Manipulating single electrons in semiconductor devices for quantum computing

SAND2015-0024PE

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This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences user facility. This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

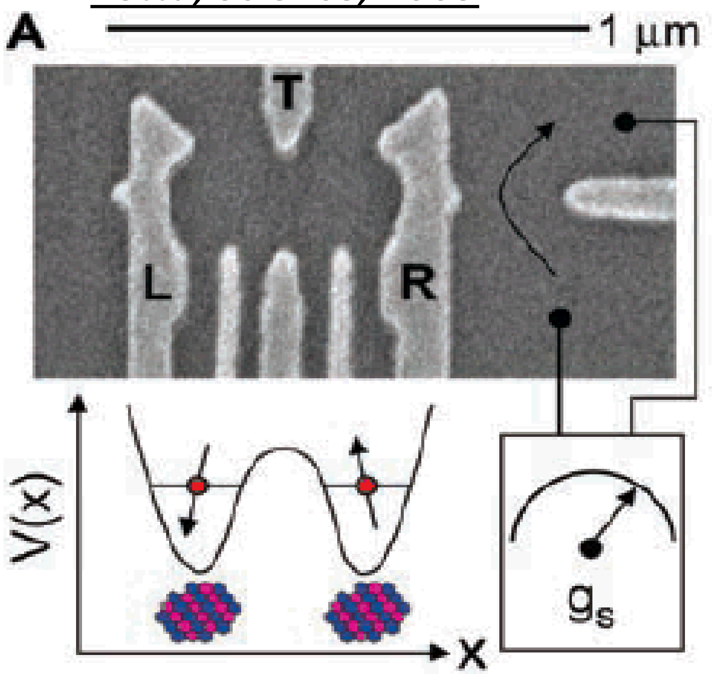
Outline

- Quantum computing with semiconductors
- Donor qubit with electron spin resonance
- Two-qubit interactions and devices

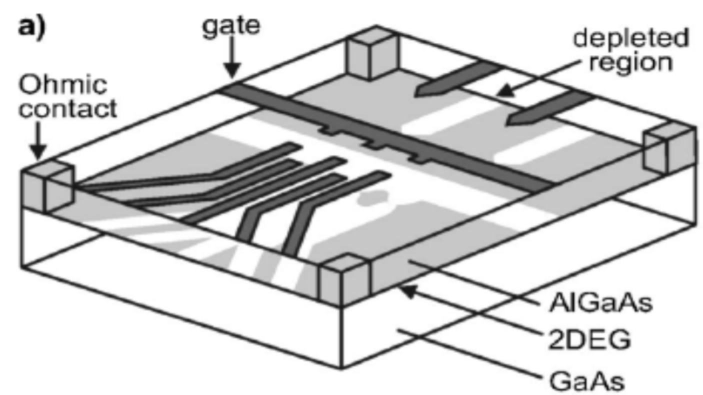
Double Quantum Dot Qubit in GaAs

- Demonstration of GaAs qubits has spurred quantum dot semiconductor qubit research (e.g., Petta et al. in 2005)

Petta, Science, 2005



Hanson, Rev. Mod. Phys. 2007



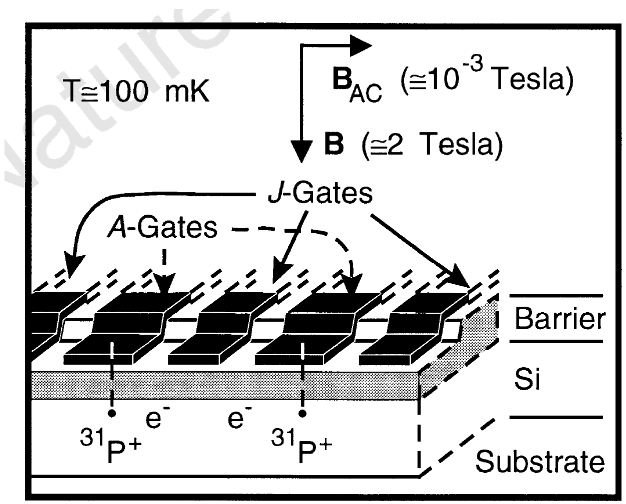
Need
- Isolate singlet triplet system
- Electrically tunable rotations
- Charge sense (fast is desirable)

Donor qubit

In silicon, the natural potential defined by a donor provides an alternative to surface dot approaches in semiconductors.

Kane architecture

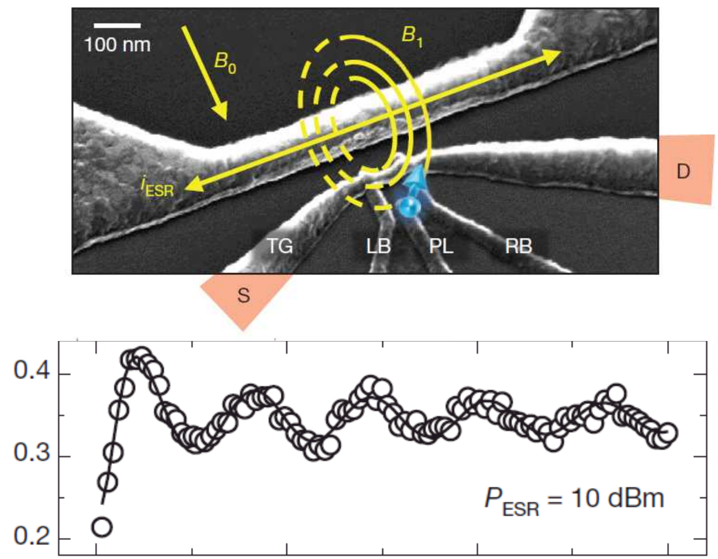
*B. E. Kane, Nature **393**, 1998*



Silicon donor research efforts

Australian CQC2T group (MOS, STM)

*J. Pla, Nature **489**, 2012*



Requirements for donor electron spin qubit

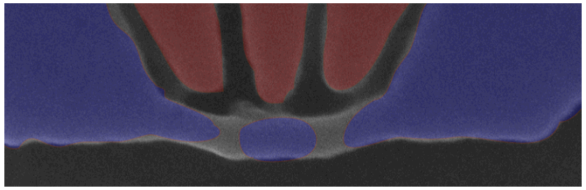
1. Isolation of a single electron for a spin qubit
2. Single spin readout technique
3. Long spin lifetime (T1)
4. Spin initialization
5. Spin rotations
6. Long dephasing time (T2)

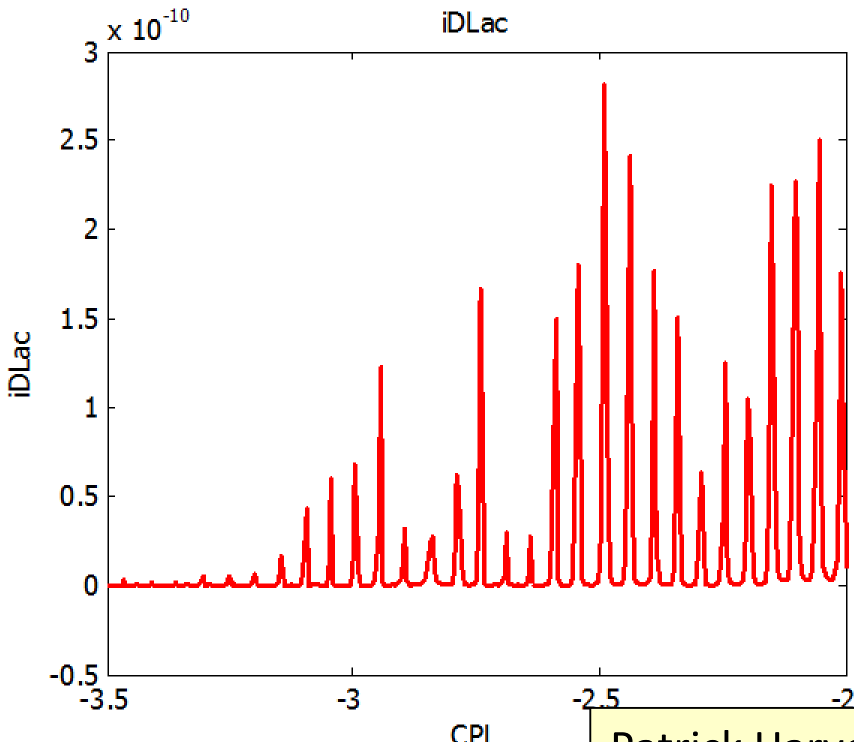
Single electron transistor

Si quantum dots

- Wire gate (blue) biased positively to accumulate electrons.
- Plunger gates (red) biased negatively to create barriers.
- Uniform Coulomb blockade indicates electrostatic dot.

polysilicon wire structure with plungers





Patrick Harvey-Collard

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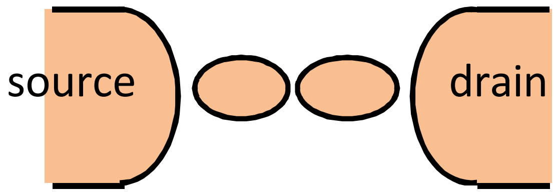
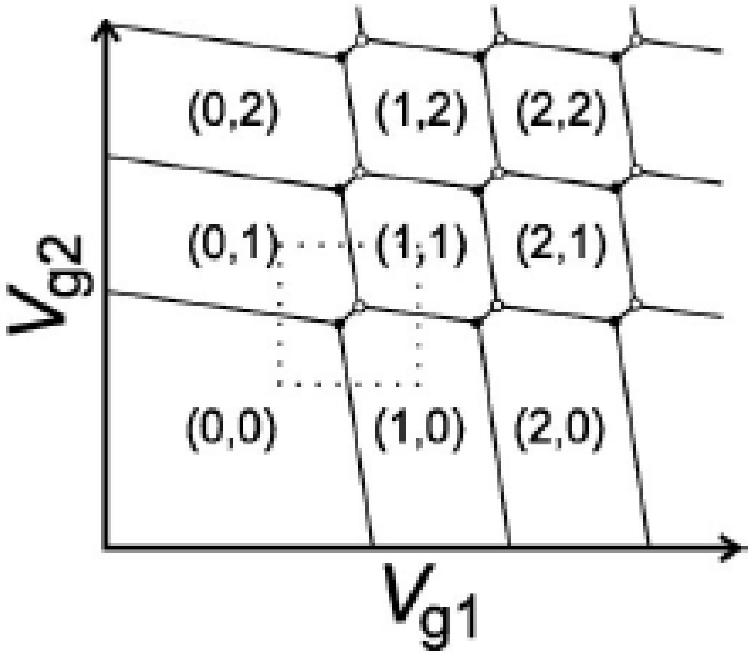
Isolation of a single electron spin

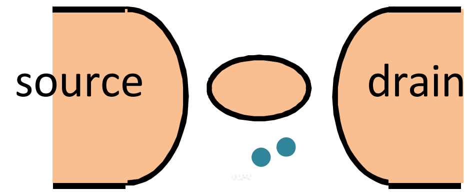
Series double quantum dot

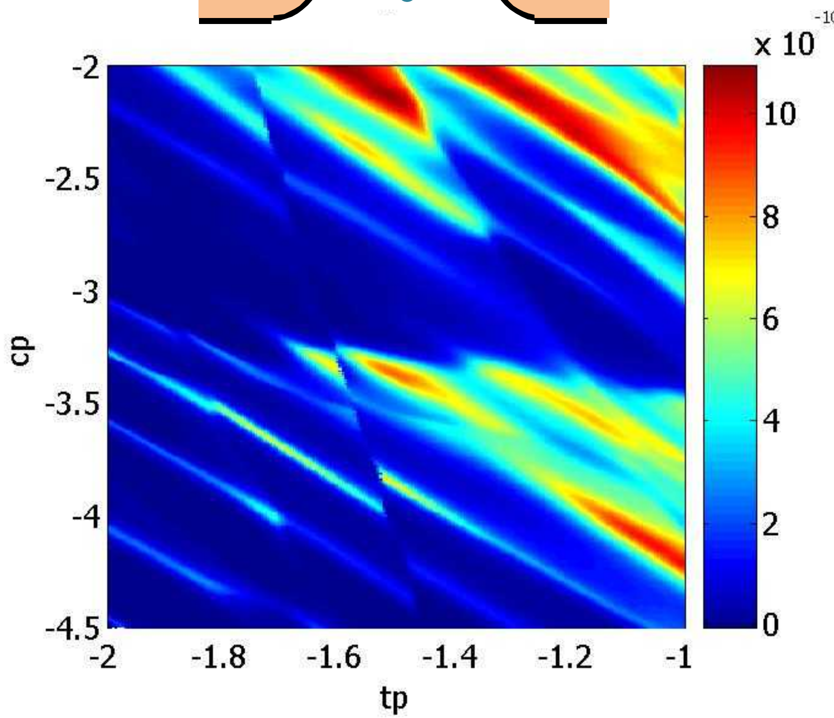




W.G. Van der Weil, RMP (2003)

Parallel dot / donor system

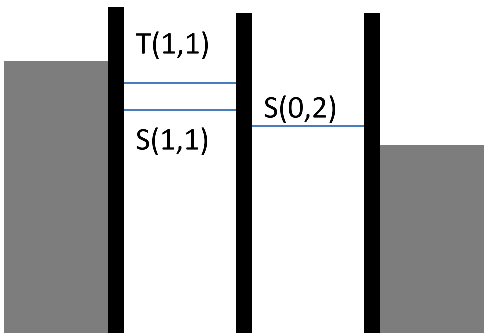




Tzu-Ming Lu

Single spin readout technique

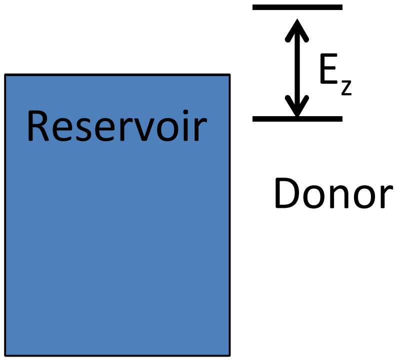
Double quantum dot



- Pauli blockade
- Used to measure states in DQD
- S-T splitting depends DQD config

L. Kowenhoven, et al., Science (1997)
A.C. Johnson, et al., PRB (2005)

Electron on a donor



- Reservoir is a quantum dot
- Pulsing techniques are used to determine spin state
- E_z @ 1 Telsa = 1.3 K = 115 μeV

J. M. Elzermann, et al., Nature (2004)
A. Morello, et al., Nature (2010)

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Electron spin resonance

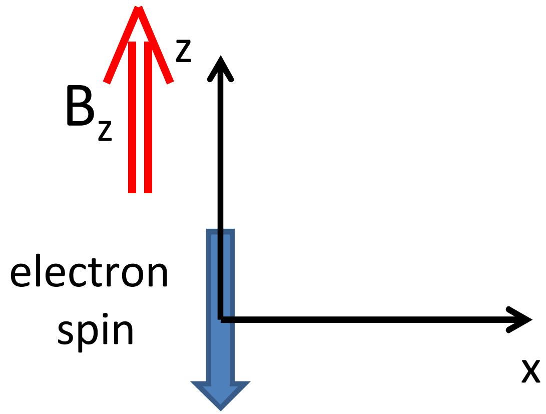
Zeeman splitting

$E_{zeeman} = g\ \mu_B\ B_z$

$\mu_B = e\ \text{hbar}\ /2\ m_e$

At 1 Tesla,

$E_{zeeman} = 116\ \mu V = 1.34\ K = 28.0\ GHz$



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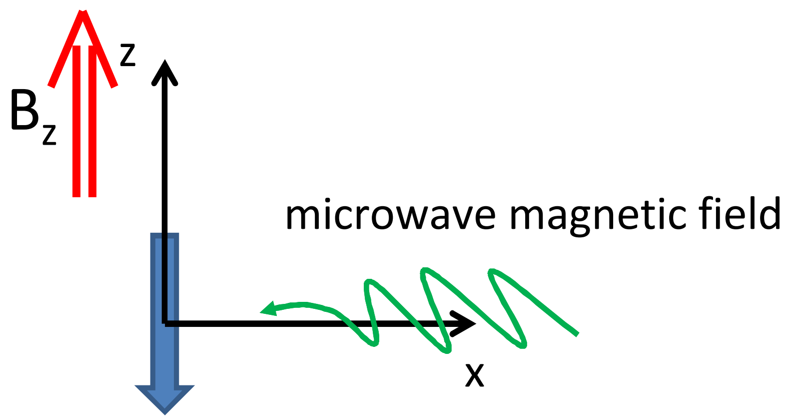

Use rotating frame:

- DC field is 0 *exactly* on resonance
- AC field is along the x-direction
- B_{AC} should be large compared to B_z

Electron spin resonance

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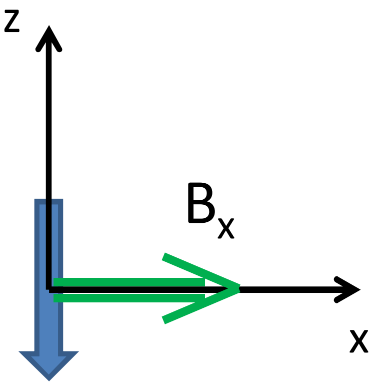

Rotating frame

- B_{AC} produces an x-rotation (or x-gate)
- Rotation frequency is proportional to B_{AC}
- Rabi frequency: $\nu = g\ \mu_B\ B_{AC}\ /\ h$

Electron spin resonance with P donor

Zeeman splitting

$E_{zeeman} = g\ \mu_B\ B_z$
$\mu_B = e\ \text{hbar}\ /2\ m_e$

At 1 Tesla,
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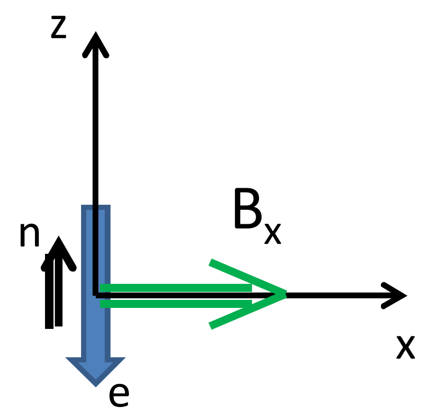
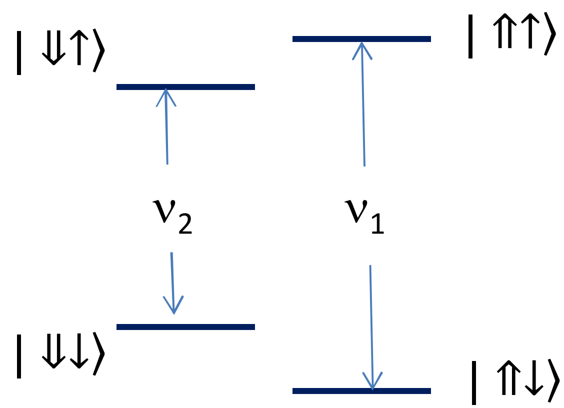


Hyperfine coupling

$$H = \gamma_e B_0 S_z - \gamma_N B_0 I_z + A S \cdot I$$

A = 117 MHz for P



Why silicon?

Long spin lifetime

T1: energy relaxation time
T2: dephasing time

Natural silicon

- T1 > seconds
- T2* ~ 50 ns
- T2 ~ 200 usec

(*Pla, Nature (2012))*

Si28 (single donor)

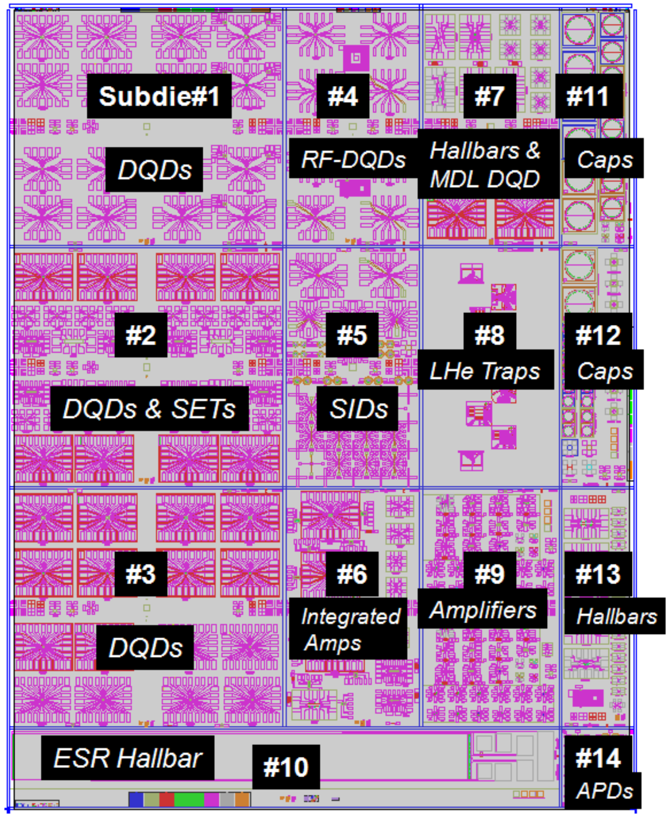
- T2* ~ 200 usec
- T2 ~ 1 msec

(*Australian CQC2T, presentations)*

Si28 (bulk, Avagadro material)

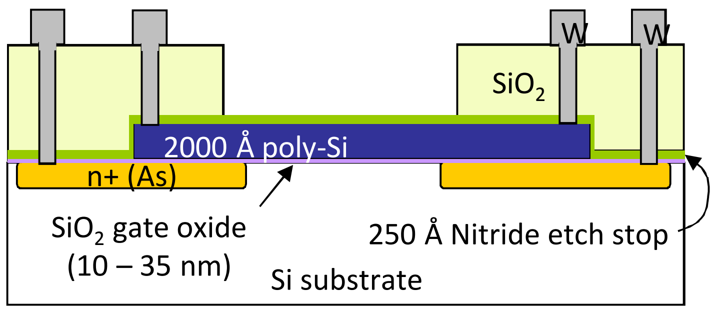
- T2 ~ 10 sec

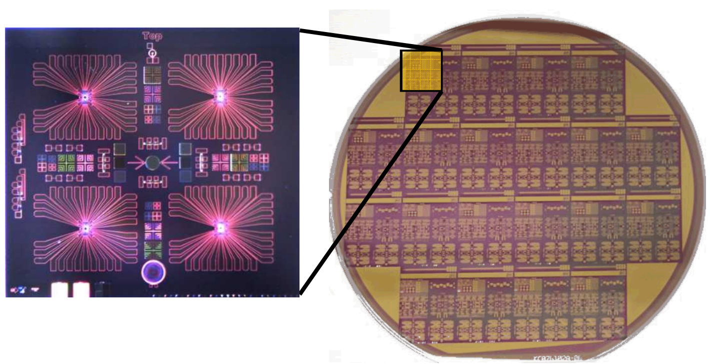
Si fabrication is well known



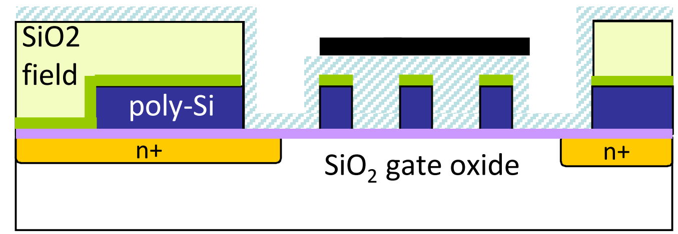
Si MOS Fabrication

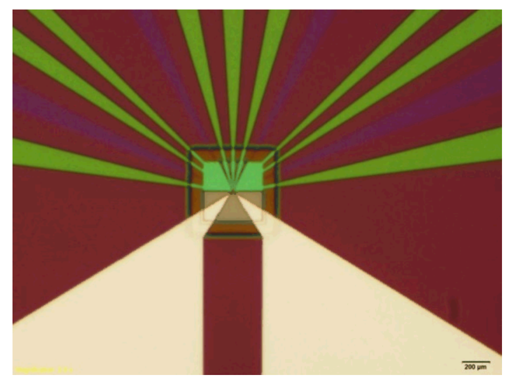
Front-end in silicon fab

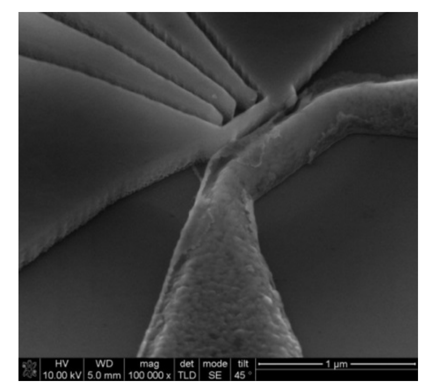




Back-end nanolithography







Multiple bandwidths in a dilution refrigerator

DC lines

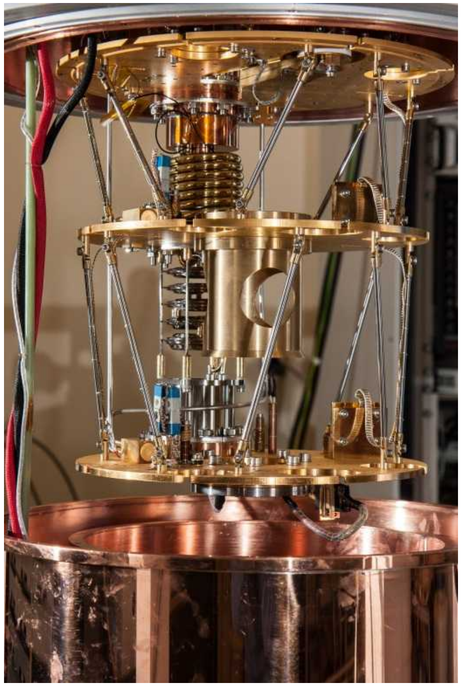
- static bias, or slowly changing bias

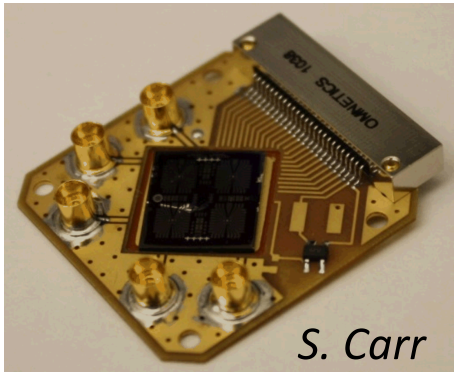
Pulsing lines and fast current measurement

- SS/SS flexible coax (10 MHz BW)a
- 400 kHz current preamp
- x10 voltage preamp with filters

High frequecy ESR lines

- AG-SS/SS at high T
- NbSn at low T
- extremely delicate
- good microwave techniques required





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Outline

- Quantum computing with semiconductors
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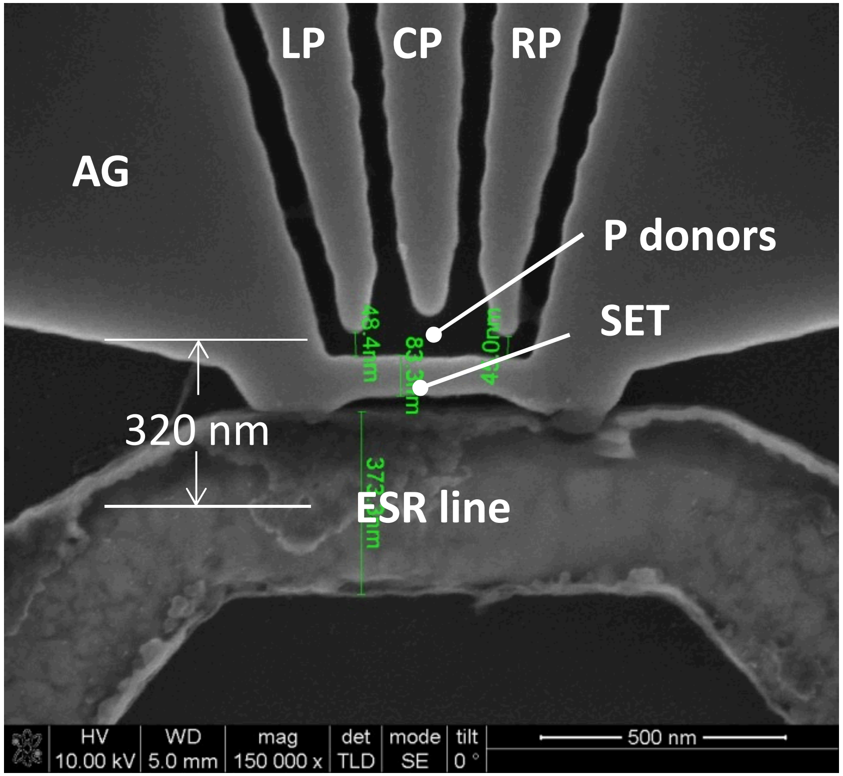
Device layout for ESR experiment

1275 dev 4

- Natural Si
- 35 nm gate oxide
- Timed implant of P donors
  - ~ 30 donors between CP and AG.
  - 120 keV -> ~30 nm below oxide
- ESR line resistance ~ 15 ohm at RT.
- P to center of ESR < 400 nm



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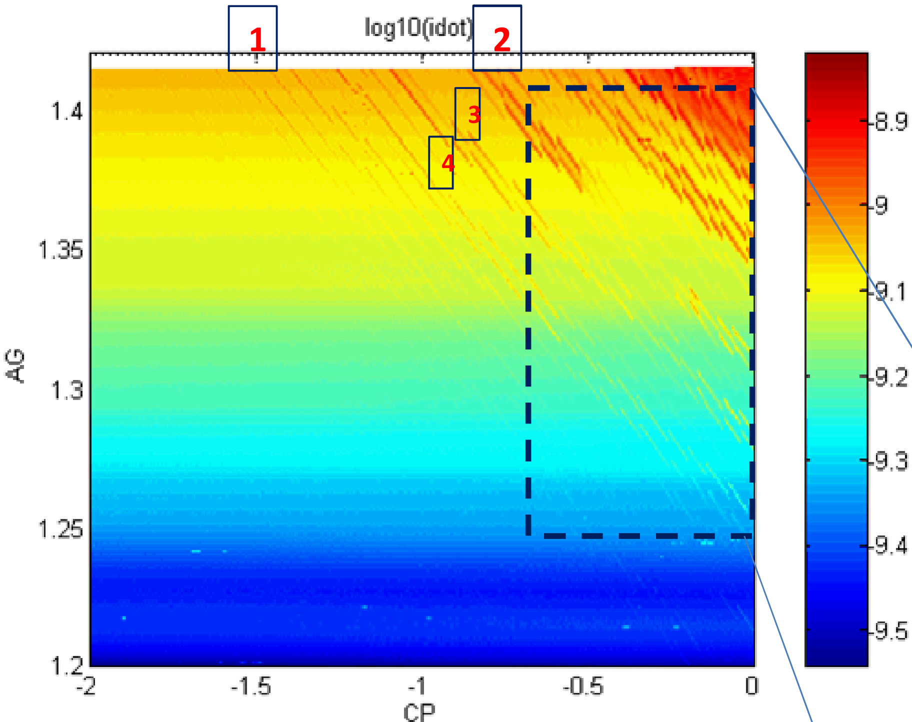
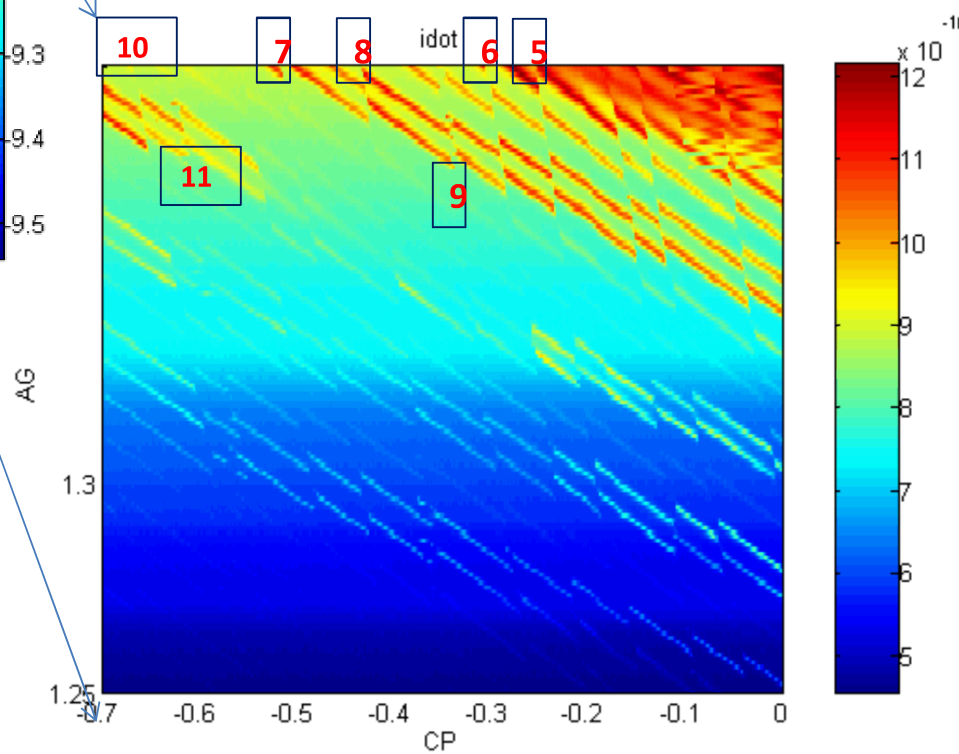
Offsets and tunnel times



1. 15 offsets observed (30 implanted). Donors close enough to couple should have an offset.
2. Background current is present (not ideal).
3. Tunnel times are random.



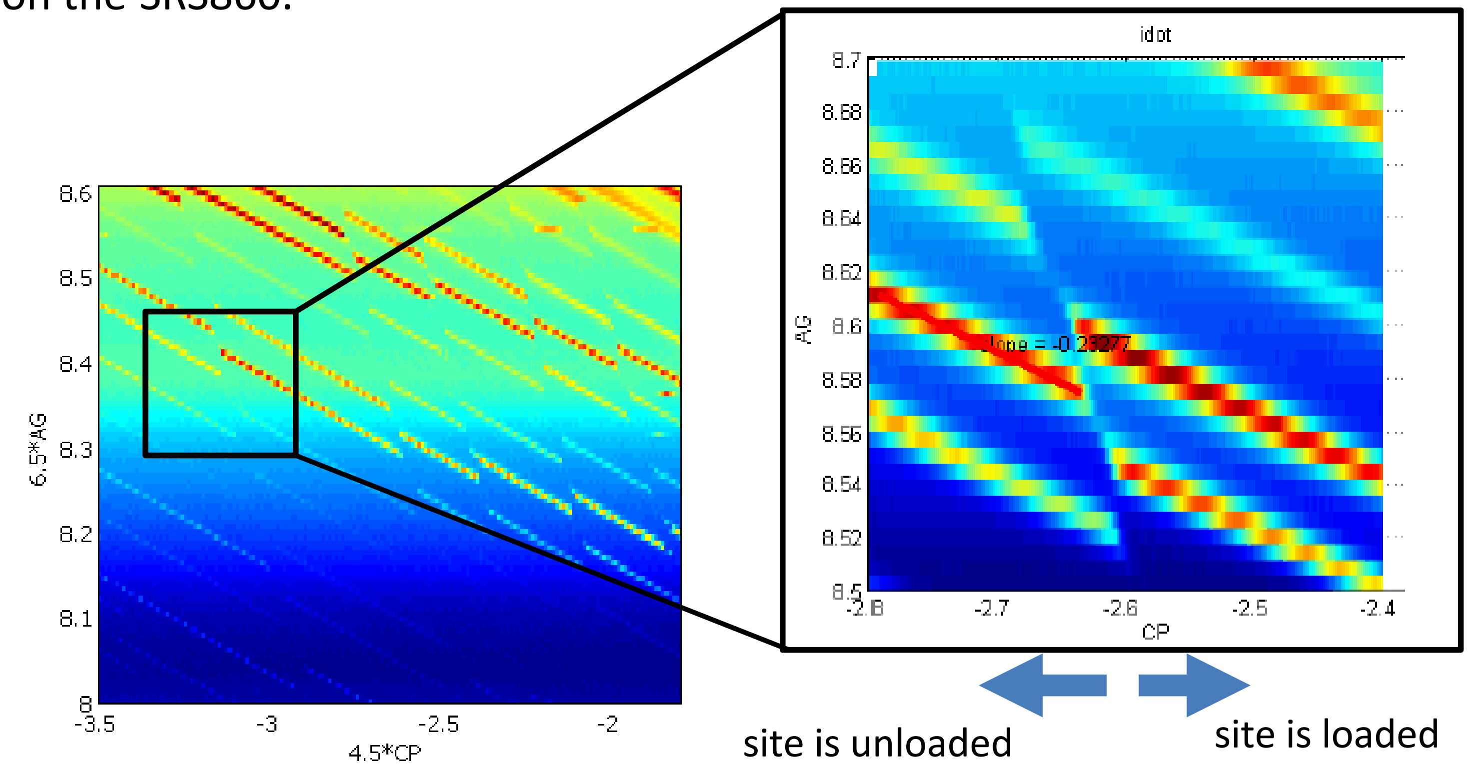
#2: tunnel time changes from time to time, from us to tens of ms

#5: load time = 50 ms, unload time = very fast, ~ us
#6: load time = very fast, unload time = 300 us
#7: load time = ~ 100ms, unload time = very fast
#8: load time = ~ 50ms, unload time = ~ 30 ms

Quantum dot electrometer

Donor induced charge offset observed in transport through the quantum dot

Load and unload times for offset #10 are fast (~10 usec). When tuned to the readout window they slow significantly and allows a 10 kHz bandwidth to be used on the SRS860.



site is unloaded

site is loaded

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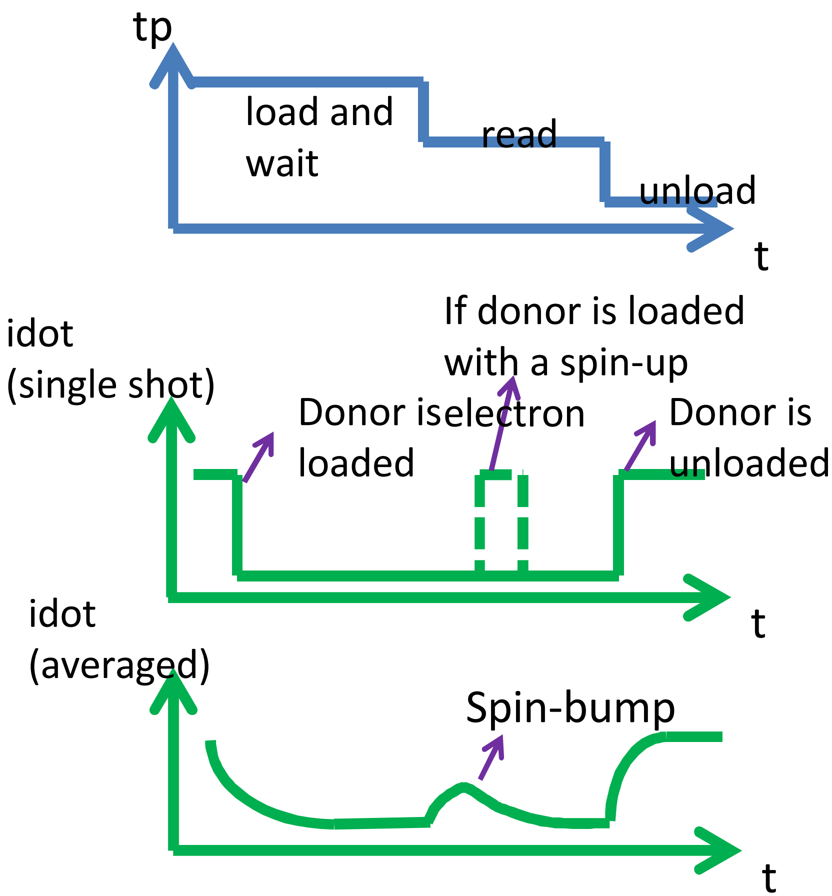
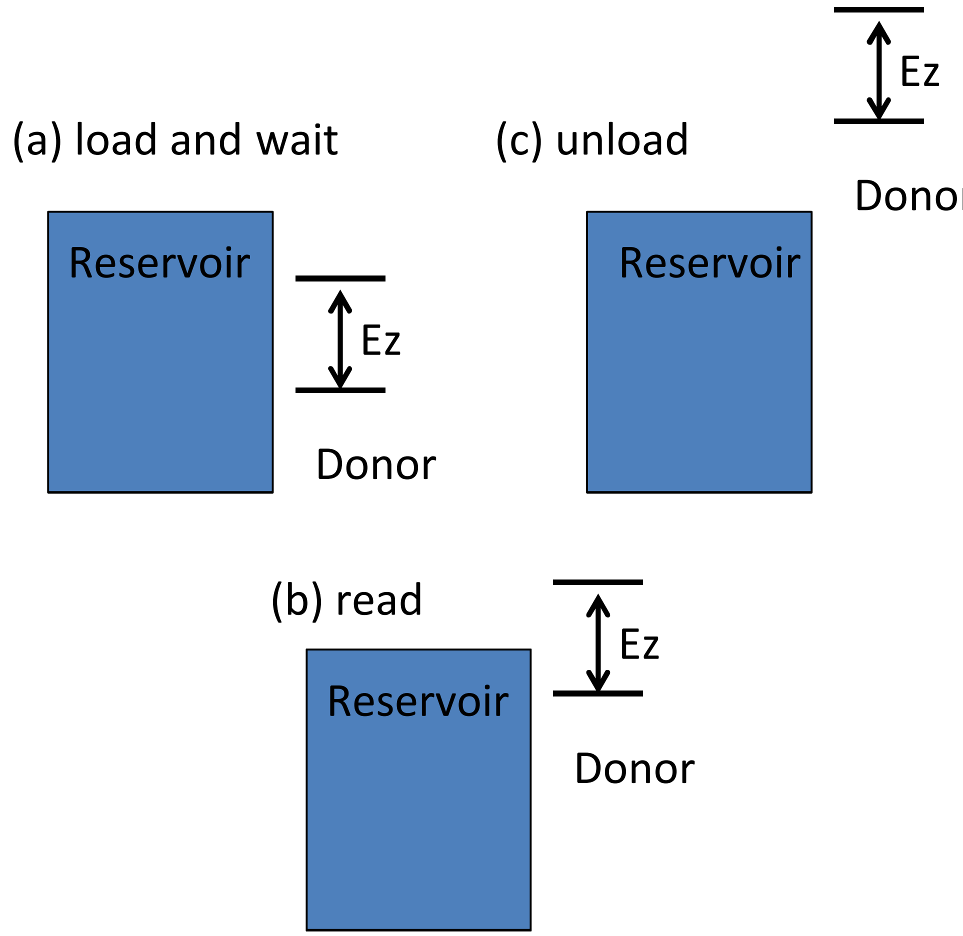
Pulse Sequence

Three-level probing sequence



Energy level alignment



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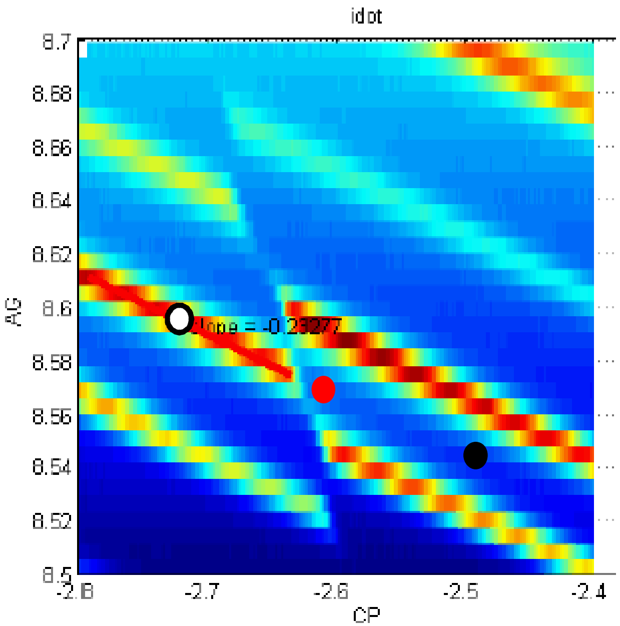
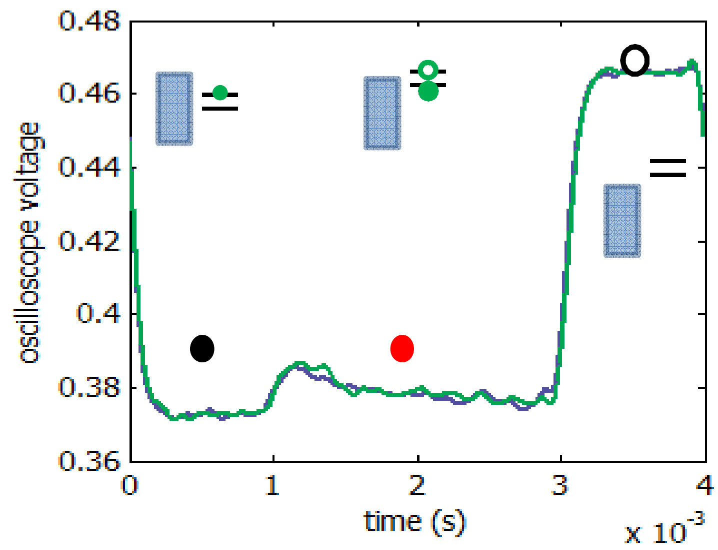
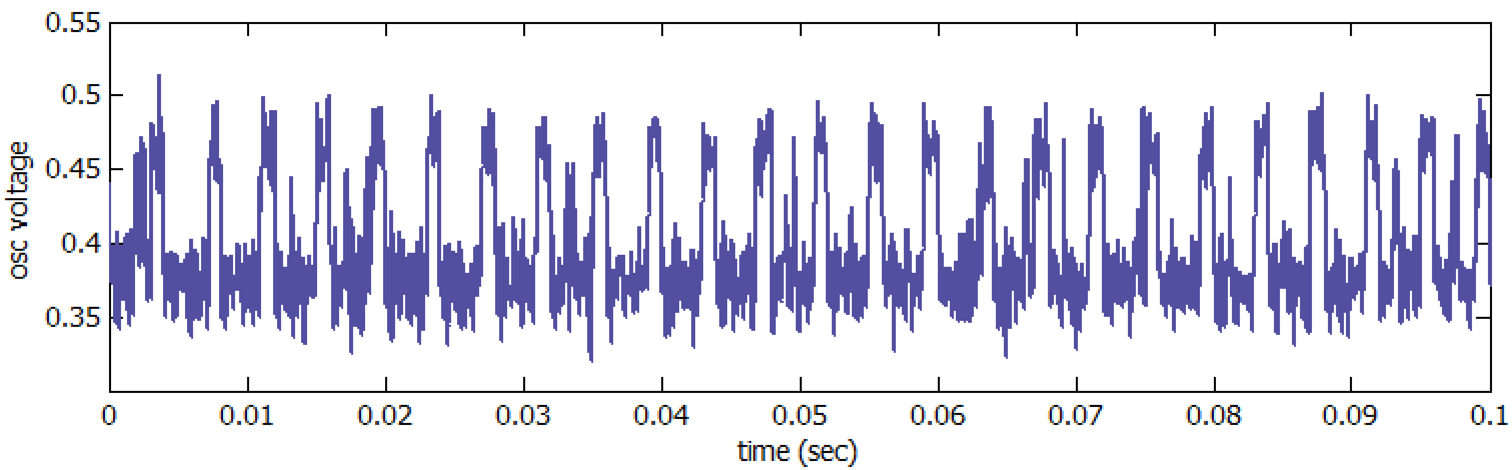
Spin readout: averaged and single shot



256 averages



25 single shot measurement



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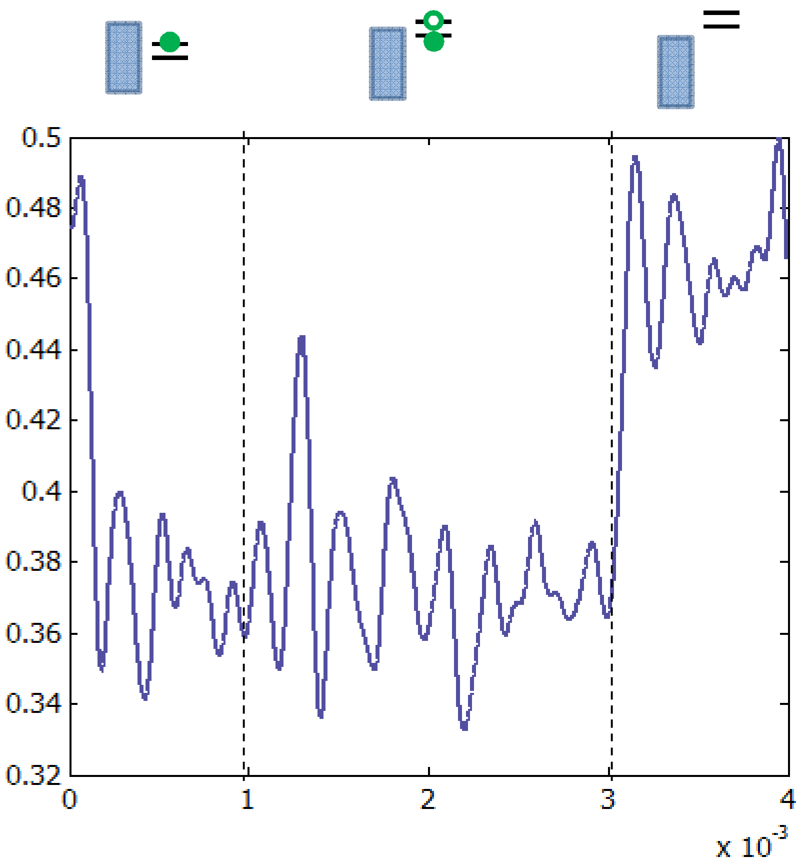
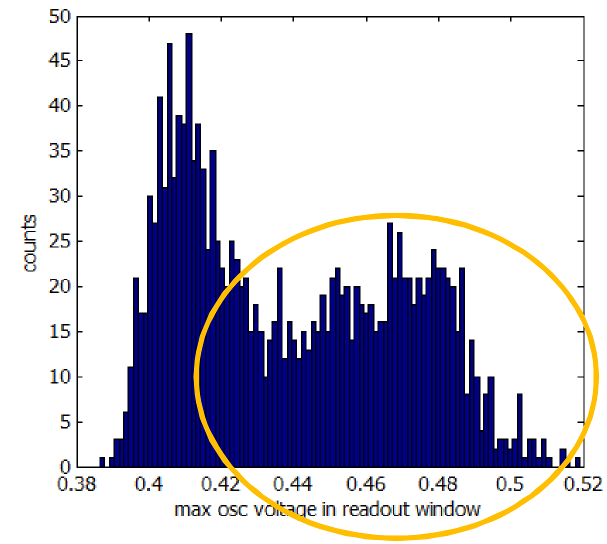
Single shot readout analysis

Single shot, spin up event



CQC2T technique for identifying spin up



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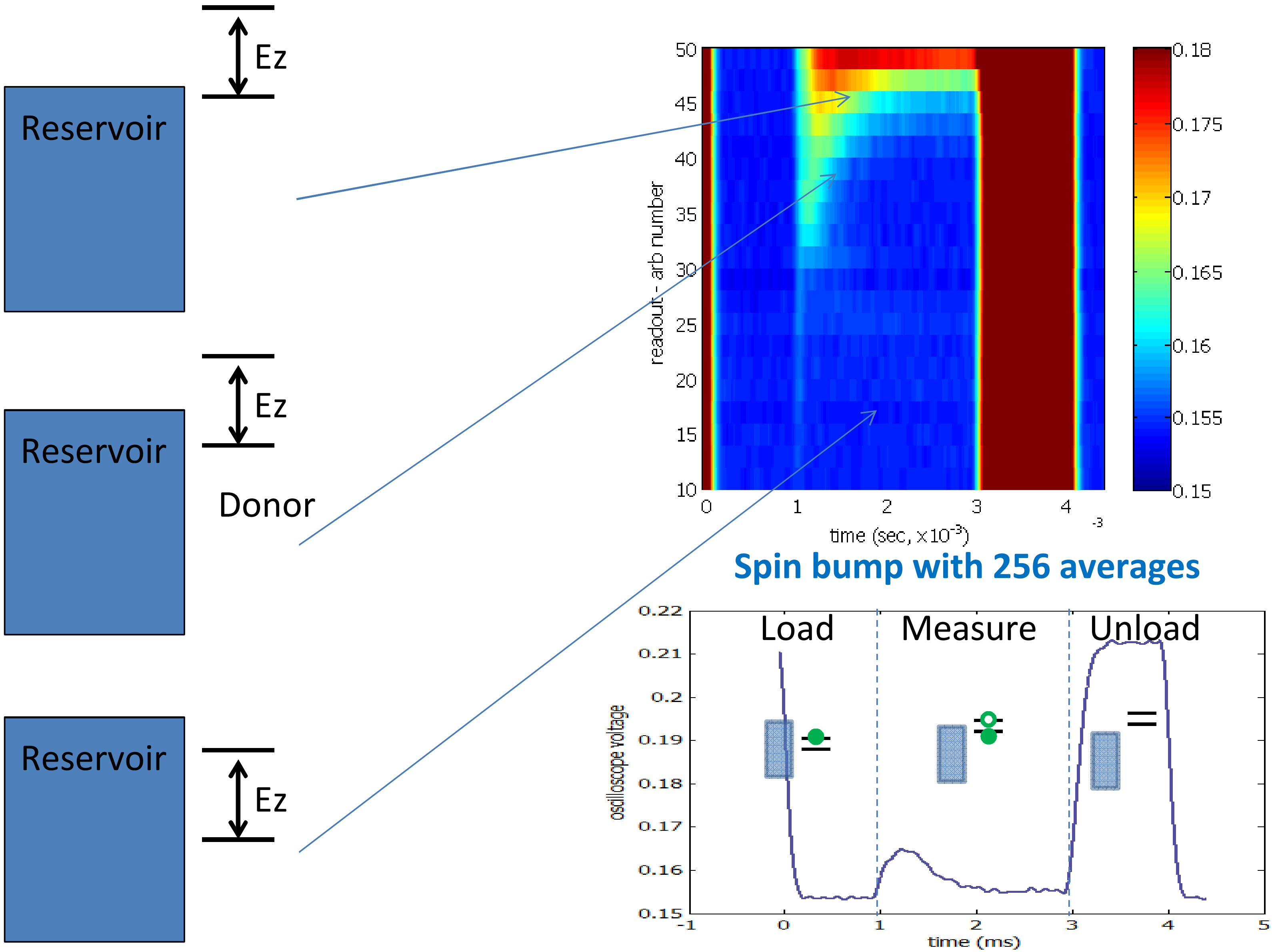
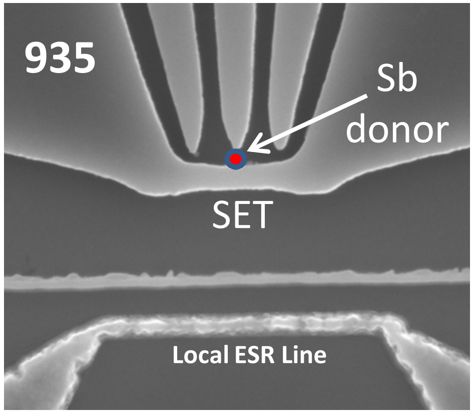
Tuning spin readout

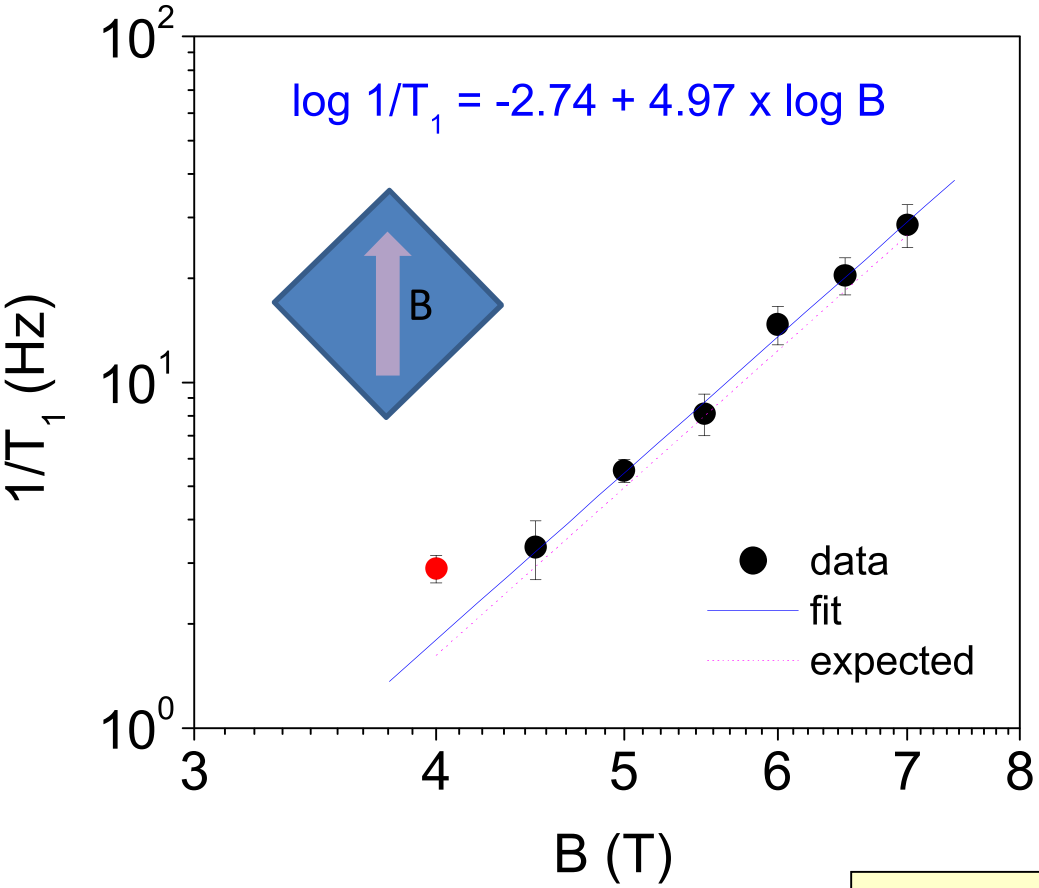


Magnetic field dependence of T1

Sb donors implanted near silicon SET



T1 decreases with increasing field



- B^5 dependence expected for electron on donor
- Long T_1 times beneficial for silicon qubit.

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For 1275, T1 = 250 msec (1/T1=4 Hz)

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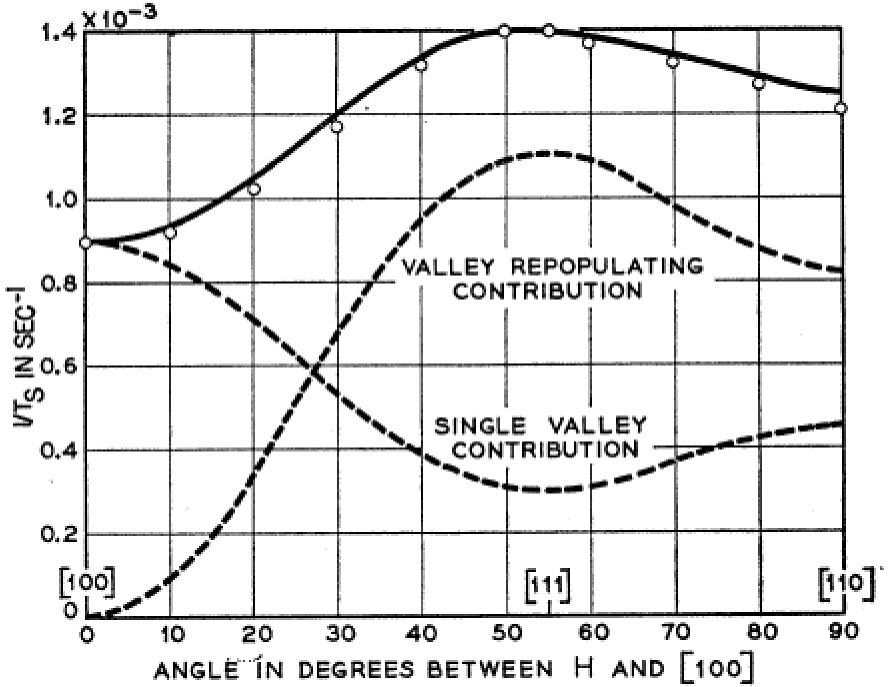
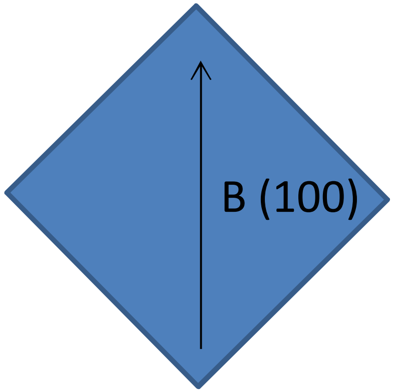
Spin relaxation in silicon



Phys. Rev. 124, 1068 – 1083 (**1961**).

Sample orientation in dry fridge



For B in (100) direction, expect single valley contribution only to T_1 relaxation.
Due to change in g-factor from mixing between bands with strain.

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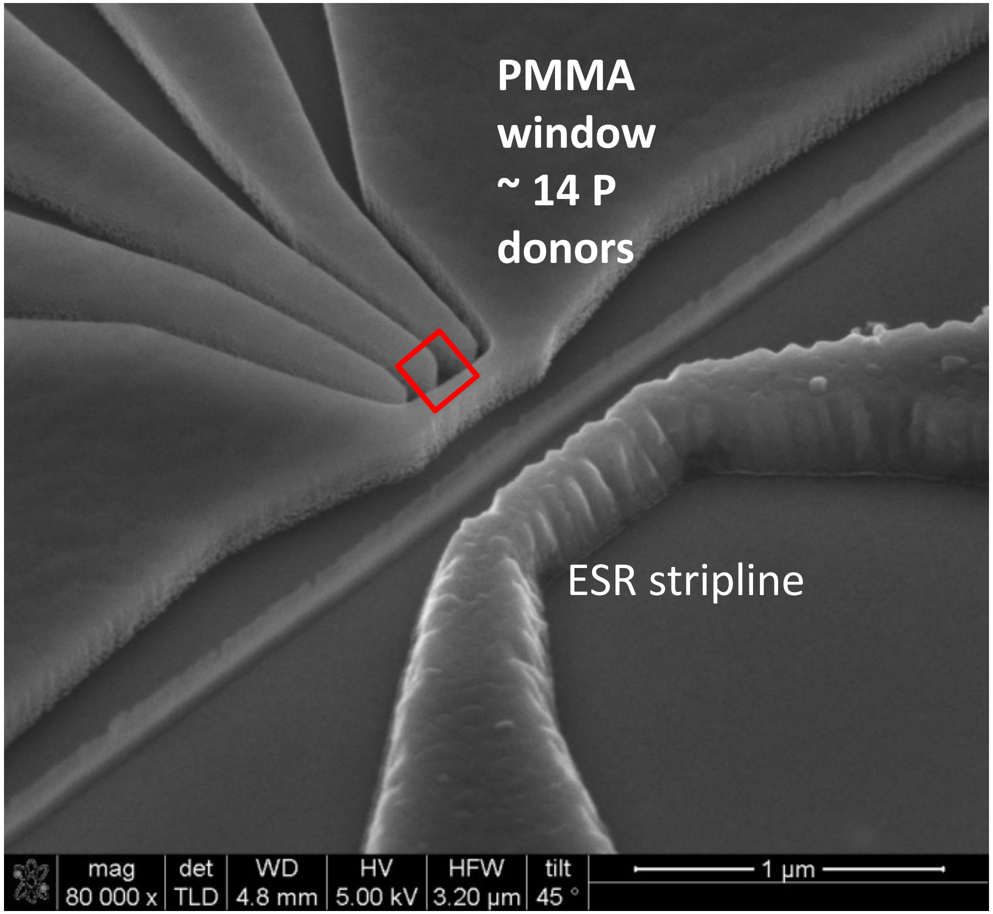
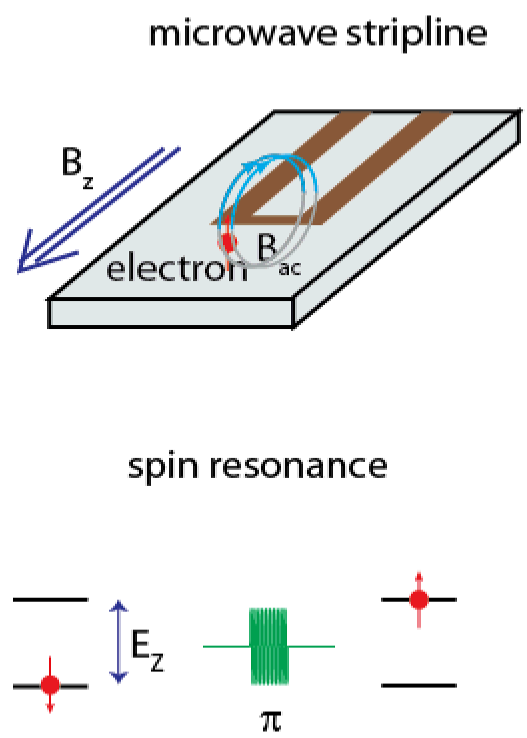
Next Steps: Local Electron Spin Resonance

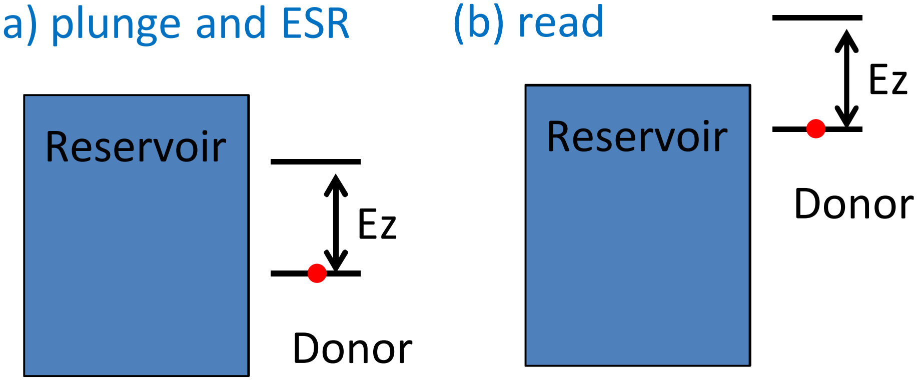




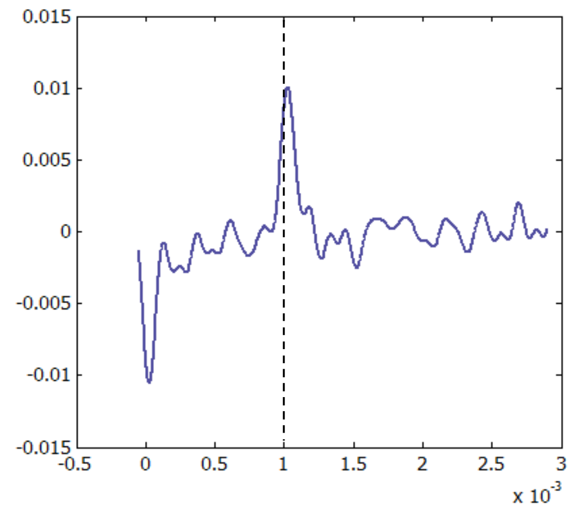
Lisa Tracy, Dwight Luhman, Khoi Nguyen

ESR pulse sequence – two level pulse

(a) plunge and ESR (b) read



Off resonance – no spin up signal



1. At the end of the readout pulse, a spin down is loaded. (b)
2. Pulse energy levels down to manipulate. (a)
3. Apply microwaves. (a)
4. Spin readout (b)

ESR pulse sequence – two level pulse

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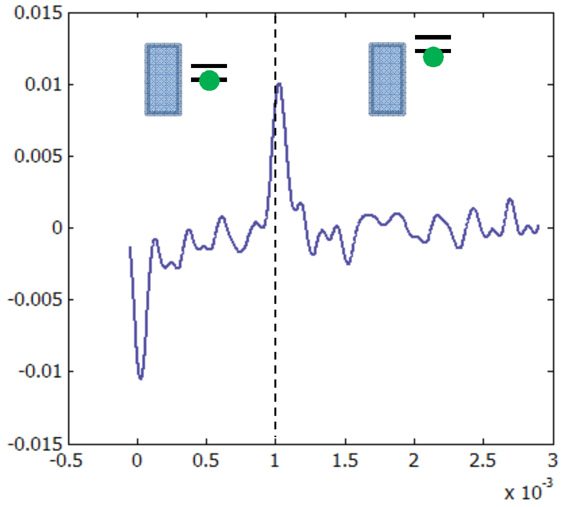

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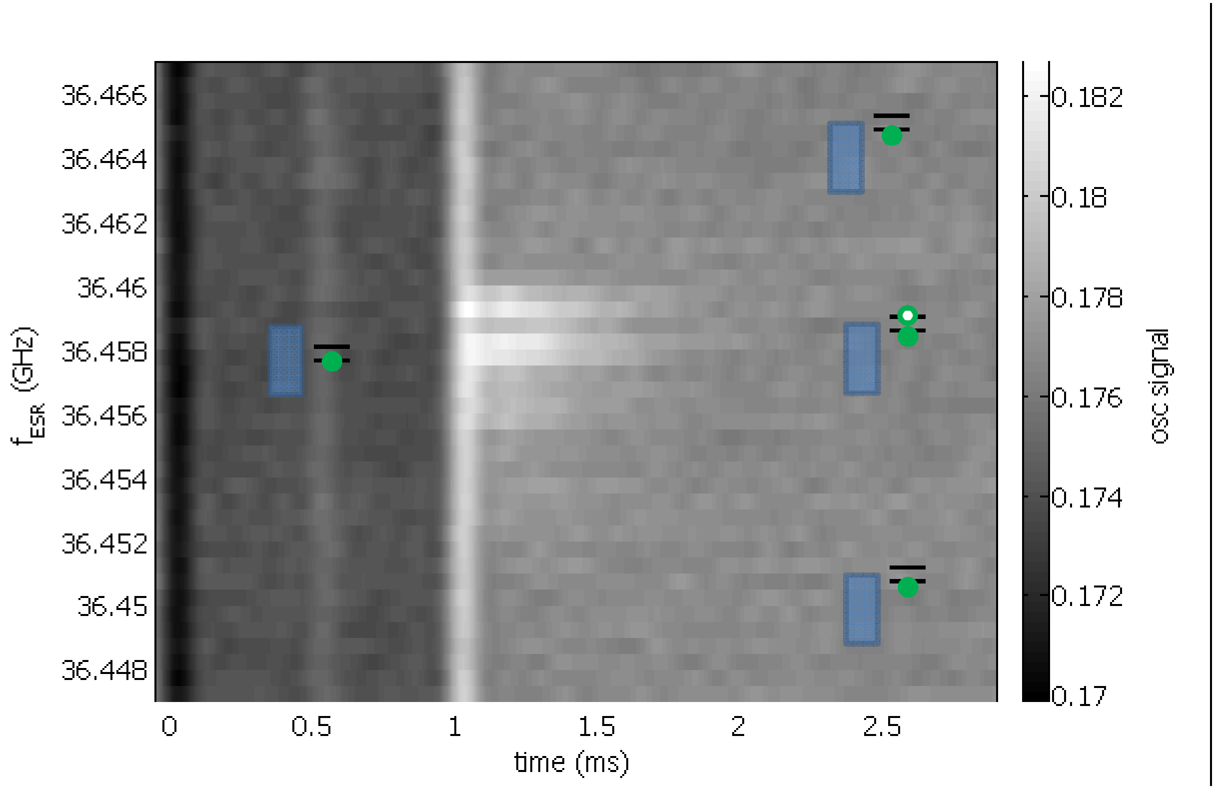
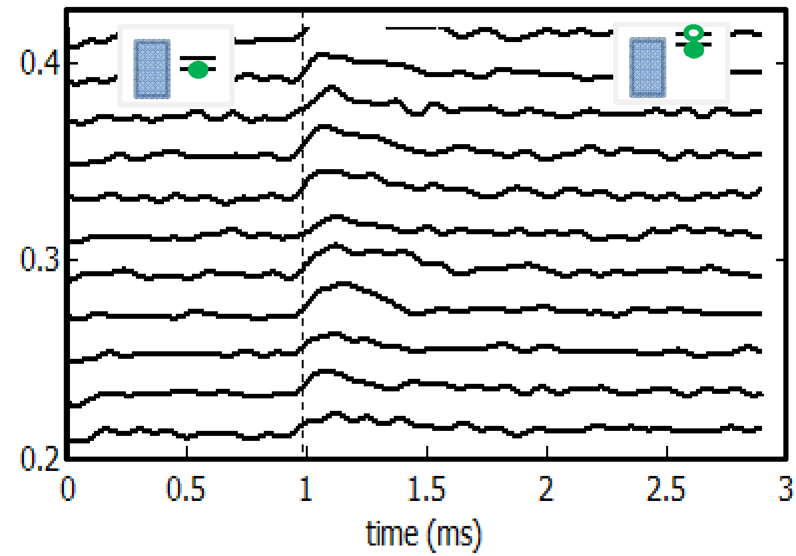
ESR frequency sweeps

- In the ESR regime, the spin signal comes and goes (as Si29 nuclei reorient).
- In the ESR regime, the spin signal at a fixed f can vanish for a minutes (nuclear spin flips).

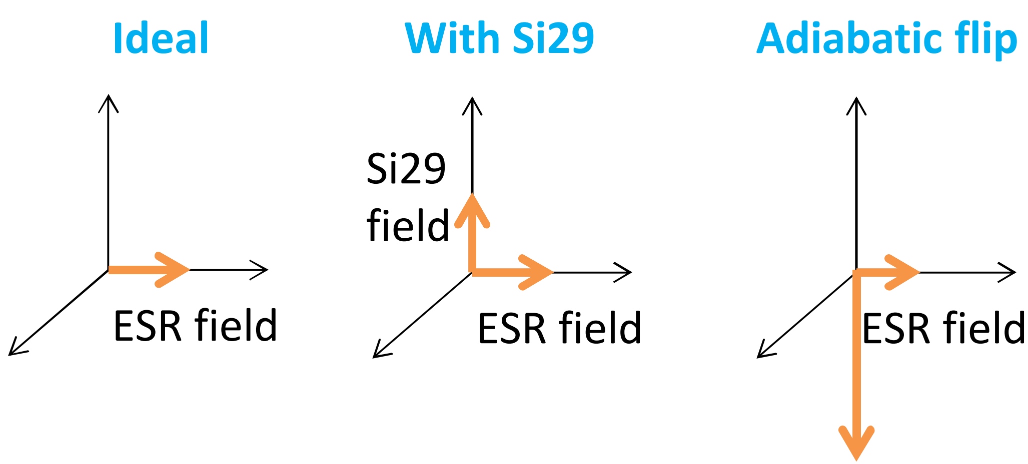


How do we deal with resonant frequency shifts?

- Take lots of data at a fixed frequency and power.
  - Sometimes the spin signal is small, sometimes large.
  - Use max peak value, max peak integral, averaged peak value, averaged integral, ...



- Start using better ESR pulsing techniques
  - Sweep microwave frequency and flip the spin adiabatically
- Use Si28



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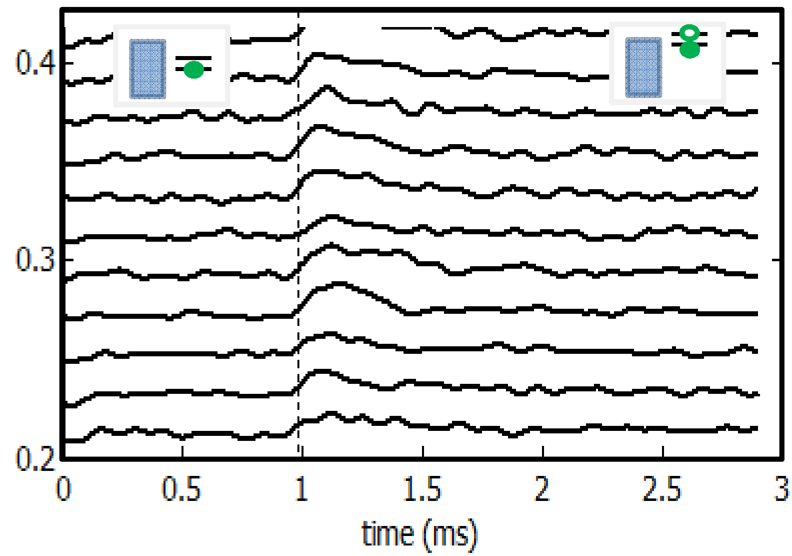

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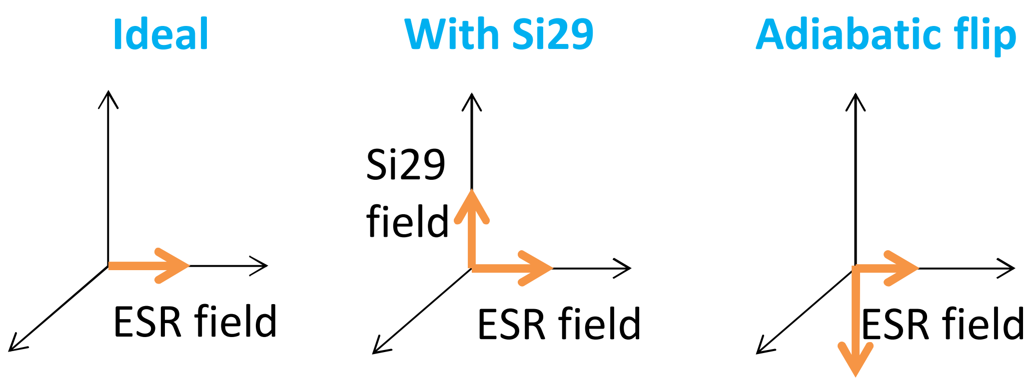

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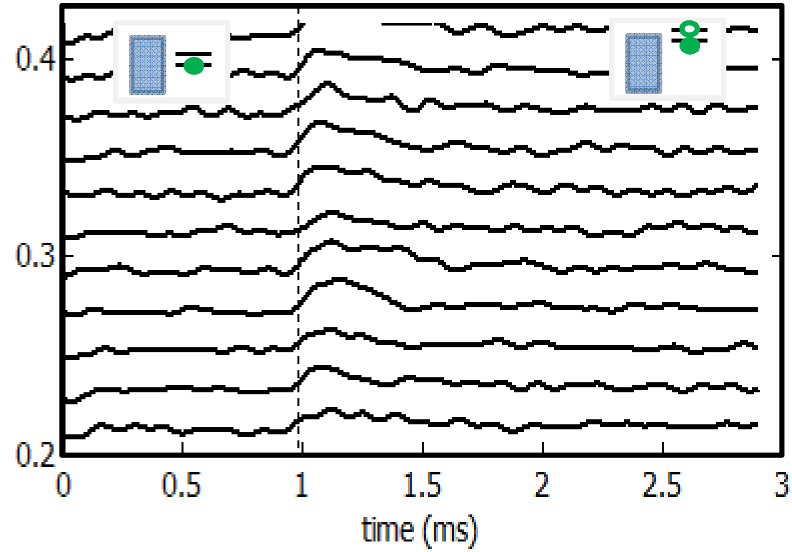

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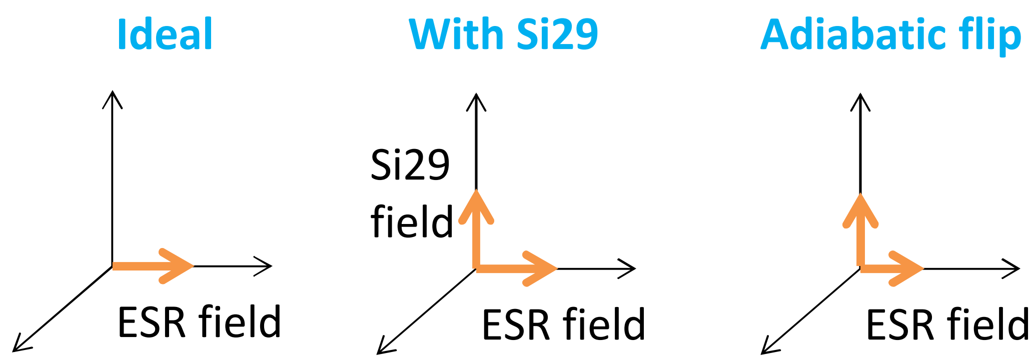

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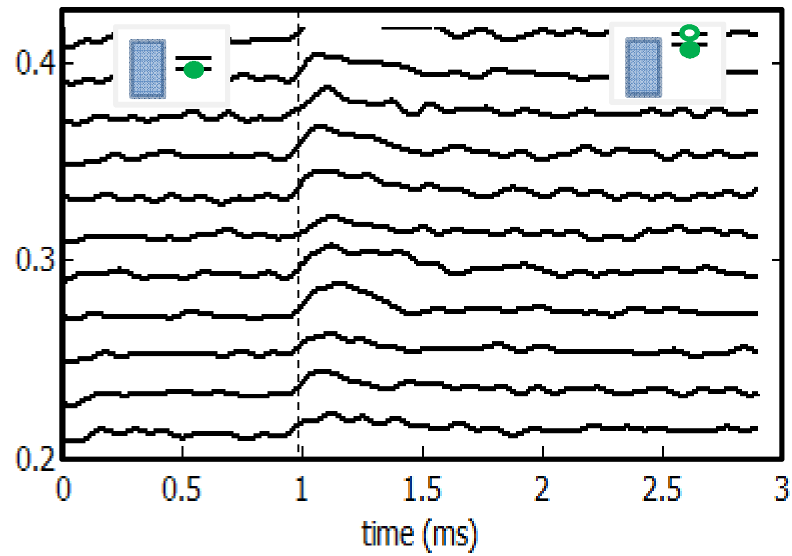
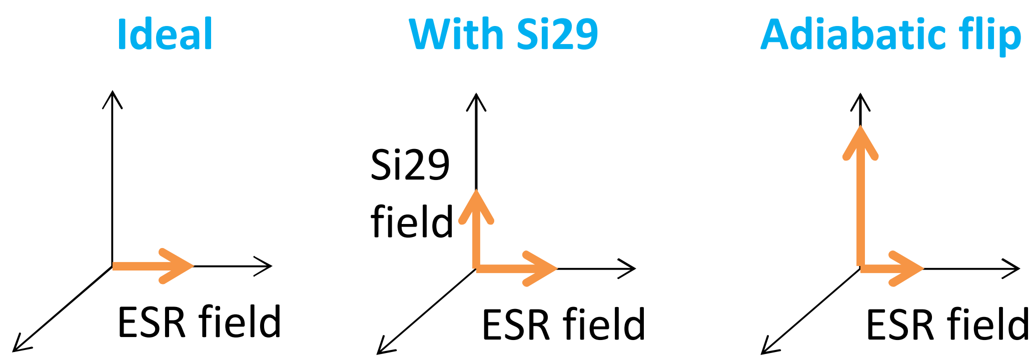
    - Sometimes the spin signal is small, sometimes large.
    - Use max peak value, max peak integral, averaged peak value, averaged integral, ...



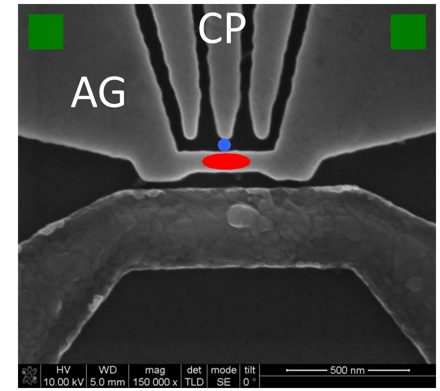
- Start using better ESR pulsing techniques
    - Sweep microwave frequency and flip the spin adiabatically



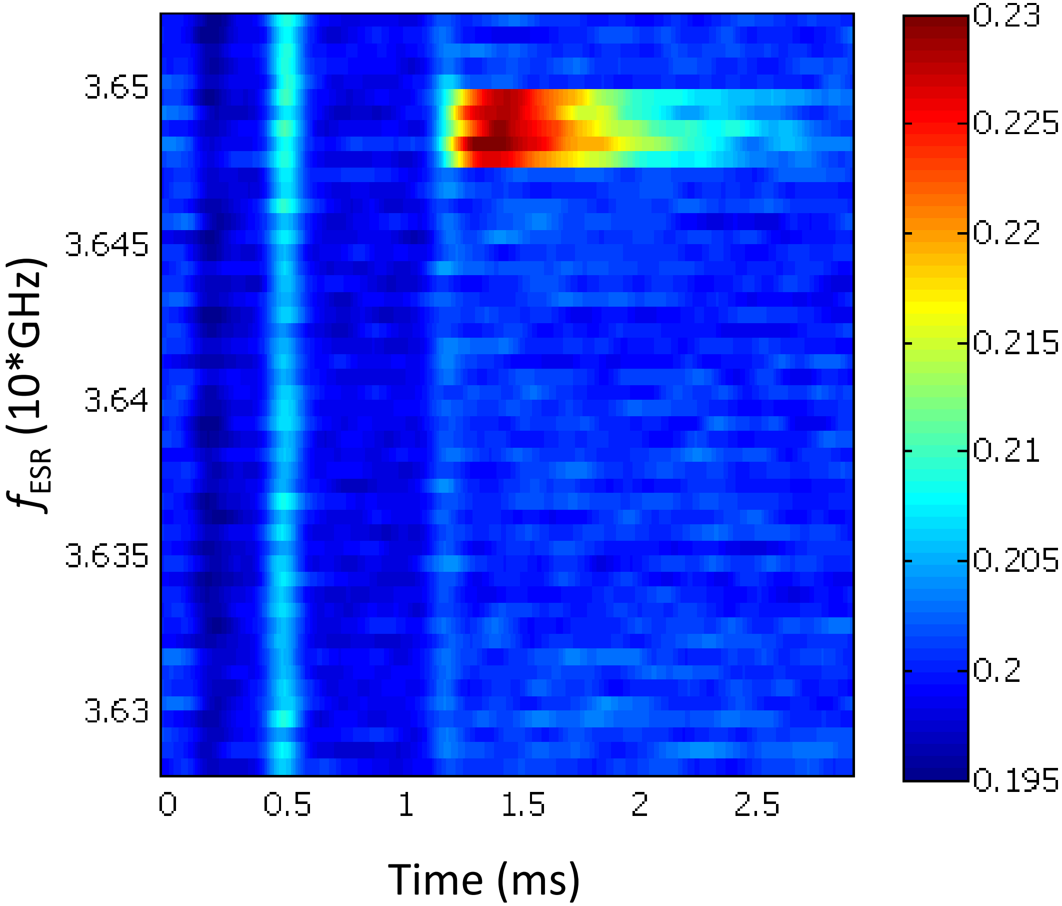
- Use Si28

Adiabatic spin flip

B=1.3 T



Scan μ-wave frequency, look for spin bump



For electron on a spin ½ donor

$$\nu_{ESR} = \gamma_e B \pm A/2$$

μ-wave pulse is a 10 μs adiabatic linear sweep across 25 MHz

128 averages

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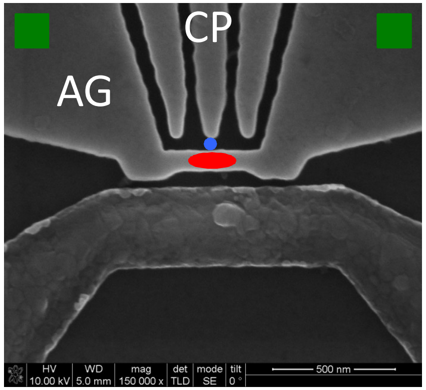
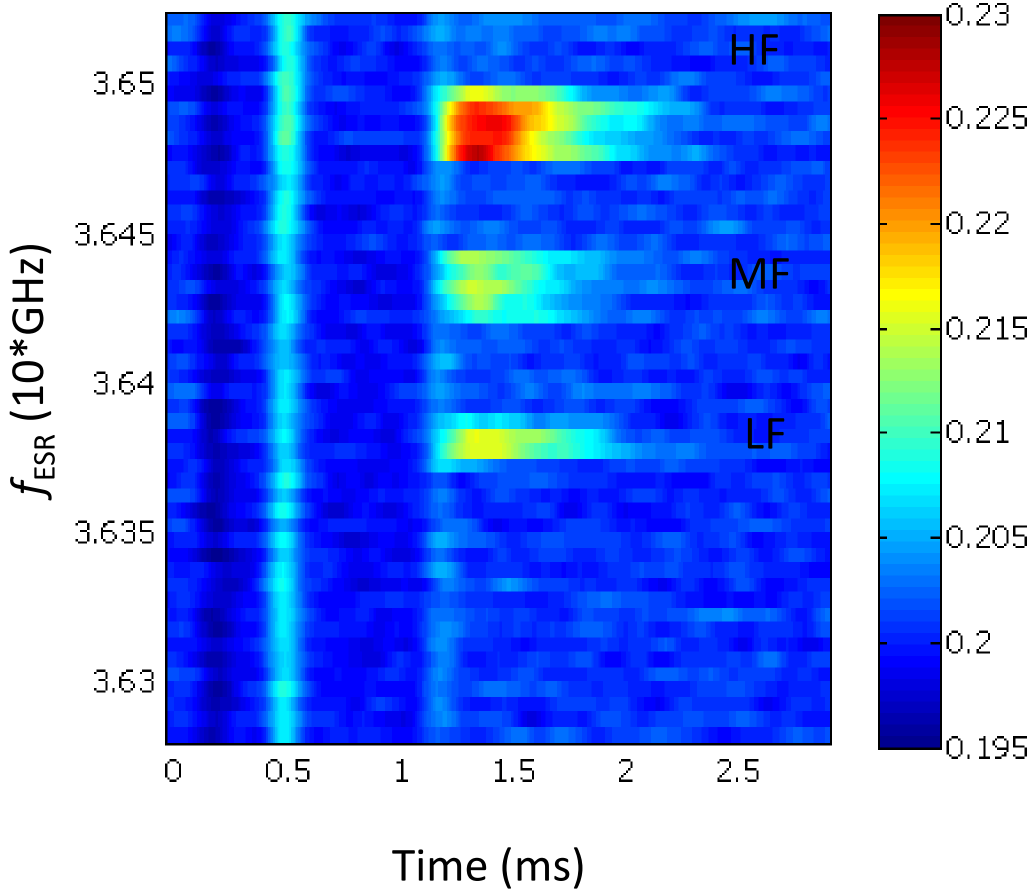
Identify ESR resonances

B=1.3 T



Scan μ-wave frequency, look for spin bump



For electron on a spin ½ donor

$$\nu_{ESR} = \gamma_e B \pm A/2$$

μ-wave pulse is a 10 μs adiabatic linear sweep across 25 MHz

We observe 3 distinct ESR resonances

128 averages

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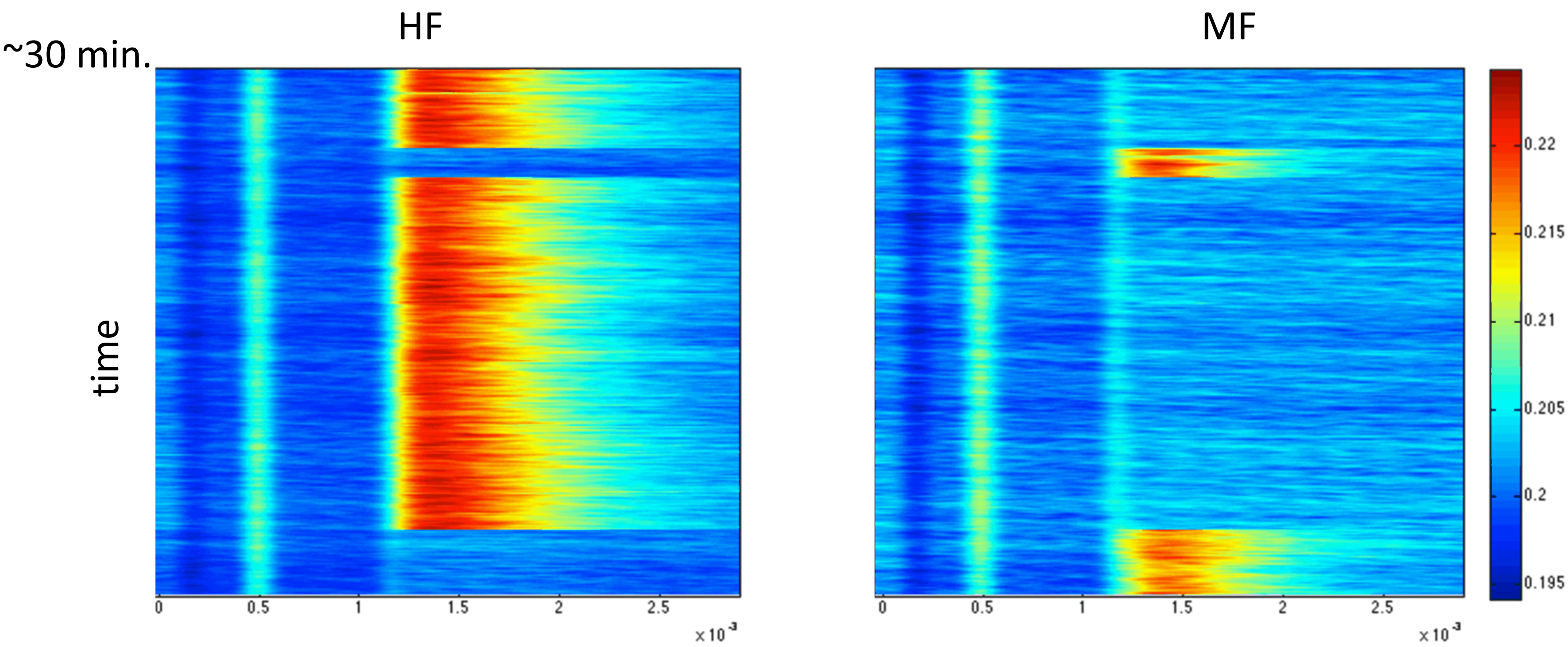
B=1.3 T

Evidence for nuclear spin flips



- Different states not occupied simultaneously
- State changes occur on ~minutes
- HF dominant, MF common, LF rare

μ-wave pulse: 10 μs
adiabatic linear sweep across
25 MHz

128 averages

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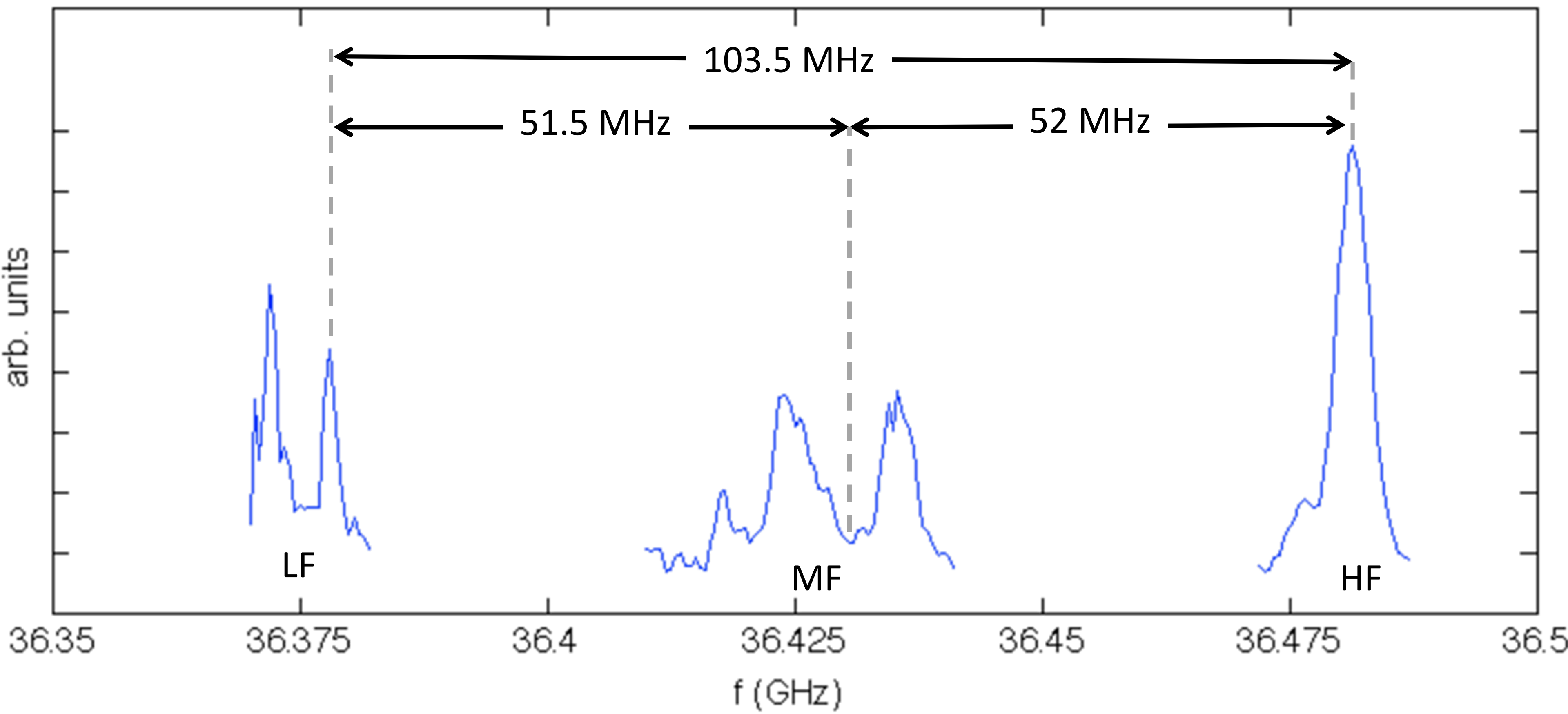
ESR Spectra

B=1.3 T



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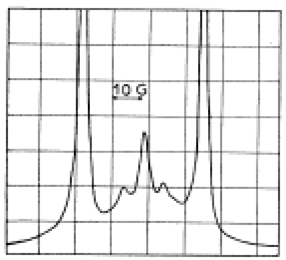
B=1.3 T

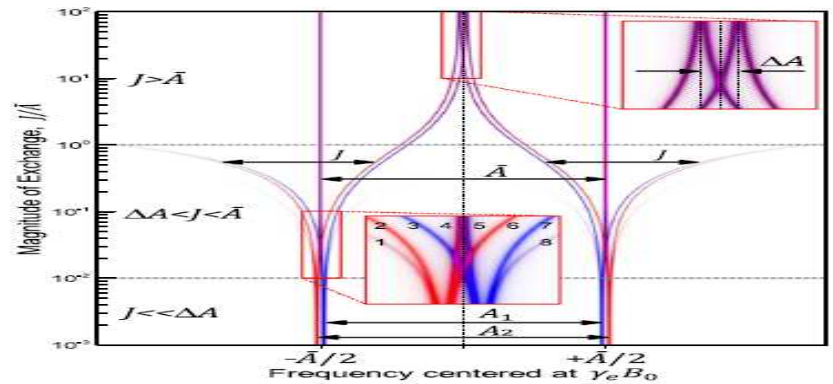
Interacting donors

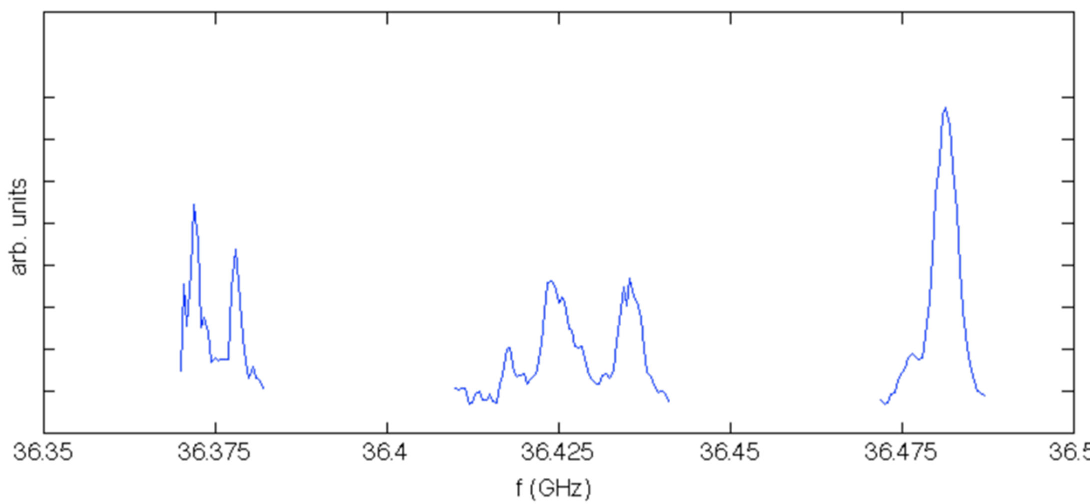
Two exchange coupled phosphorus donor atoms will have an ESR signature with multiple lines.

Jerome and Winter, 1964



Karla, Laucht, Hill and Morello, 2014





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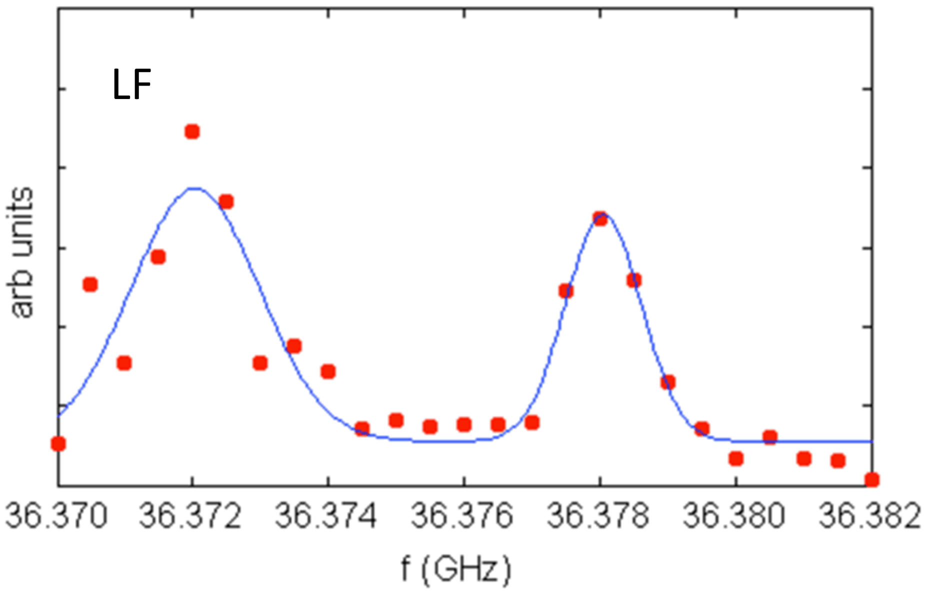
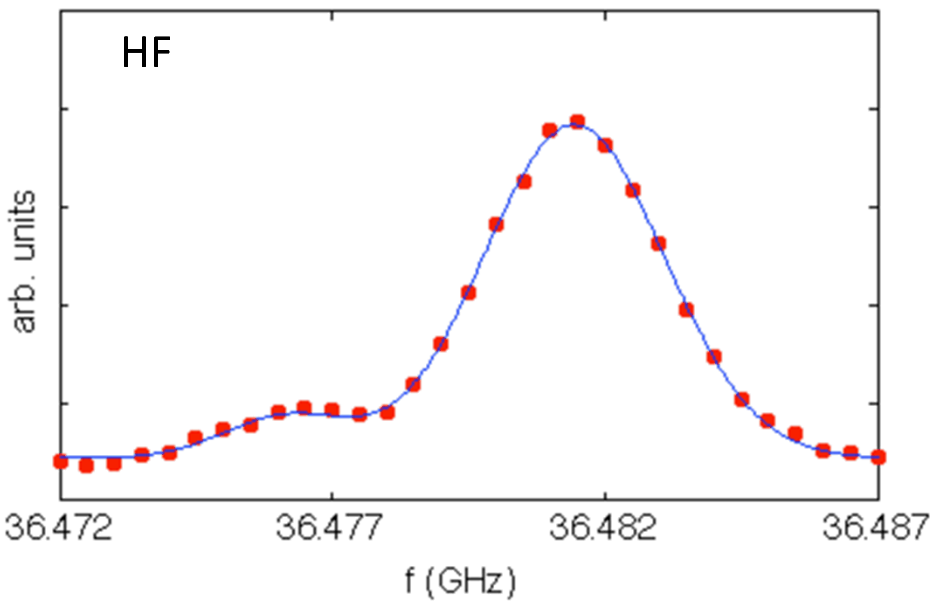
B=1.3 T

ESR Spectra



Lines are a fit to two Gaussians

LF Peak Splitting:
6.0 ± 0.2 MHz



HF Peak Splitting:
5.26 ± 0.09 MHz

Splitting likely due to a nearby ^{29}Si

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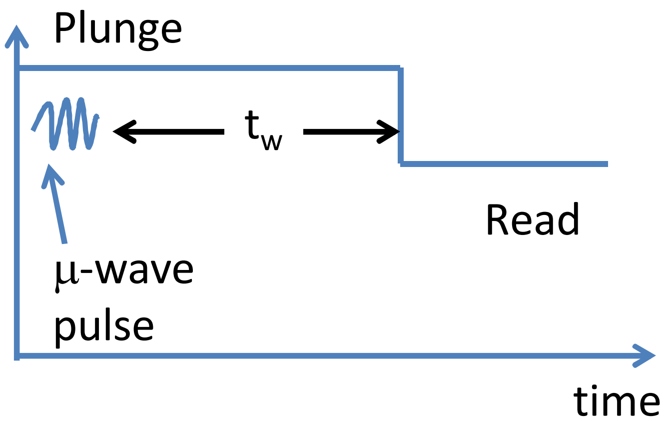
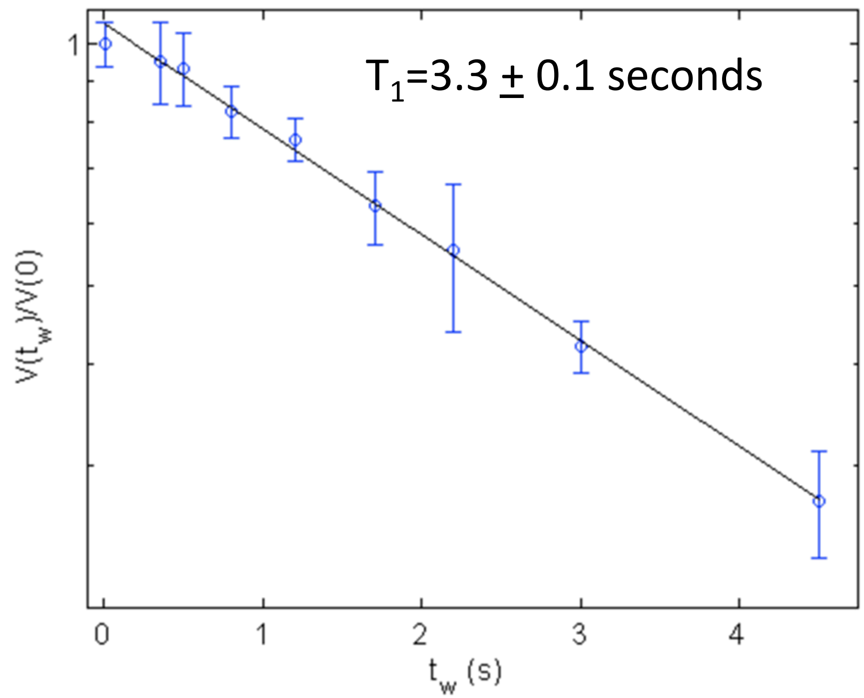
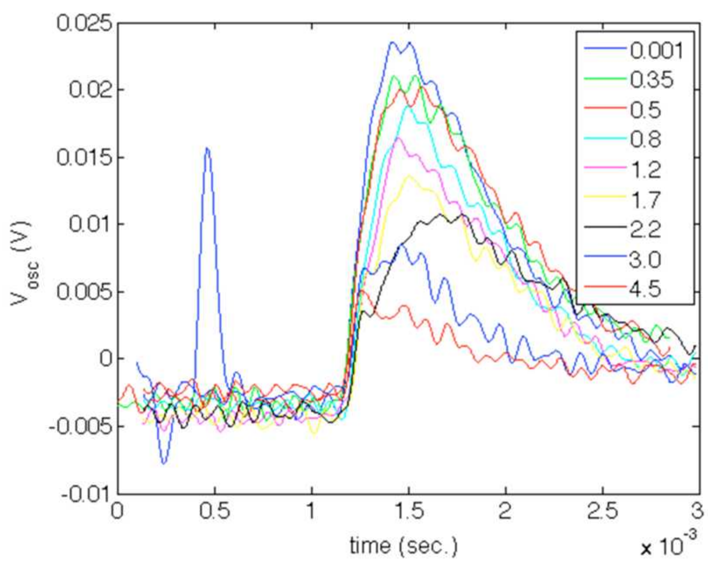
B=1.3 T

T_1 Measurement

Prepare spin up state with adiabatic sweep across HF

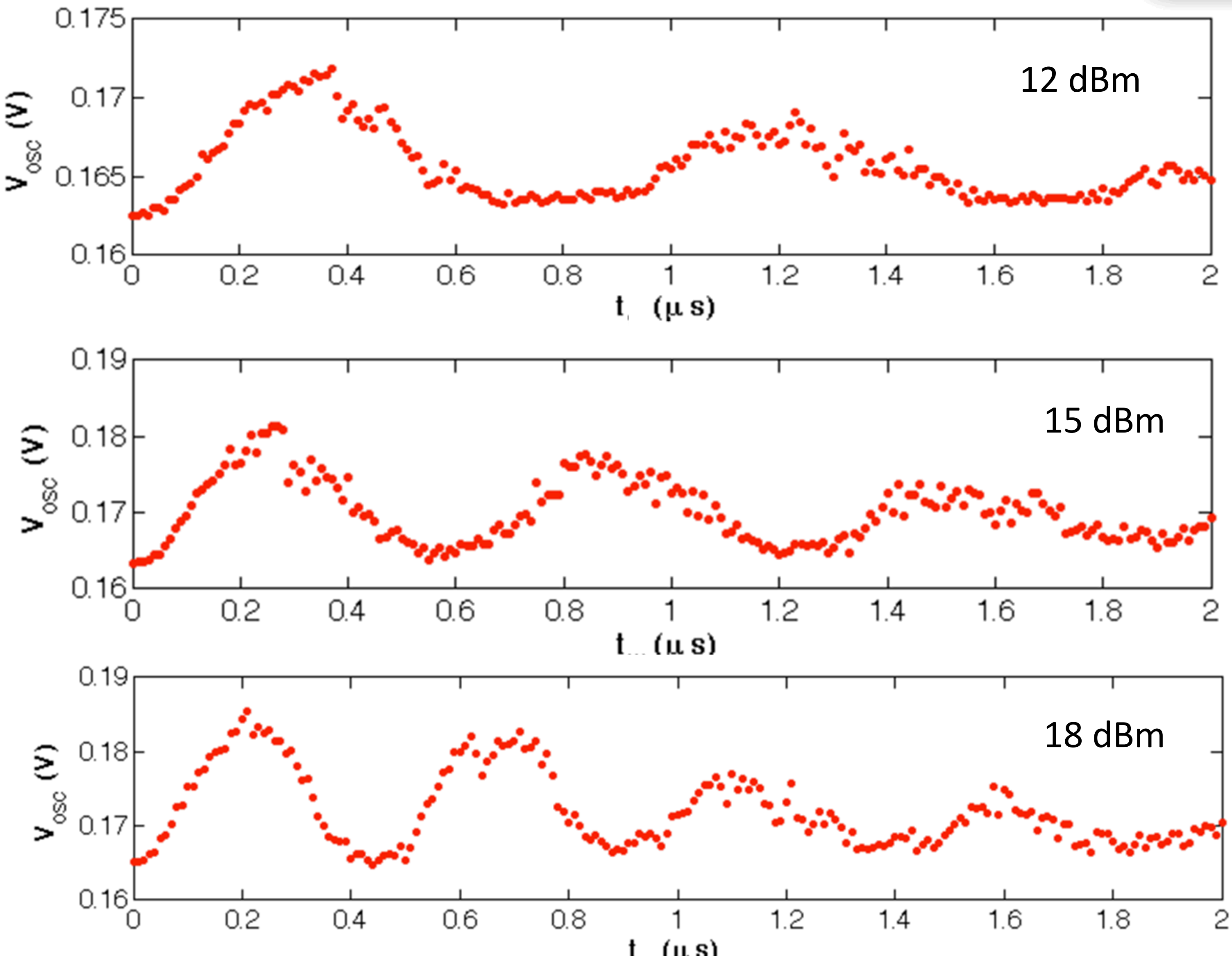






Rabi Oscillations

B=1.3 T



5760 averages

1920 averages

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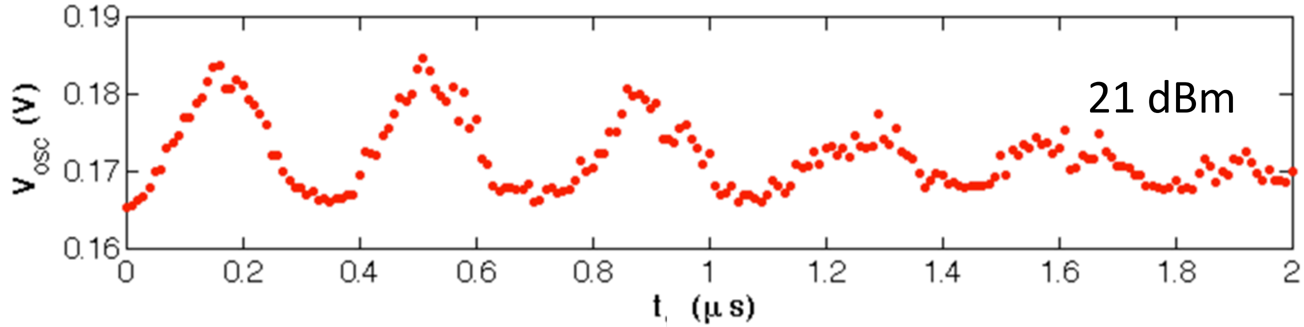
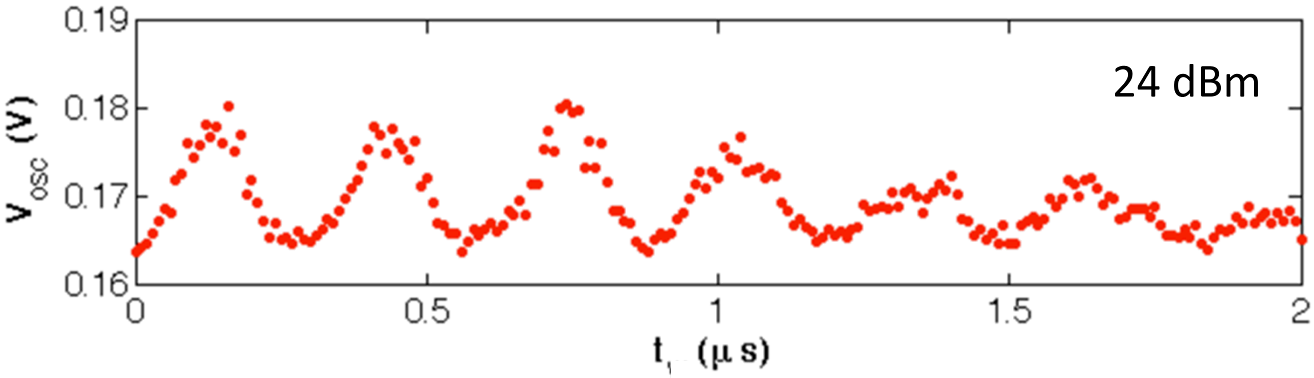
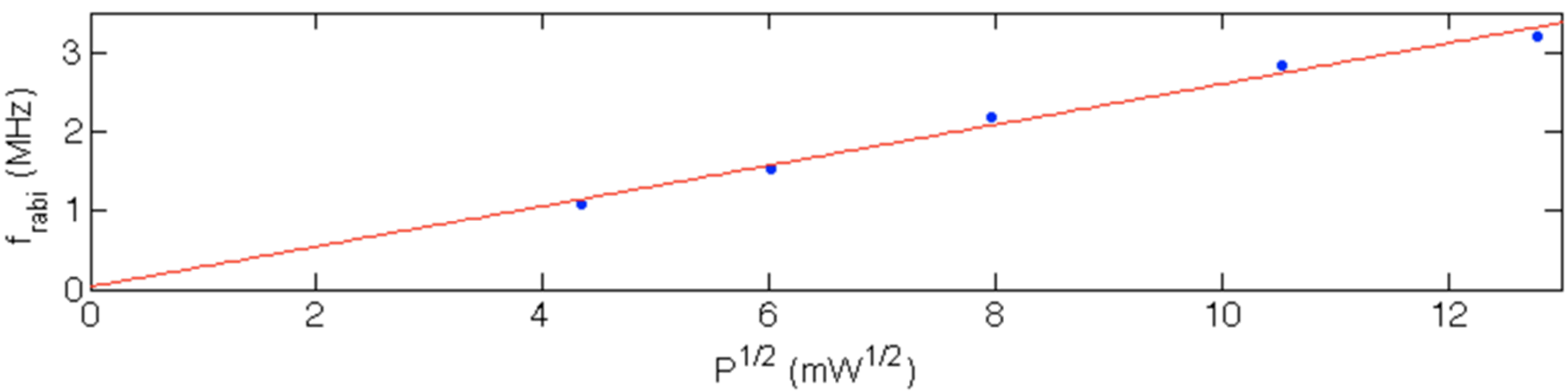
B=1.3 T

Rabi Oscillations

1920 averages







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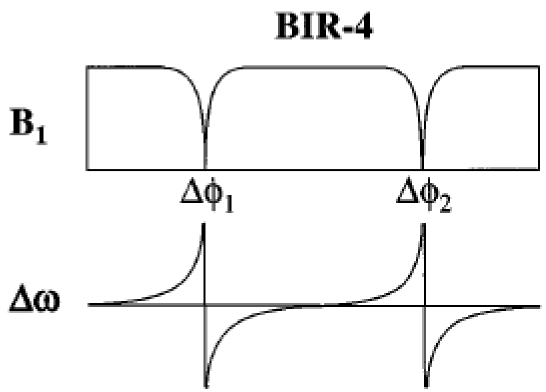
B=1.3 T

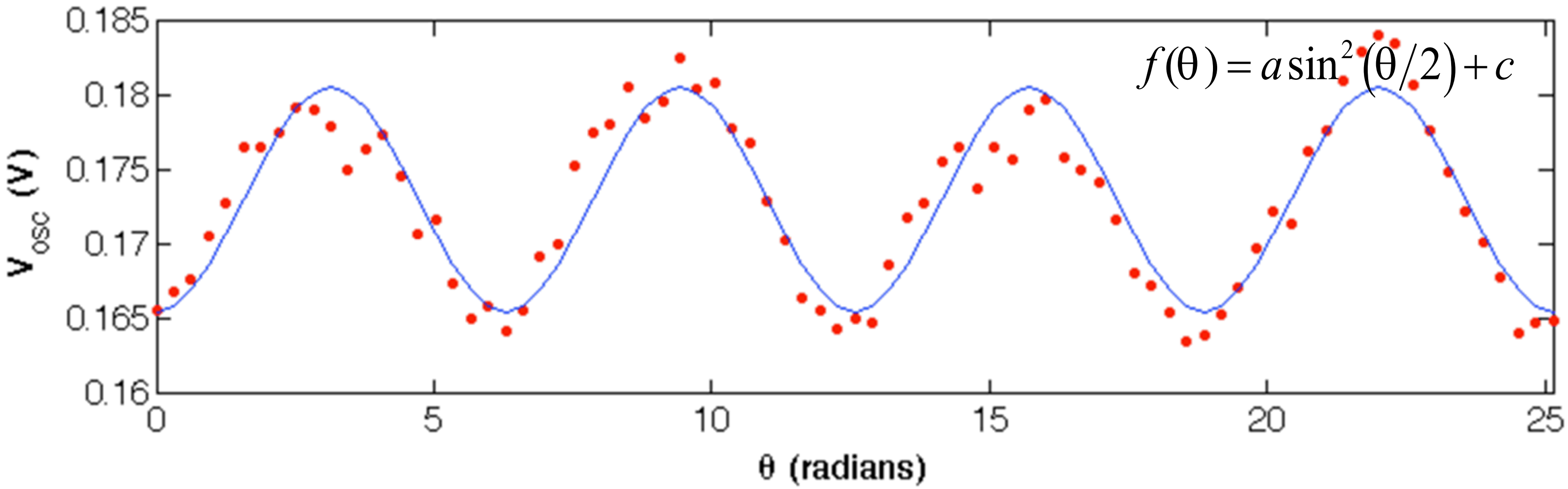
BIR4-WURST Rabi Oscillations

15 dBm
2048 averages

Tannus, 1997



BIR4-WURST pulses use a sequence of adiabatic half passages and phase shifts to produce an arbitrary angle rotation.



Acknowledgements: S. Lyon

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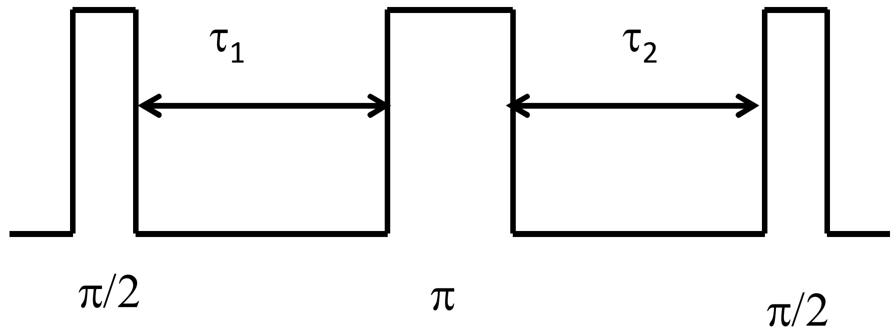
B=1.3 T

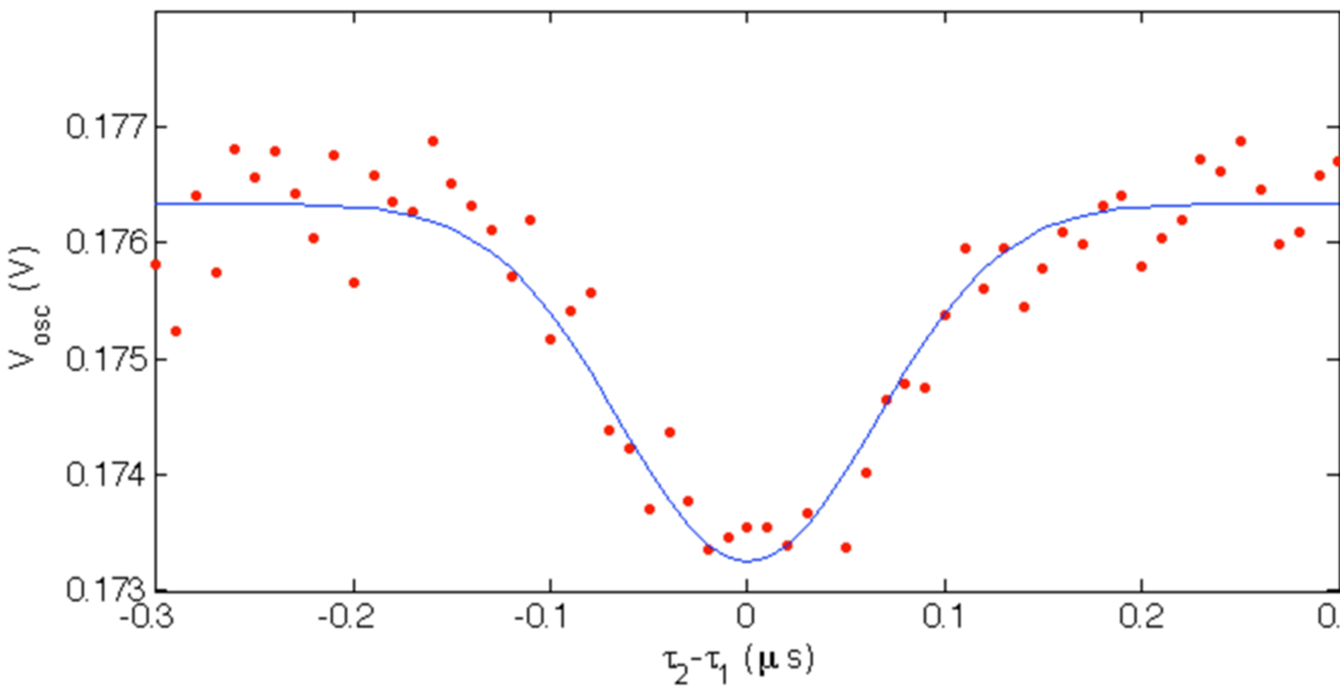
18 dBm

T_2^* Measurement

Hahn echo technique:

Vary τ_2 relative to $\tau_1=10\ \mu s$





$T_2^*= 77\pm5$ ns

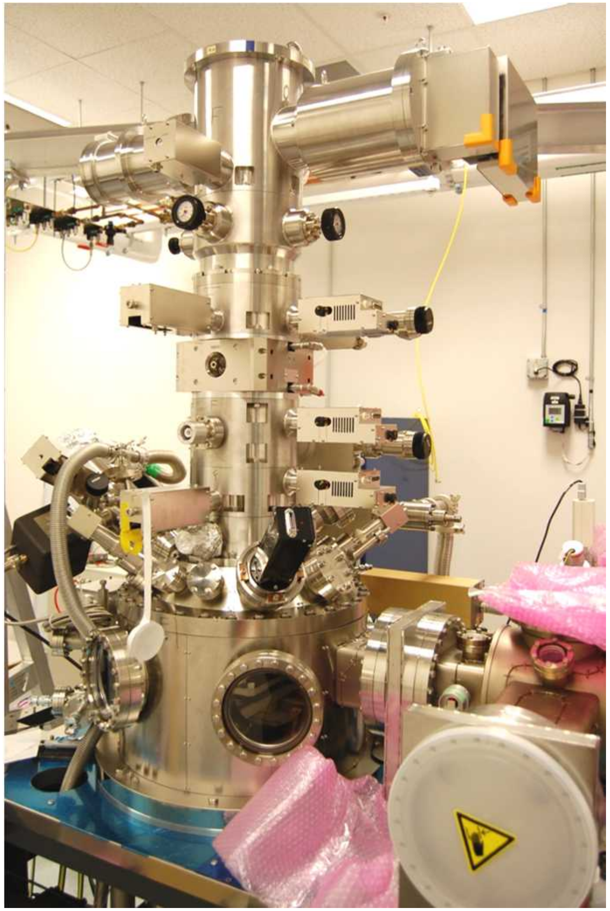
Line is a fit to a Gaussian

Outline

- Quantum computing with semiconductors
- Donor qubit with electron spin resonance
- Two-qubit interactions and devices

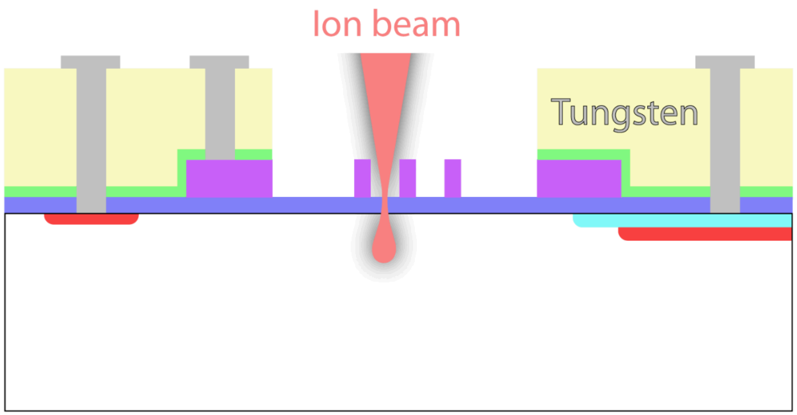
Deterministic implants using ion detection

nanoImplanter



- AuSiSb source
- ExB filter to select ion species and ionization
- Super-FIB for focus and steering donor ions
- Built in detectors surround silicon nanostructure regime

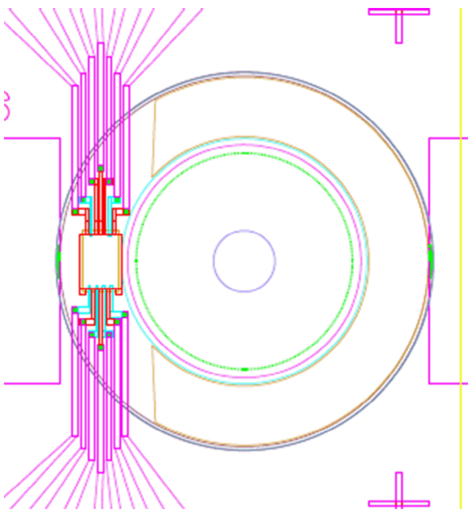
Detector schematic

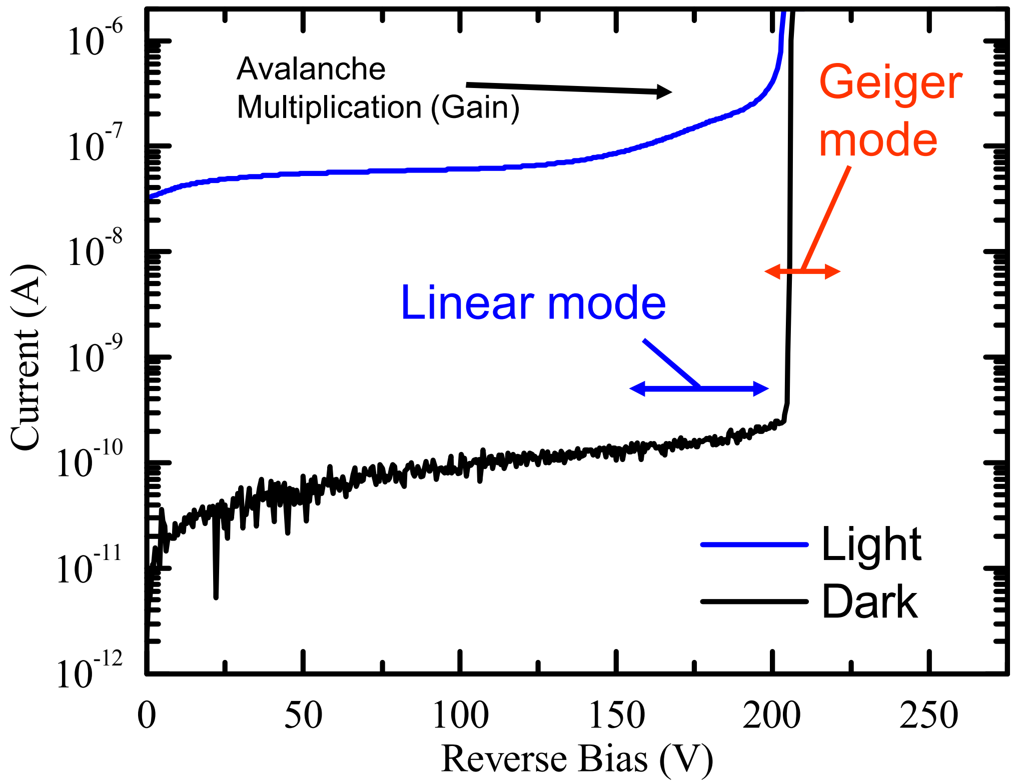


Ed Bielejec, Eli Garratt

Ion detector operation

CAD for detector and nanostructure construction zone





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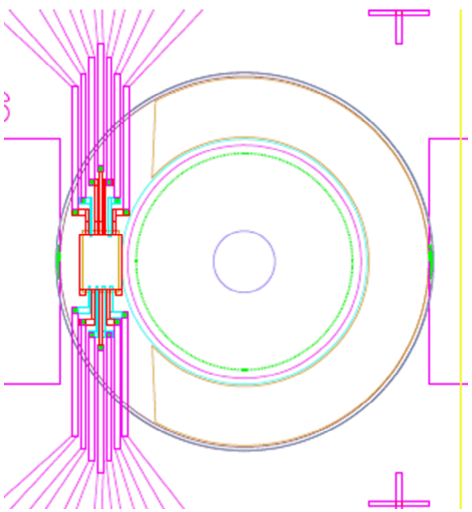
Ion detector operation

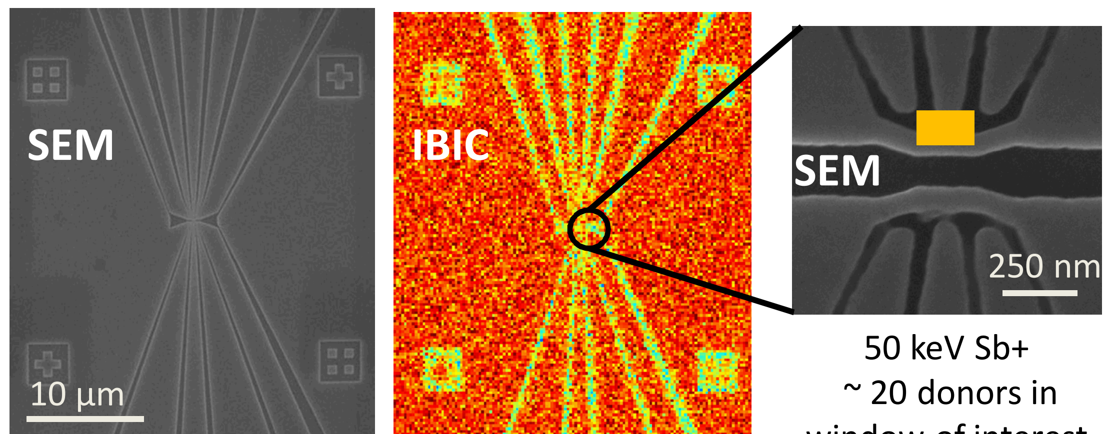
Detected single donor implantation of Sb ions allows multi-donor devices

CAD for detector and nanostructure construction zone



Ion beam map of nanostructure

SEM and IBIC map obtained in linear mode with 50 keV Sb+ (~50 ions per pulse)



50 keV Sb+
~ 20 donors in
window of interest

IBIC maps can be made with < 1 ion / pulse of 50 keV Sb

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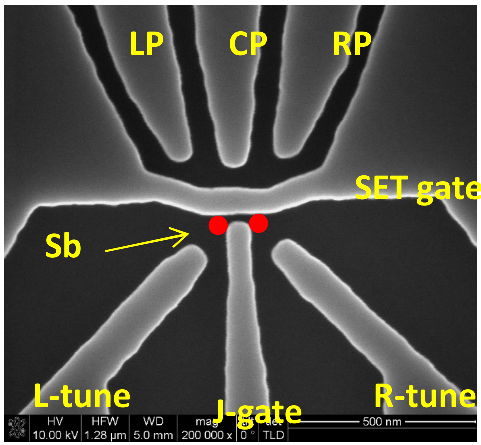
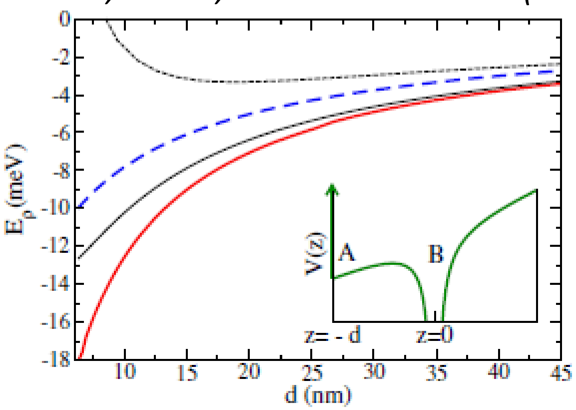
Two qubit structures

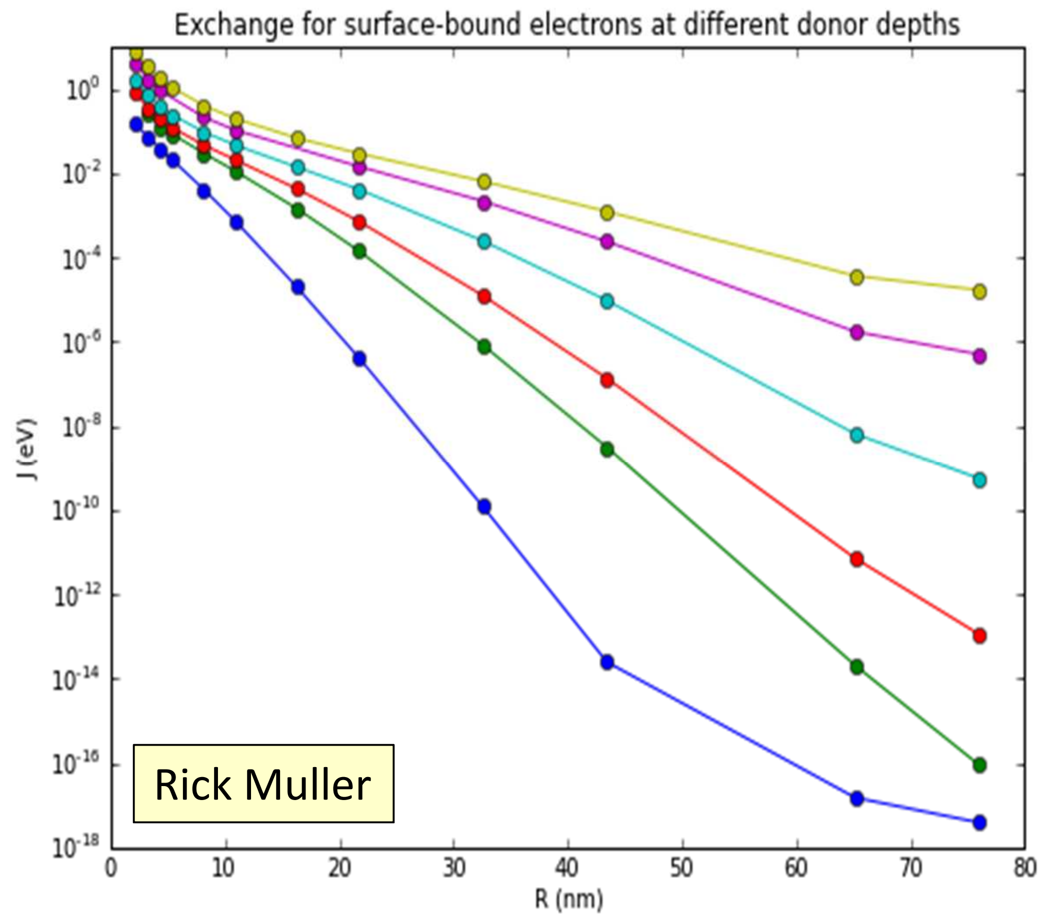
Exchange interaction due to electron wavefunction overlap is one technique for demonstrating a two-qubit device.

Exchange device



Calderon, Koiller, Hu and Das Sarma (2006)

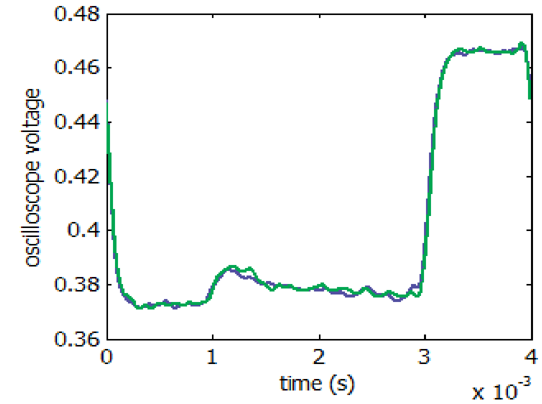




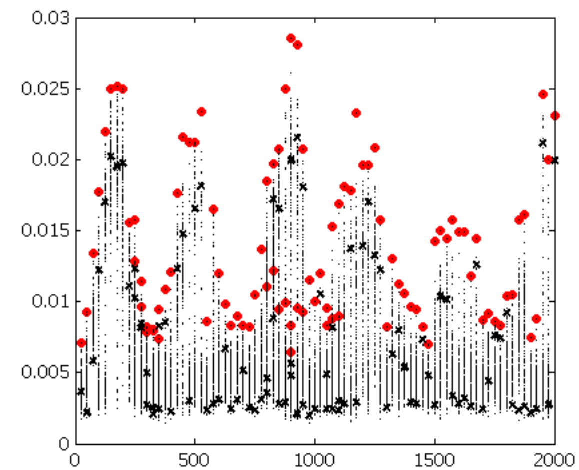
Summary

- Silicon nanoelectronics devices can be used control and measure the quantum properties of single electrons.
- Integrated charge sensors allow an all electrical readout of spin states.
- Electrically detected ESR allows controlled coherent rotation of a single electron spin.
- One approach to a two-qubit gate is using deterministically placed donors and the exchange interaction.

Spin readout



Coherent oscillations



Center for Integrated Nanotechologies

CINT is a US Department of Energy user facility open to the international research community. Our measurement lab is based in CINT, and we welcome user proposals from this community. More information is at http://cint.sandia.gov

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Acknowledgements

Sandia Co-workers

Khoi Nguyen, **Dwight Luhman**, **Lisa Tracy**, Serena Eley, Martin Rudolph, Tzu-Ming Lu , Nathan Bishop, Joel Wendt, Robert Grubbs, Tammy Pluym, Jeff Stevens, Greg Ten Eyck, Jason Dominguez, Robert Young, Rajib Rahman, Erik Nielsen, Toby Jacobson, Rick Muller and Malcolm Carroll

Collaborators

U. Wisconsin (M. Eriksson, D. Savage, M. Friesen, R. Joynt)

Australian Centre for Quantum computing Technology
(A. Dzurak, A. Morello, D. Jamieson, L. Hollenberg, and M. Simmons,)

Princeton University (S. Lyon, A. Tyryshkin)

NIST (N. Zimmerman)

U. Maryland (S. Das Sarma, M. Peckerar)

Lawrence Berkeley National Labs (T. Schenkel)

Purdue (G. Klimeck)

National Research Council (A. Sachrajda)

U. Sherbrooke (M. Pioro-Ladriere)