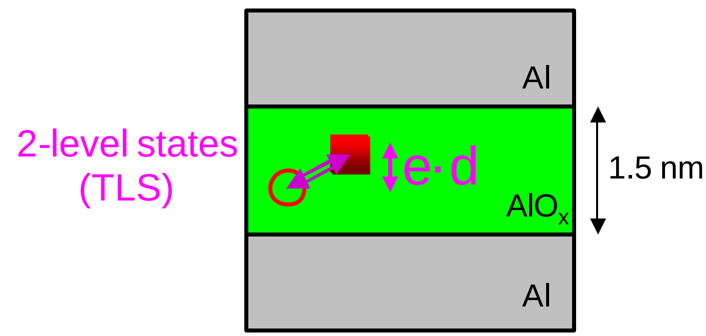
von Schickfus and Hunklinger, 1977



Junction Resonances: Dielectric Loss at the Nanoscale



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

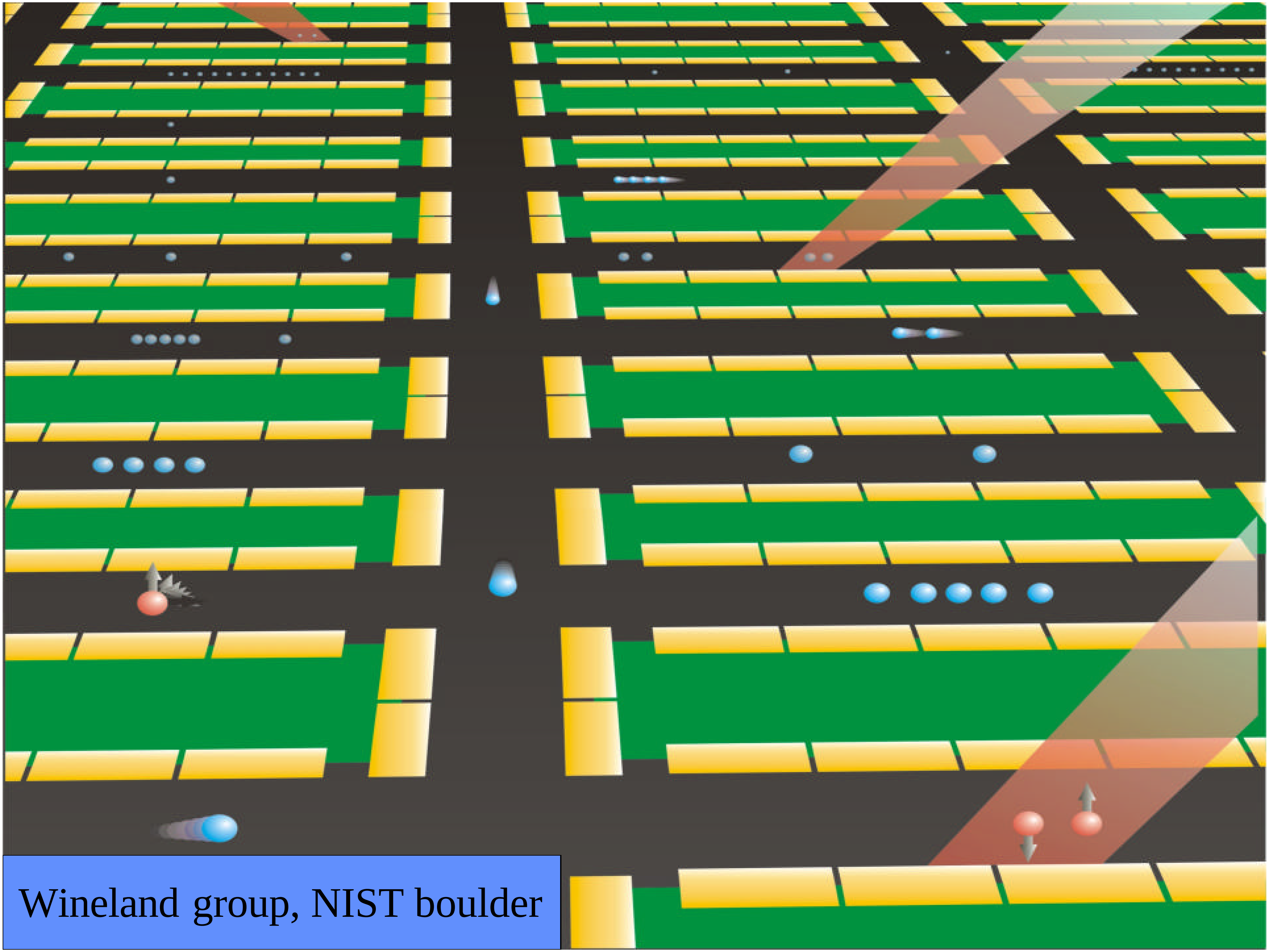


$$\frac{d^2N}{dEdS} = sA\frac{[1-(S/S_{max})^2]^{1/2}}{S}$$

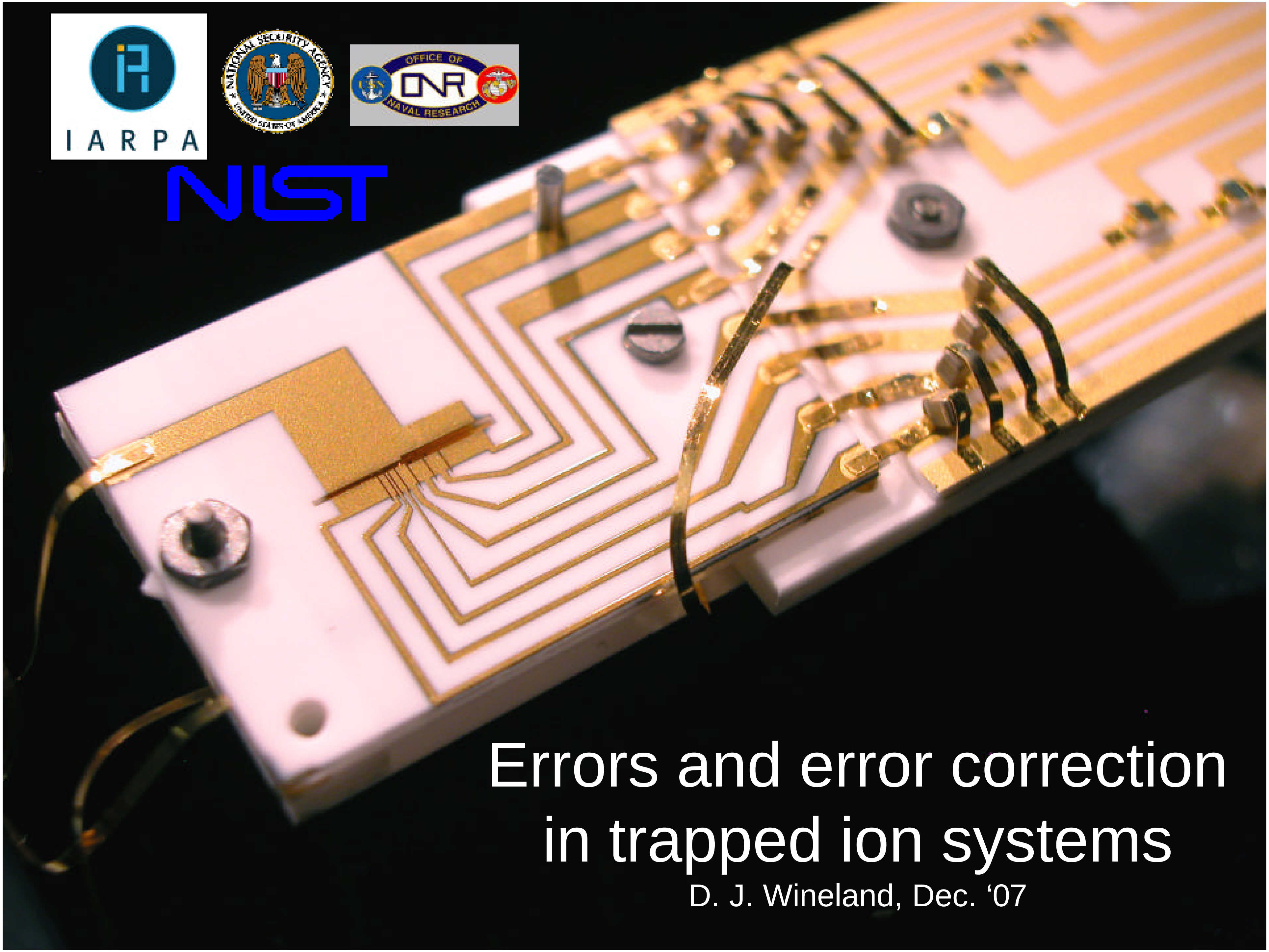
$$S_{max} = \frac{d}{1.5\text{nm}} 2\sqrt{E_{10}e^2/2C}$$

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

S_{max} in good agreement with TLS dipole moment:
Charge fluctuators at ~10 GHz explain resonances



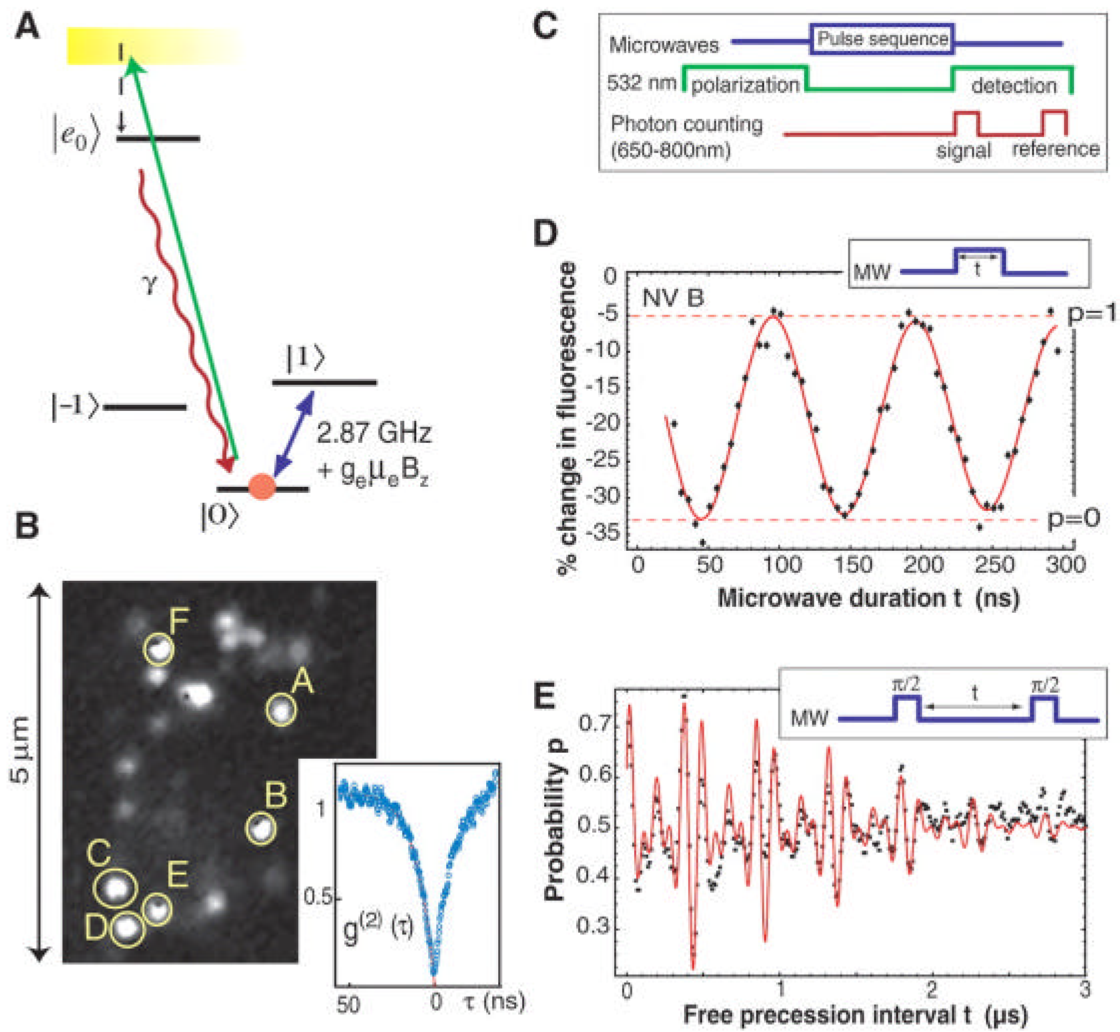
Wineland group, NIST boulder



Errors and error correction in trapped ion systems

D. J. Wineland, Dec. '07

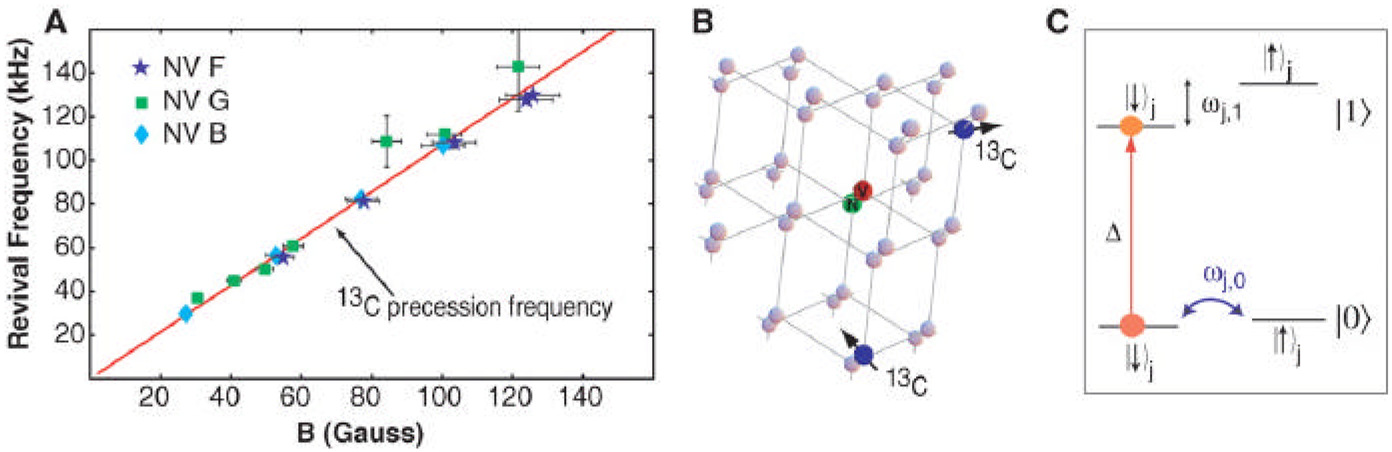
Fig. 1. (A) The energy level structure of the NV center



L. Childress et al., Science 314, 281 -285 (2006)

Published by AAAS

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

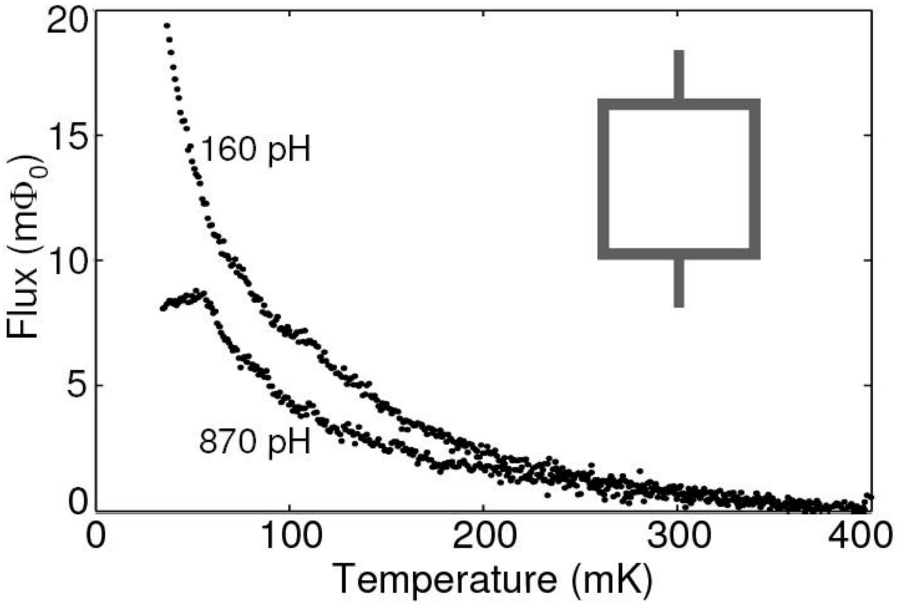


L. Childress et al., Science 314, 281 -285 (2006)

Published by AAAS

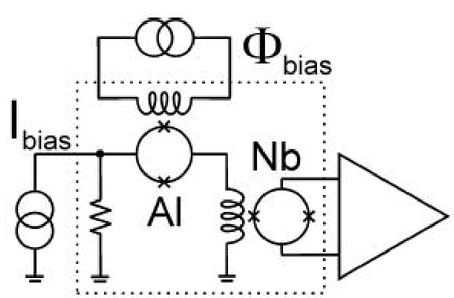
Magnetism in SQUIDs at Millikelvin Temperatures

S. Sendelbach[1], D. Hover[1], A. Kittel[2], M. Mück[3], John M. Martinis[4], and R. McDermott[1,*]

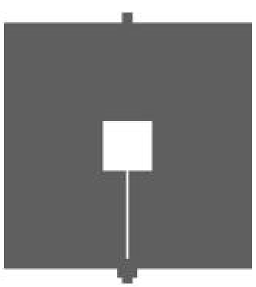


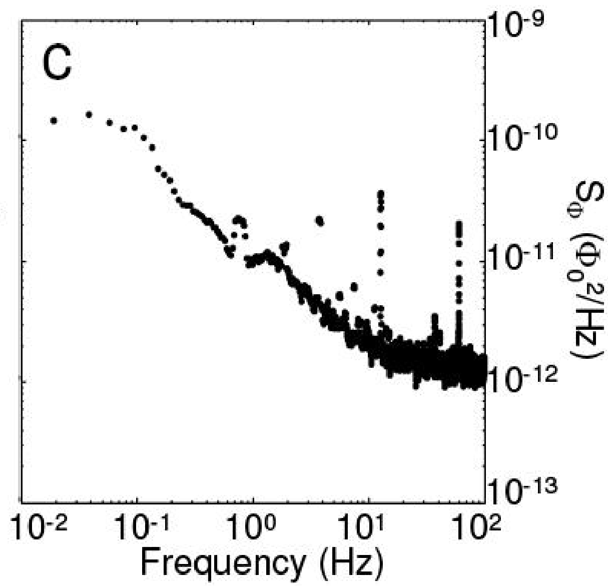
atures. This observation points to a microscopic explanation for the excess $1/f$ flux noise in Josephson circuits, a dominant source of dephasing in superconducting qubits and an open question for more than 20 years. We observe

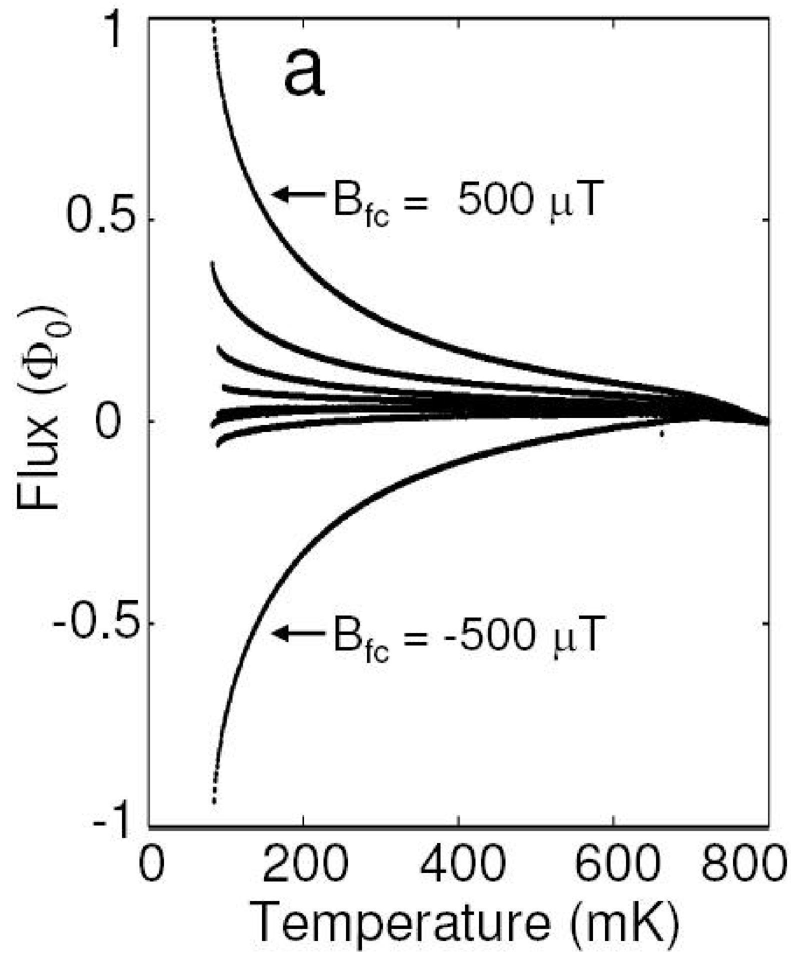
a



b







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Abstract Deadline: June 24, 2008
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