Manipulating single electrons in semiconductor devices for quantum computing

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Michael Lilly
Center for Integrated Nanotechnologies
Sandia National Laboratories

Outline

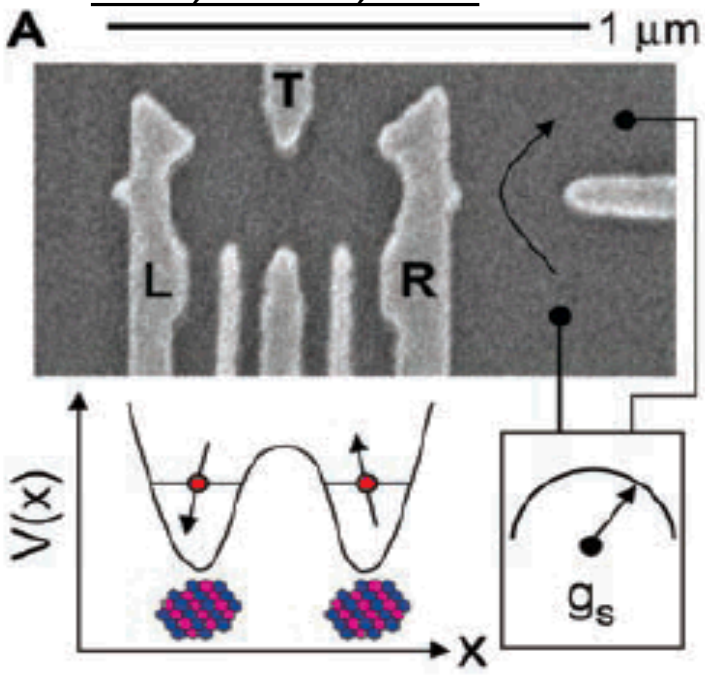
- Quantum computing with semiconductors
- Donor qubit with electron spin resonance
- Two-qubit interactions and devices

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.

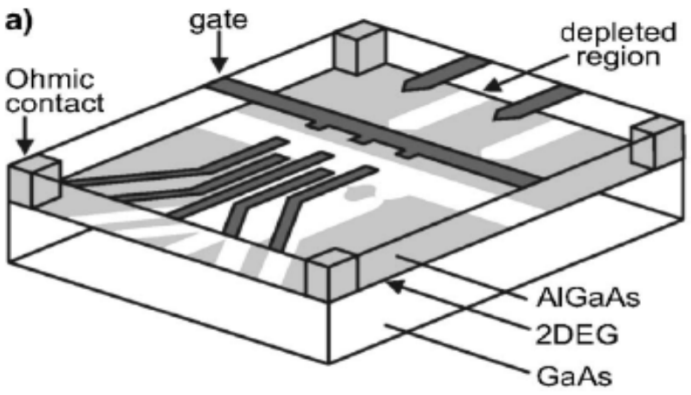
Double Quantum Dot Qubit in GaAs

- 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



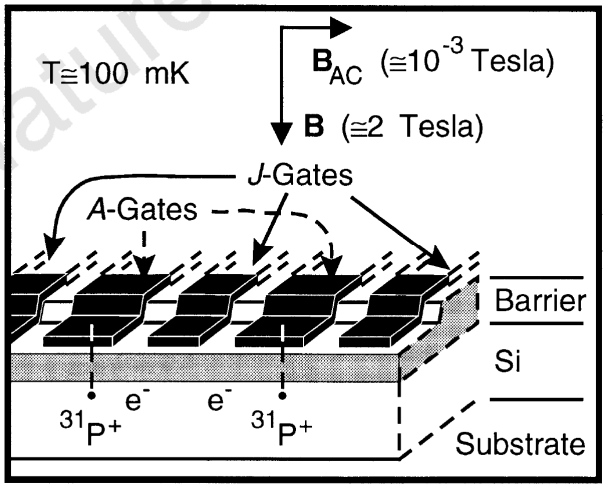
Need
- Isolate singlet triplet system
- Electrically tunable rotations
- Charge sense (fast is desirable)

Donor qubit

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

Kane architecture

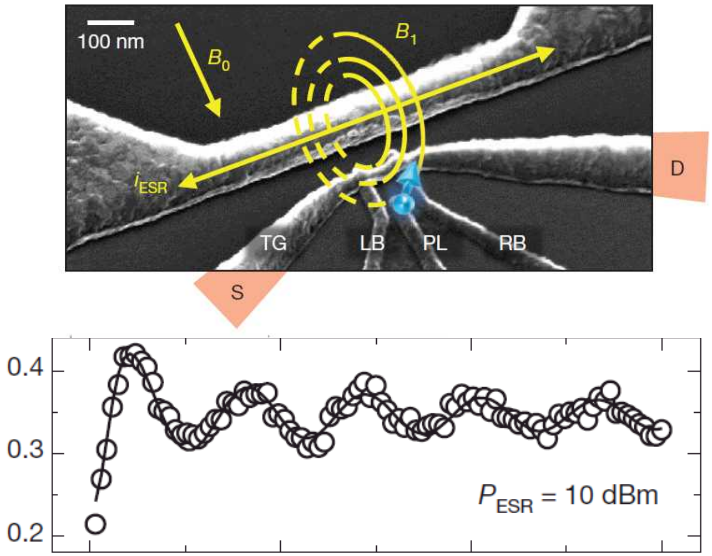
*B. E. Kane, Nature **393**, 1998*



Silicon donor research efforts

Australian CQC2T group (MOS, STM)

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



Much of the work in the silicon qubit field is supported by NEMO from Purdue group lead by Gerhard Klimeck)

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Requirements for donor electron spin qubit

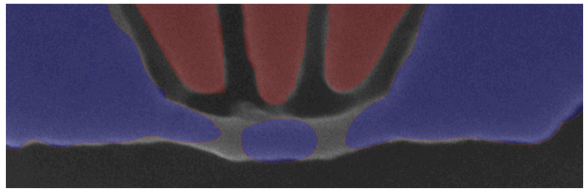
1. Isolation of a single electron for a spin qubit
2. Single spin readout technique
3. Long spin lifetime (T1)
4. Spin initialization
5. Spin rotations
6. Long dephasing time (T2)

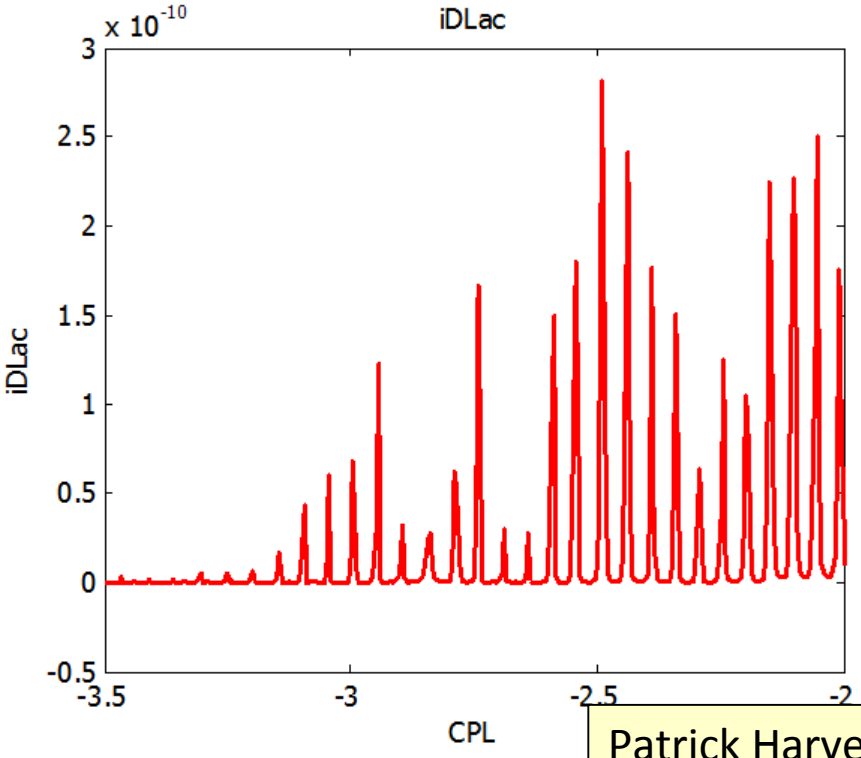
Single electron transistor

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





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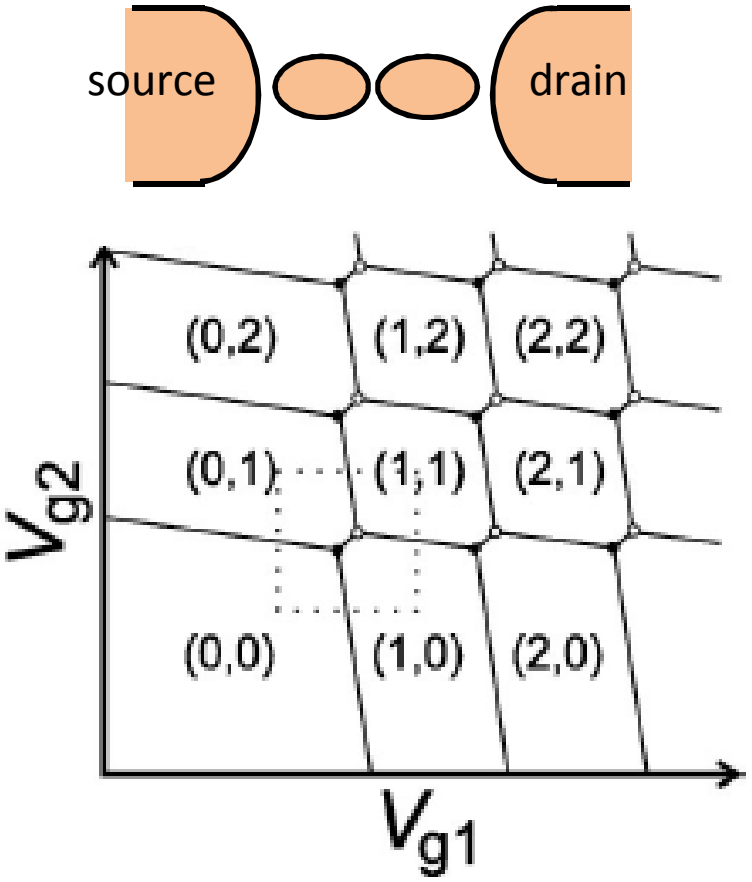
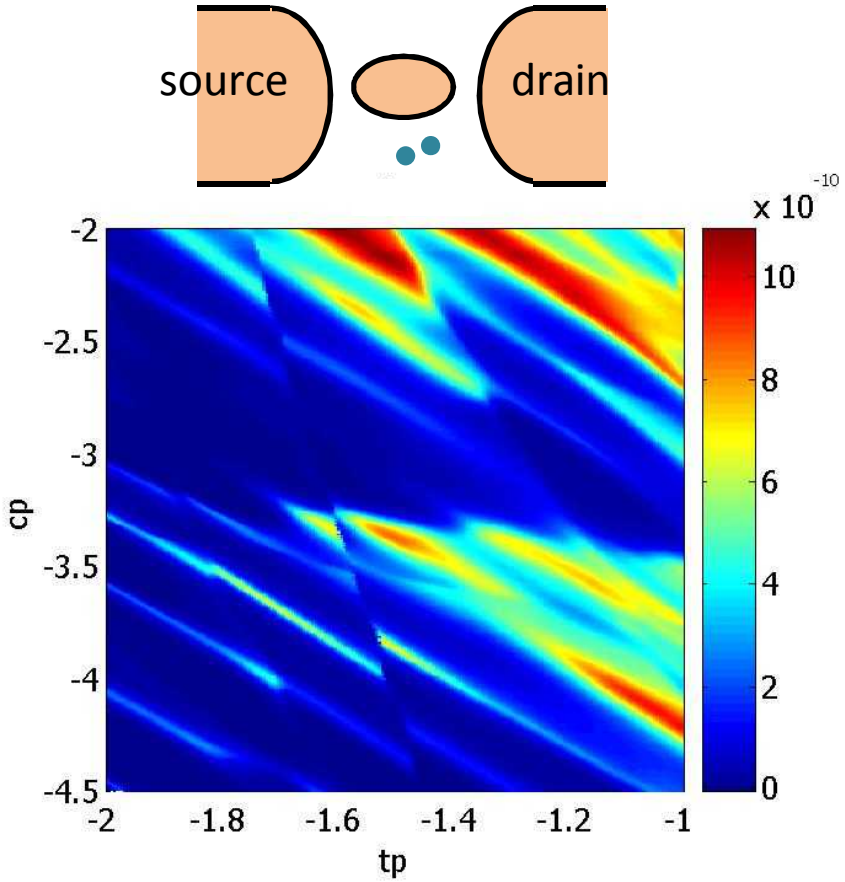
Isolation of a single electron spin

Series double quantum dot



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

Parallel dot / donor system



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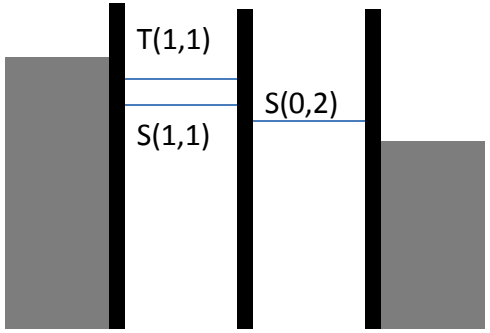
Single spin readout technique

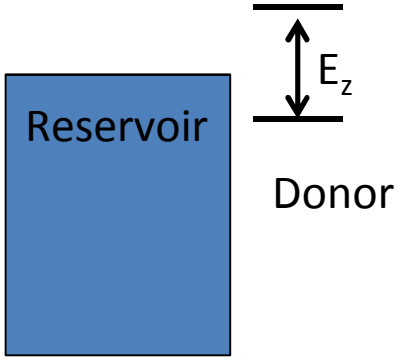
Double quantum dot



- 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

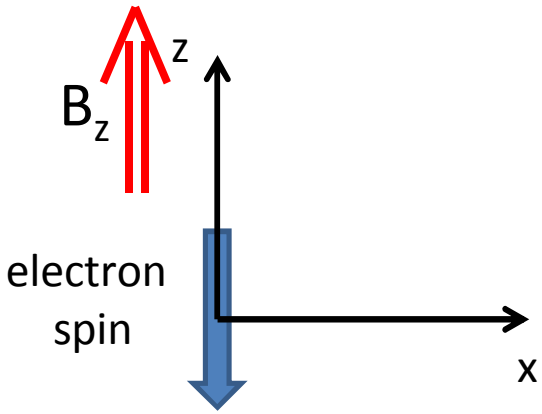
Zeeman splitting

$E_{zeeman} = g \mu_B B_z$

$\mu_B = e\ hbar / 2\ m_e$

At 1 Tesla,

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



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Electron spin resonance

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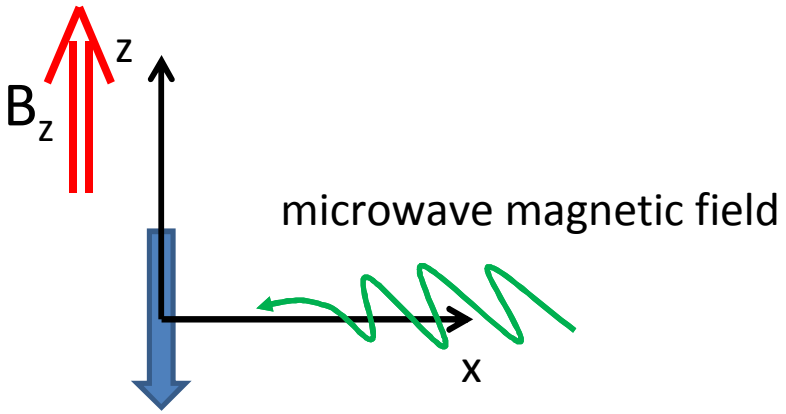

Use rotating frame:

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

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Electron spin resonance

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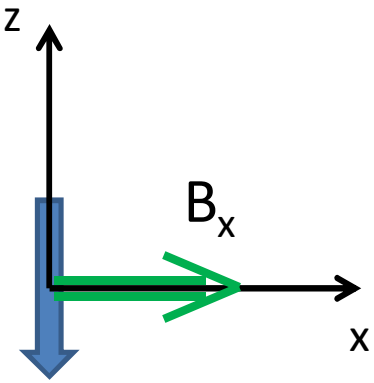

Rotating frame

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

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Electron spin resonance with P donor

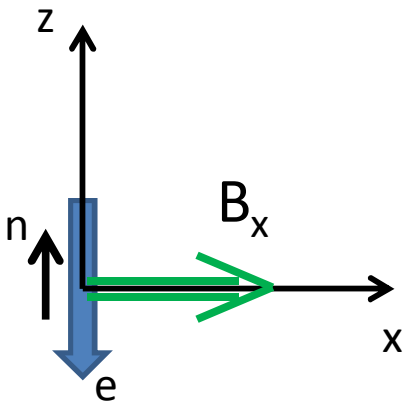
Zeeman splitting

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

$\mu_B = e\ hbar\ /2\ m_e$

At 1 Tesla,

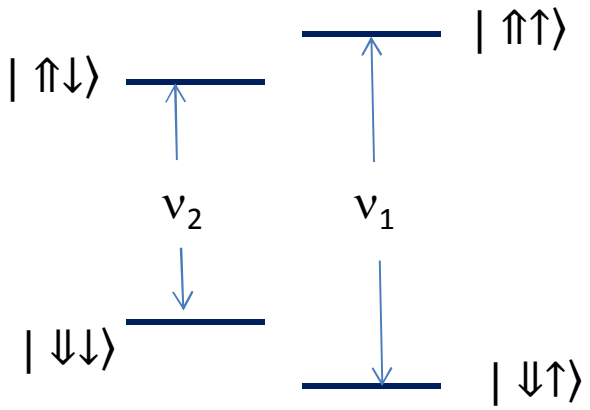
E_{zeeman} = 116 μV = 1.34 K = 28.0 GHz



Hyperfine coupling

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

A = 117 MHz for P



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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)

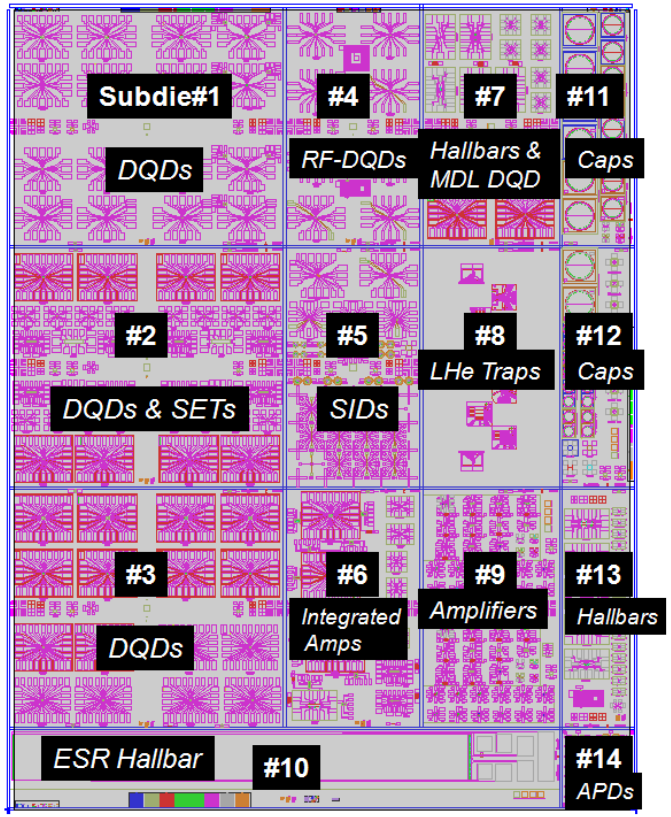
- T2* ~ 200 usec
- T2 ~ 1 msec

(*Australian CQC2T, presentations*)

Si28 (bulk, Avagadro material)

- T2 ~ 10 sec

Si fabrication is well known



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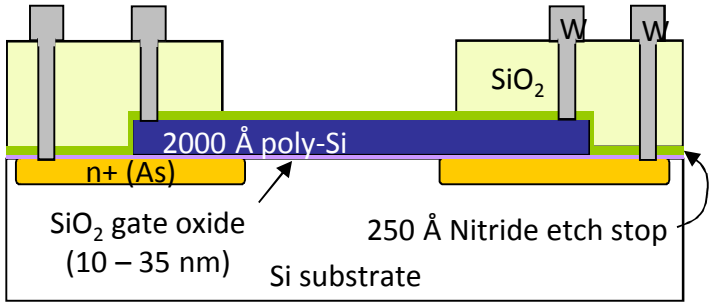
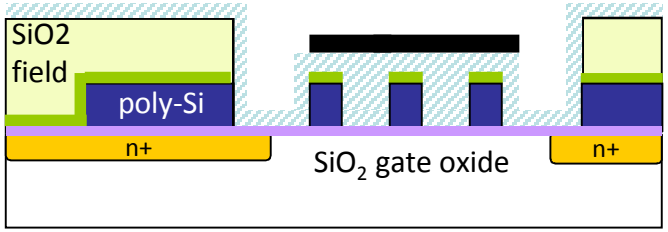
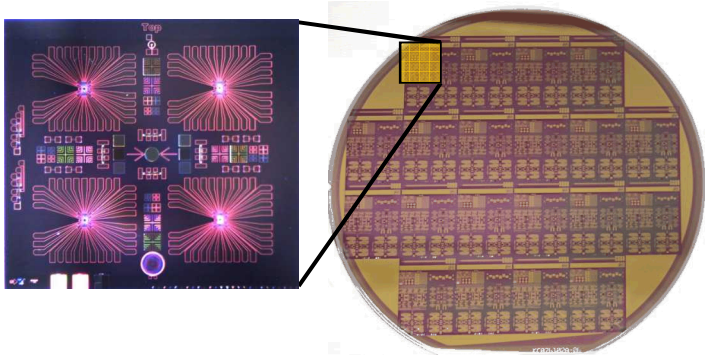
Si MOS Fabrication

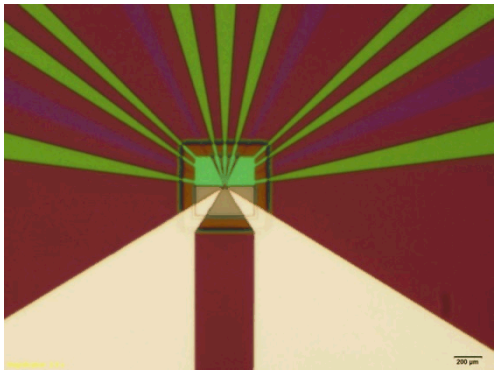
Front-end in silicon fab

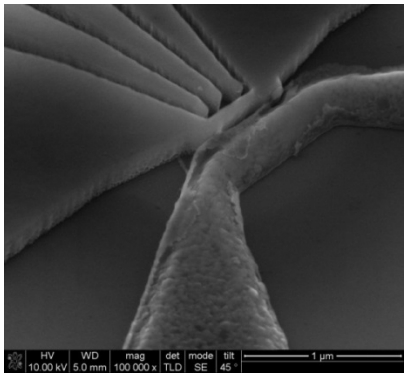


Back-end nanolithography









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Multiple bandwidths in a dilution refrigerator

DC lines

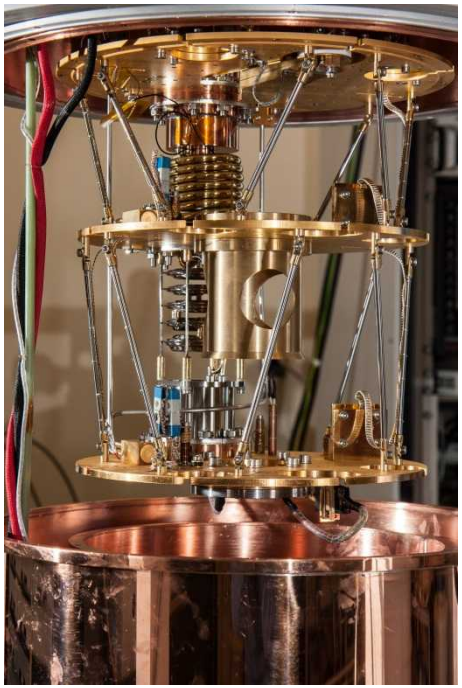
- static bias, or slowly changing bias

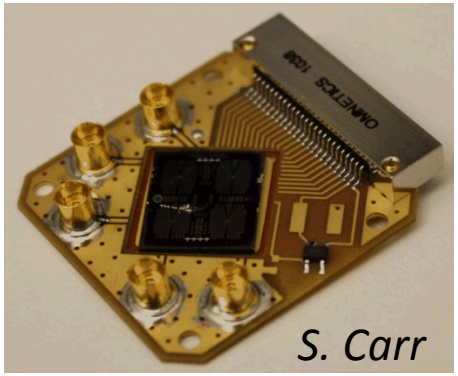
Pulsing lines and fast current measurement

- 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





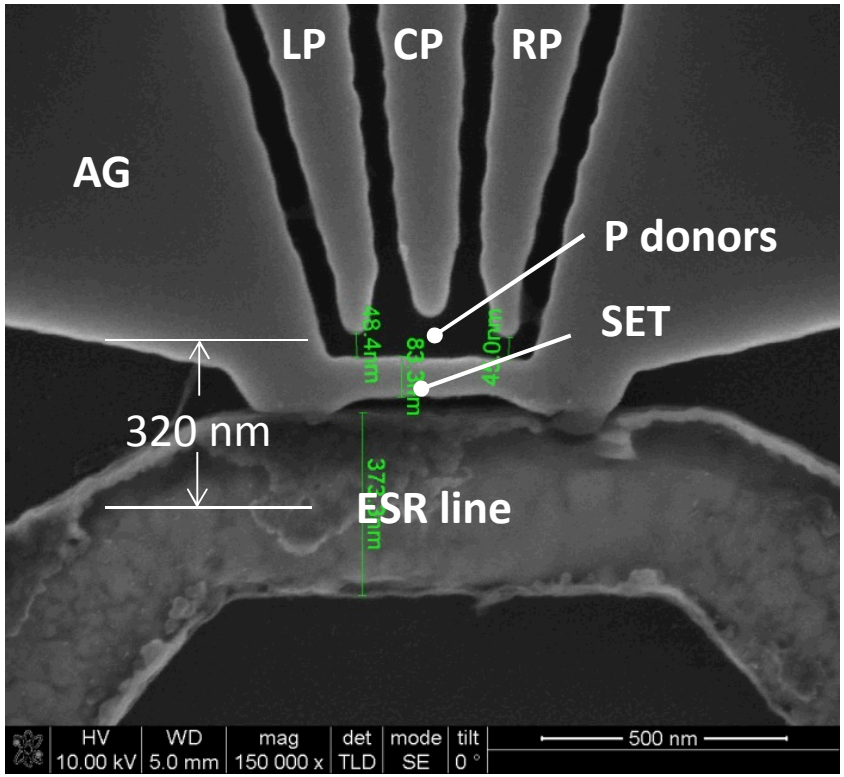
Outline

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

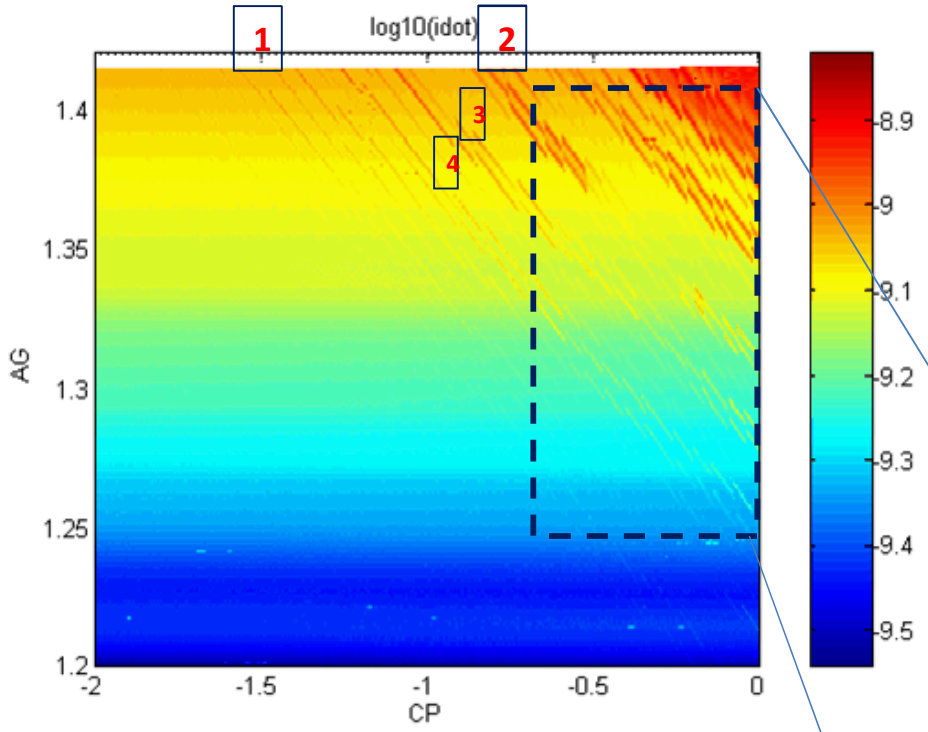
Device layout for ESR experiment

1275 dev 4

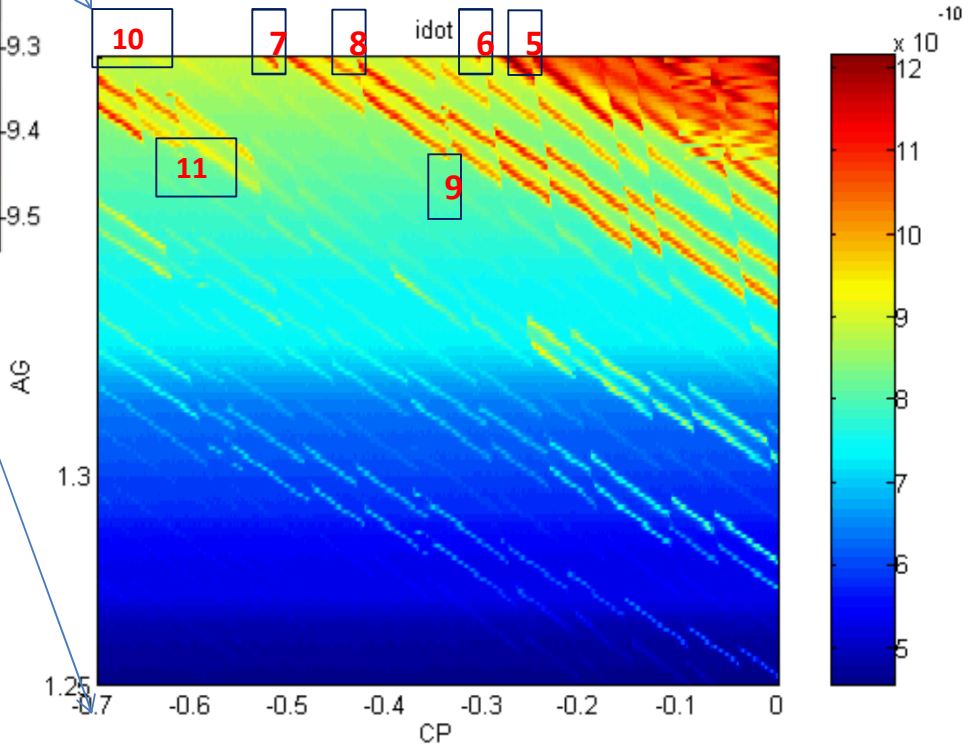
- Natural Si
- 35 nm gate oxide
- Timed implant of P donors
  - ~ 30 donors between CP and AG.
  - 120 keV -> ~30 nm below oxide
- ESR line resistance ~ 15 ohm at RT.
- P to center of ESR < 400 nm



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.



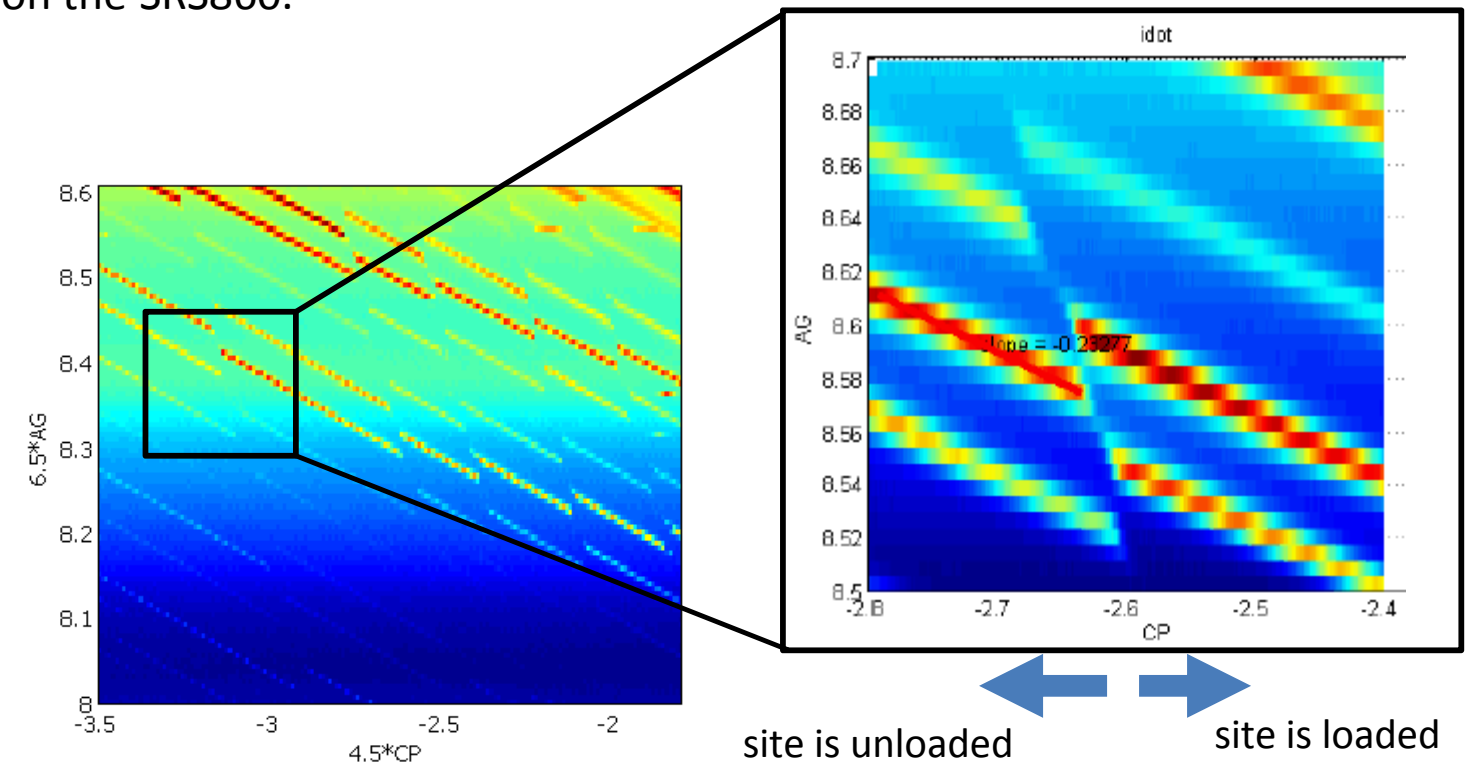
#2: tunnel time changes from time to time, from us to tens of ms

#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.



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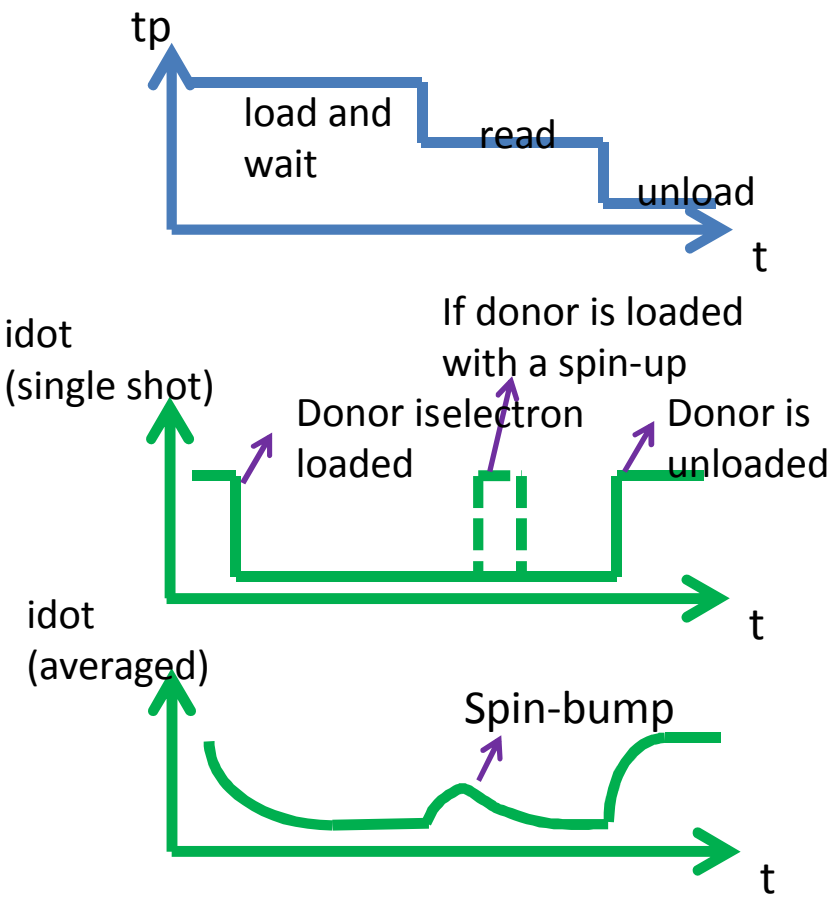
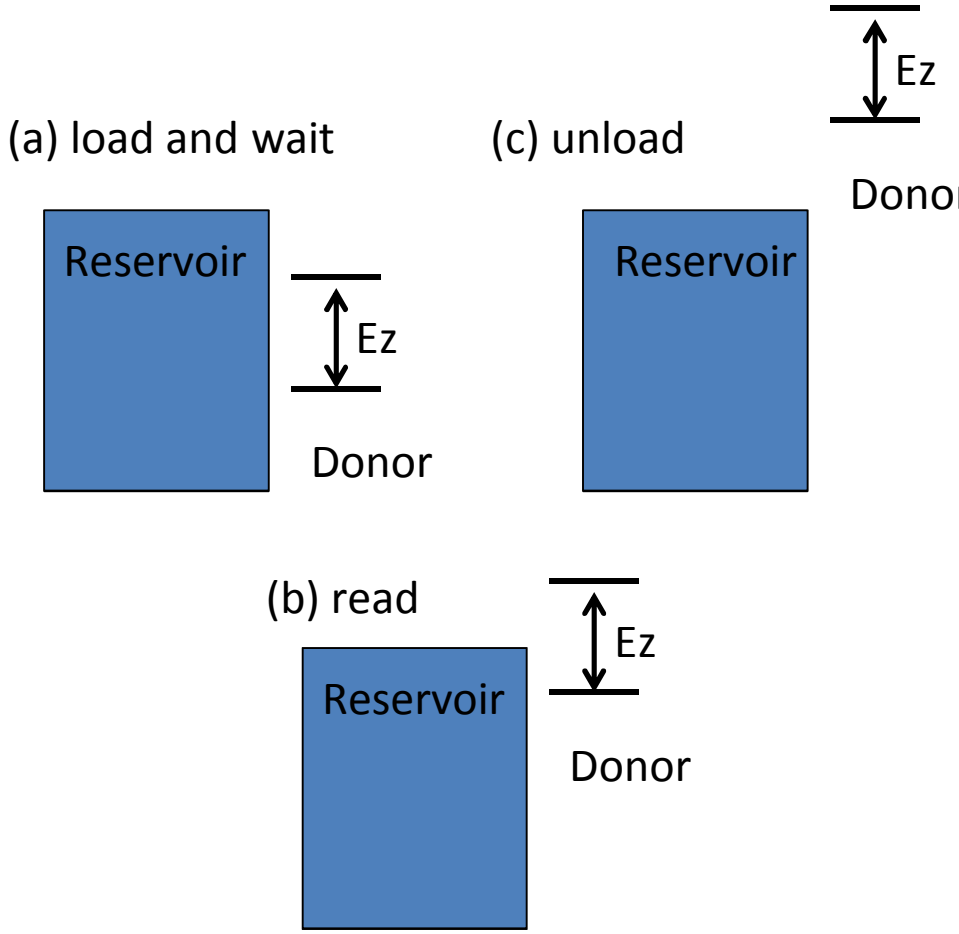
Pulse Sequence

Three-level probing sequence



Energy level alignment



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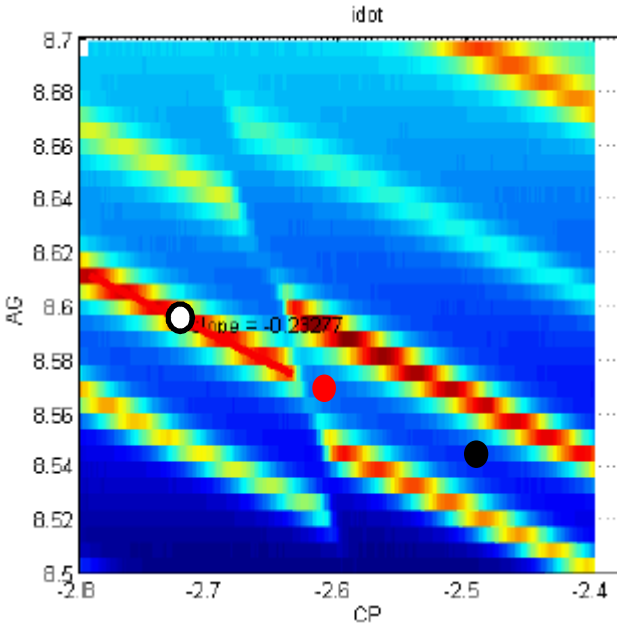
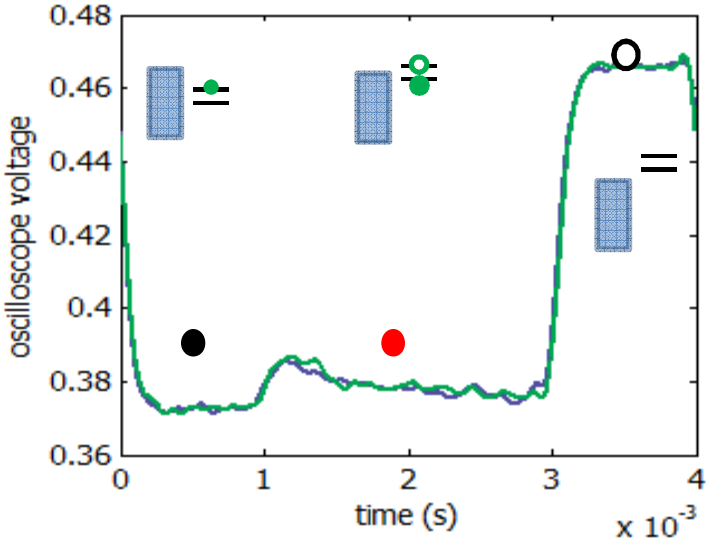
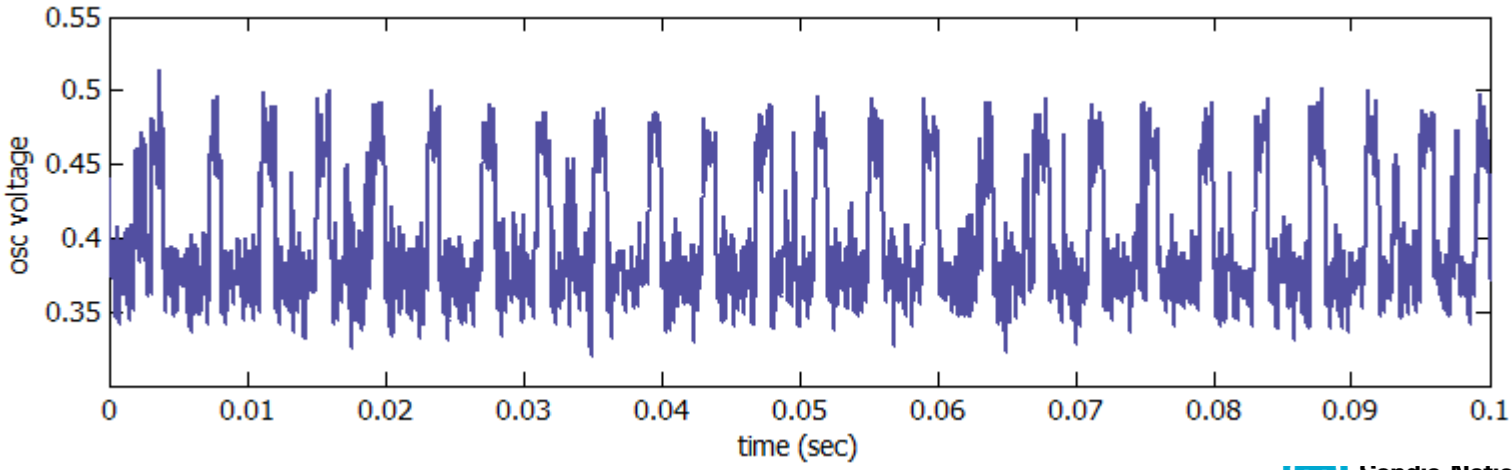
Spin readout: averaged and single shot



256 averages



25 single shot measurement



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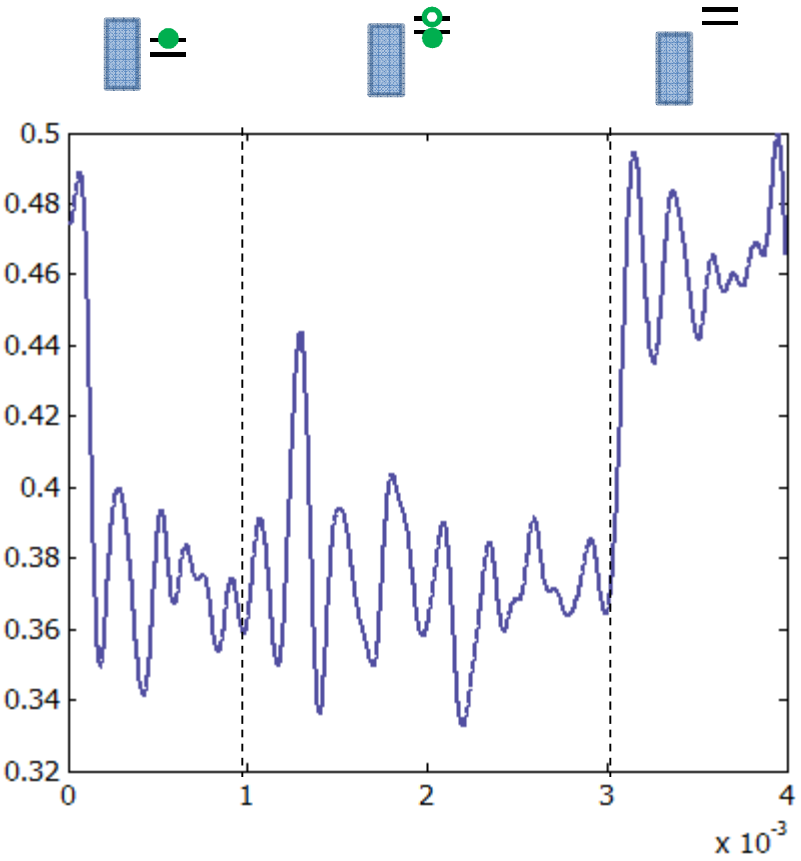
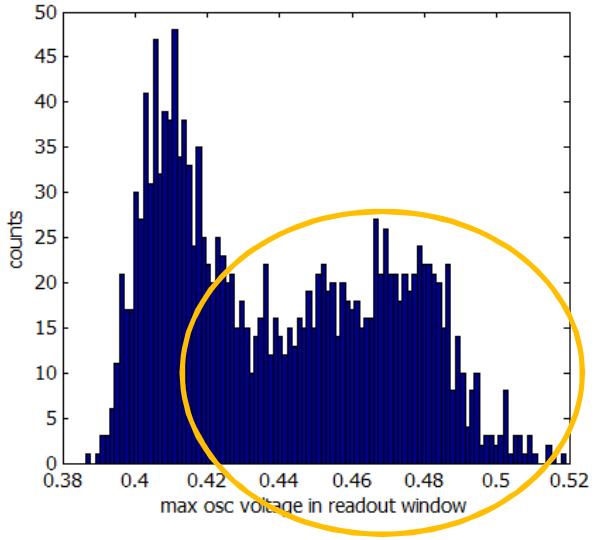
Single shot readout analysis

Single shot, spin up event



CQC2T technique for identifying spin up



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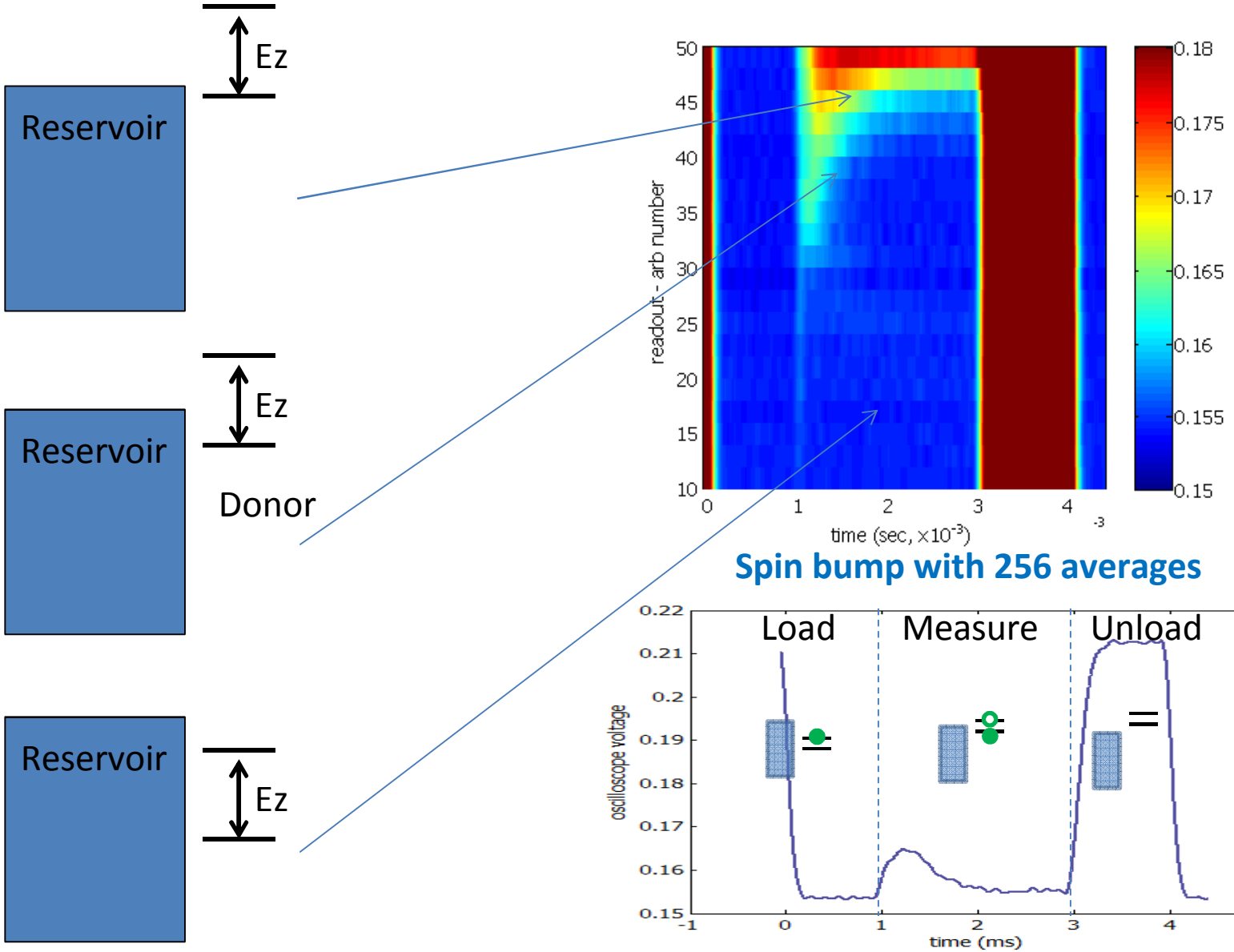
Tuning spin readout



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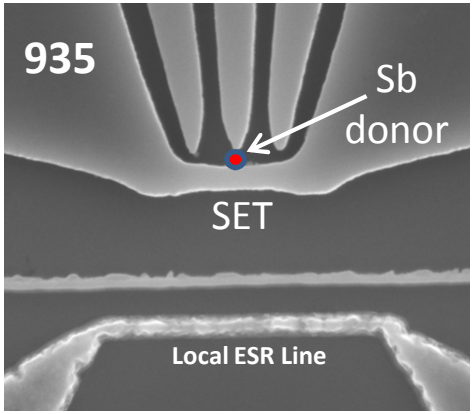
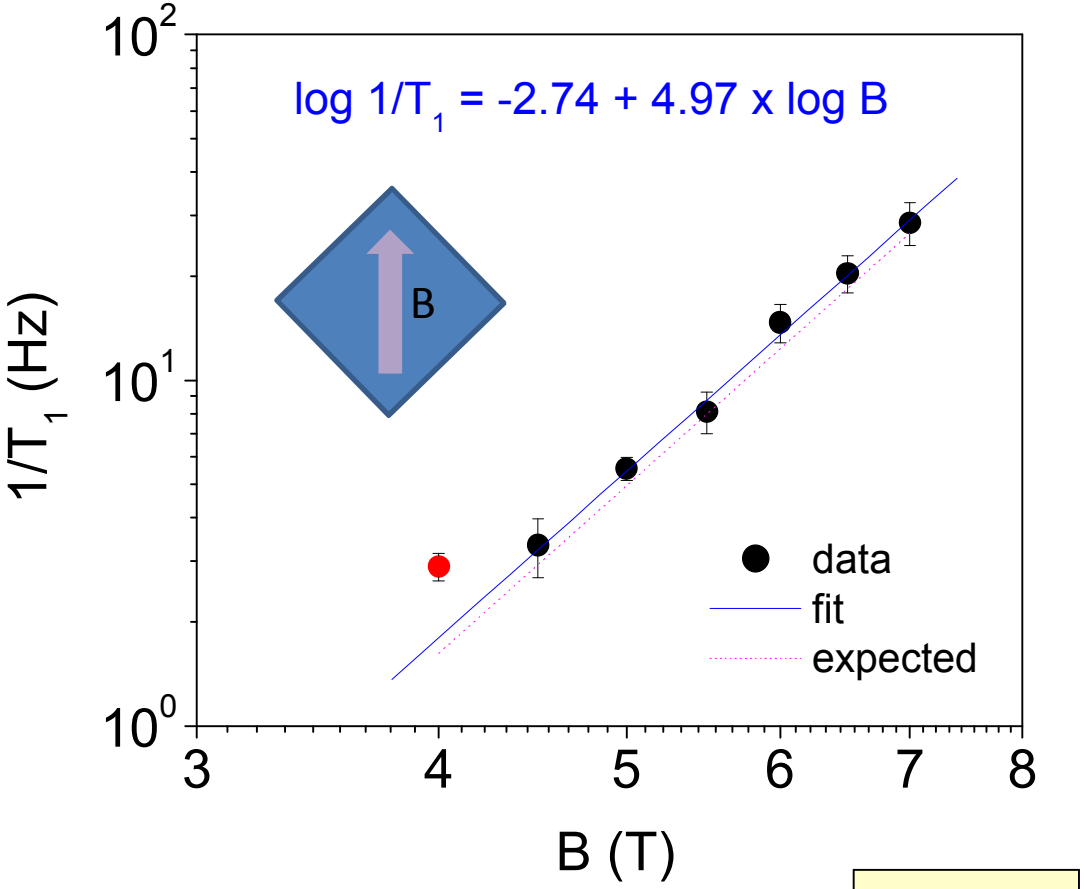
Magnetic field dependence of T1

Sb donors implanted near silicon SET



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

T1 decreases with increasing field



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

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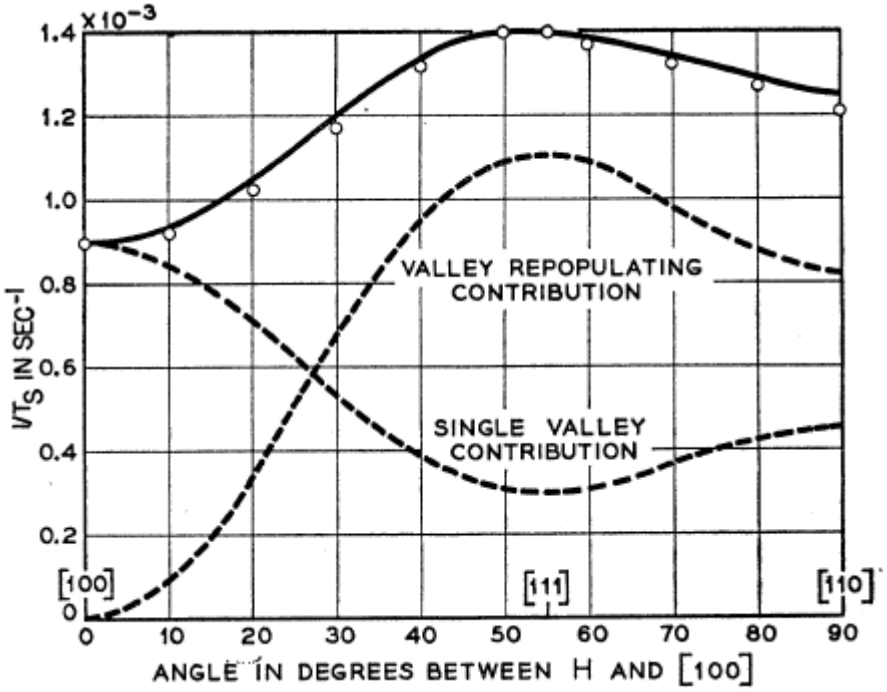
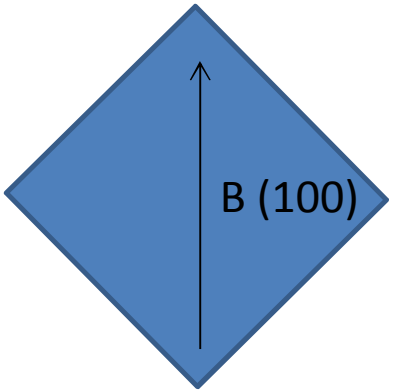
Spin relaxation in silicon



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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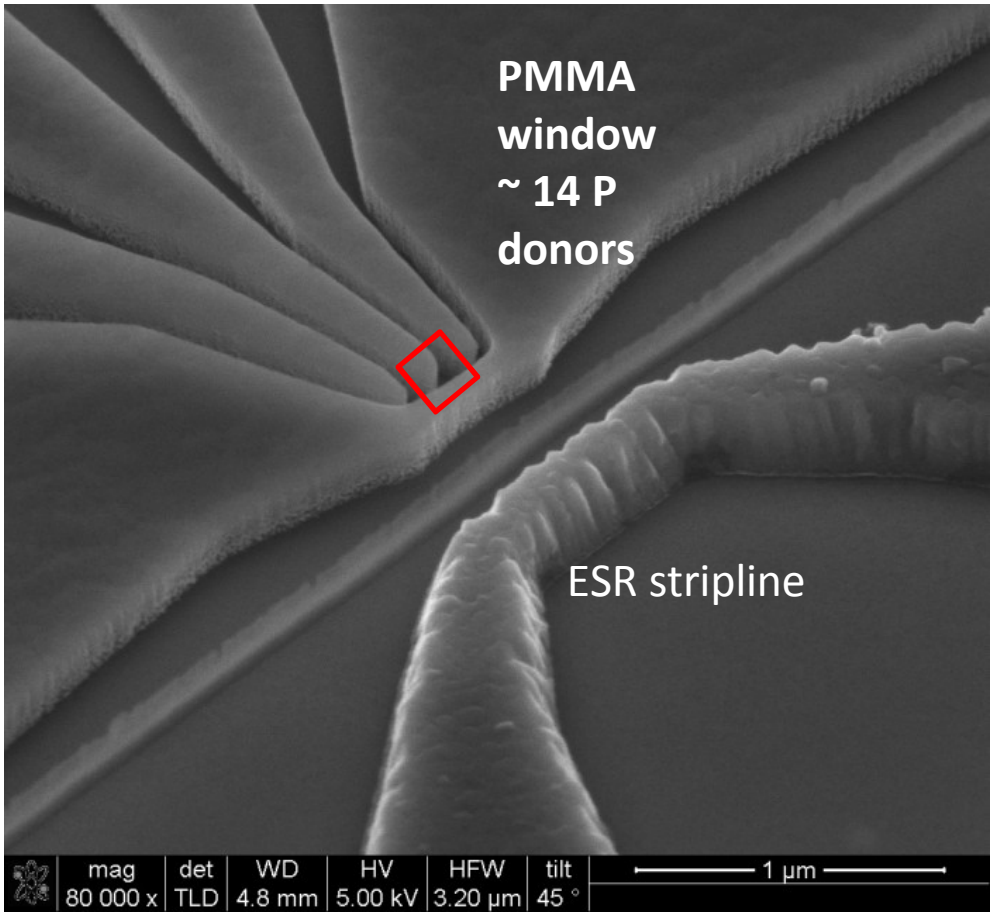
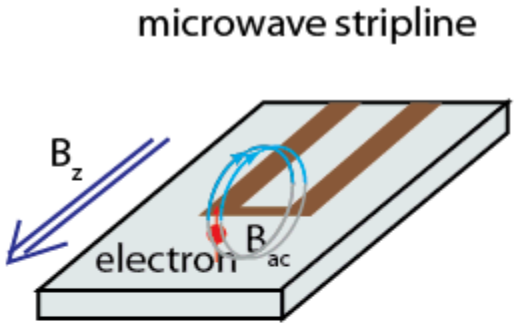
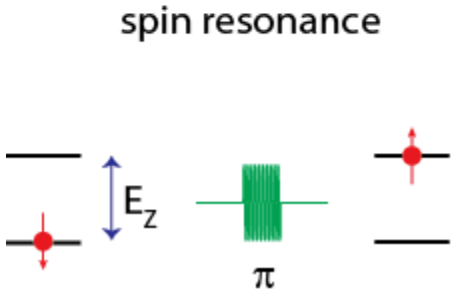
Next Steps: Local Electron Spin Resonance



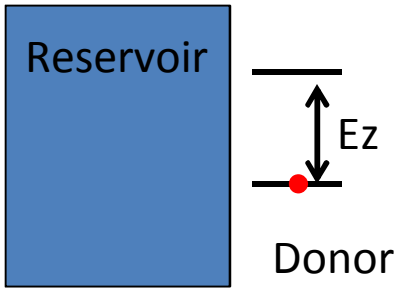




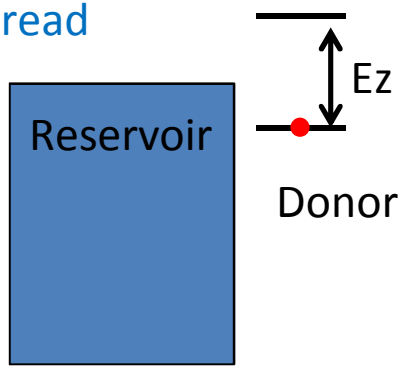
Lisa Tracy, Dwight Luhman, Khoi Nguyen

ESR pulse sequence – two level pulse

(a) plunge and ESR

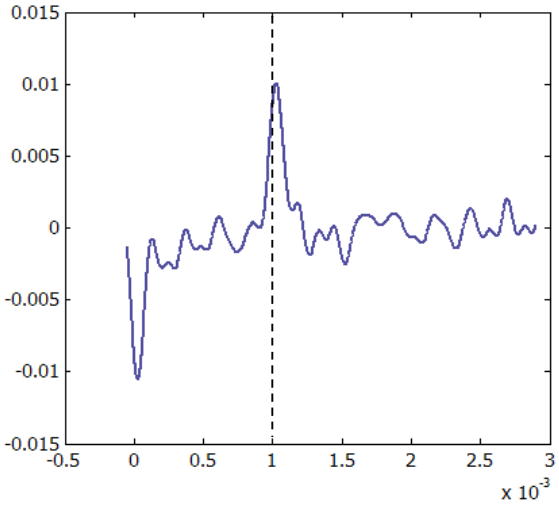


(b) read



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)

Off resonance – no spin up signal



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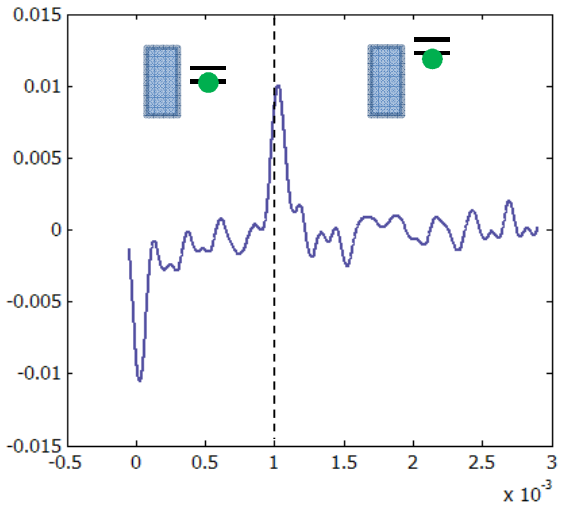
ESR pulse sequence – two level pulse

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

Off resonance – no spin up signal



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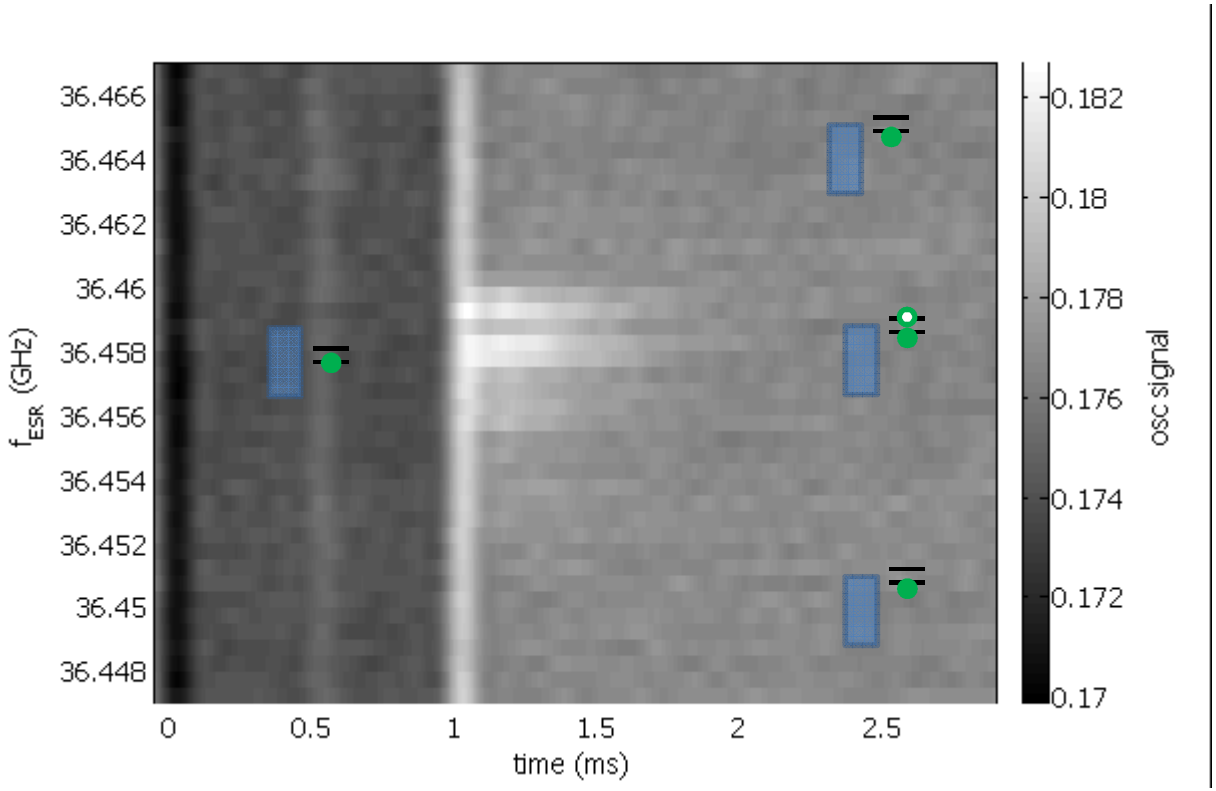
ESR frequency sweeps

- 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 (donor nuclear spin flip?).



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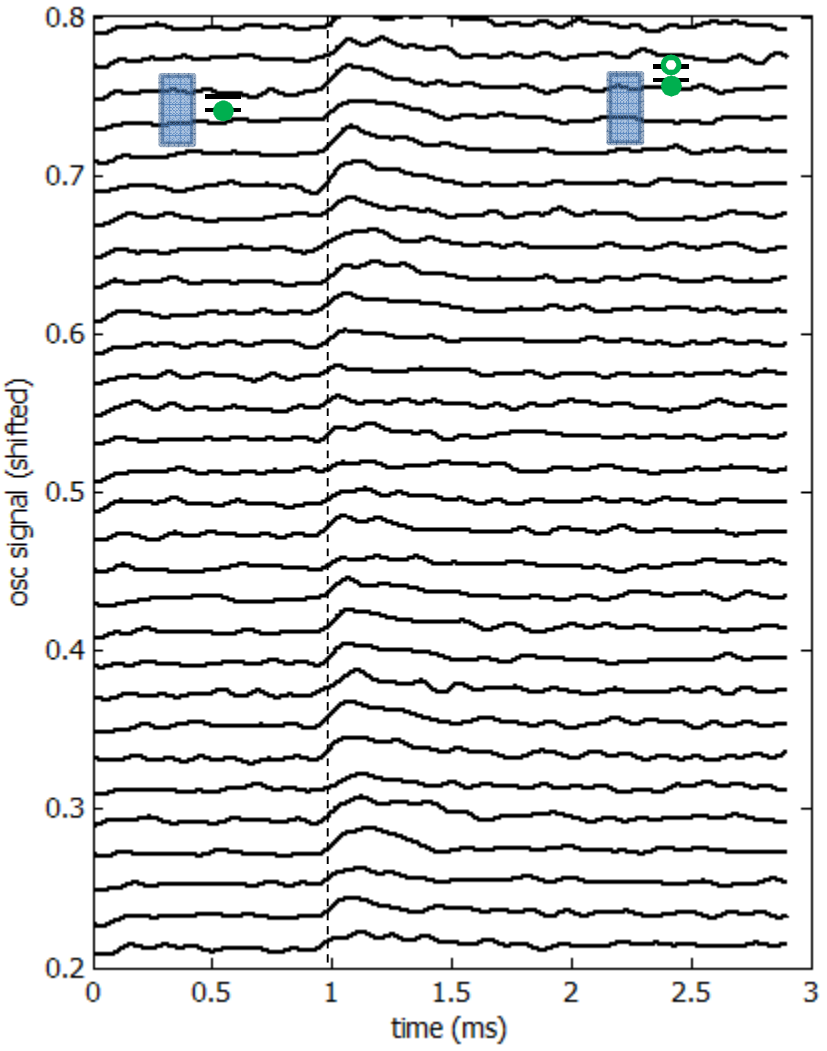
How do we deal with resonant frequency shifts?

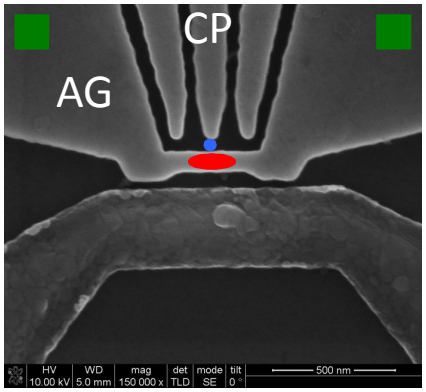
At a fixed microwave frequency (36.459 GHz), we collect 150 repeats of 128 averages of the two level pulse sequence.

- Sometimes the spin signal is small, sometimes large.
- With the data, we can find the max peak value, max peak integral, averaged peak value, averaged integral, ...
- Coherent oscillations are measured by collecting these traces for each ESR pulse time.

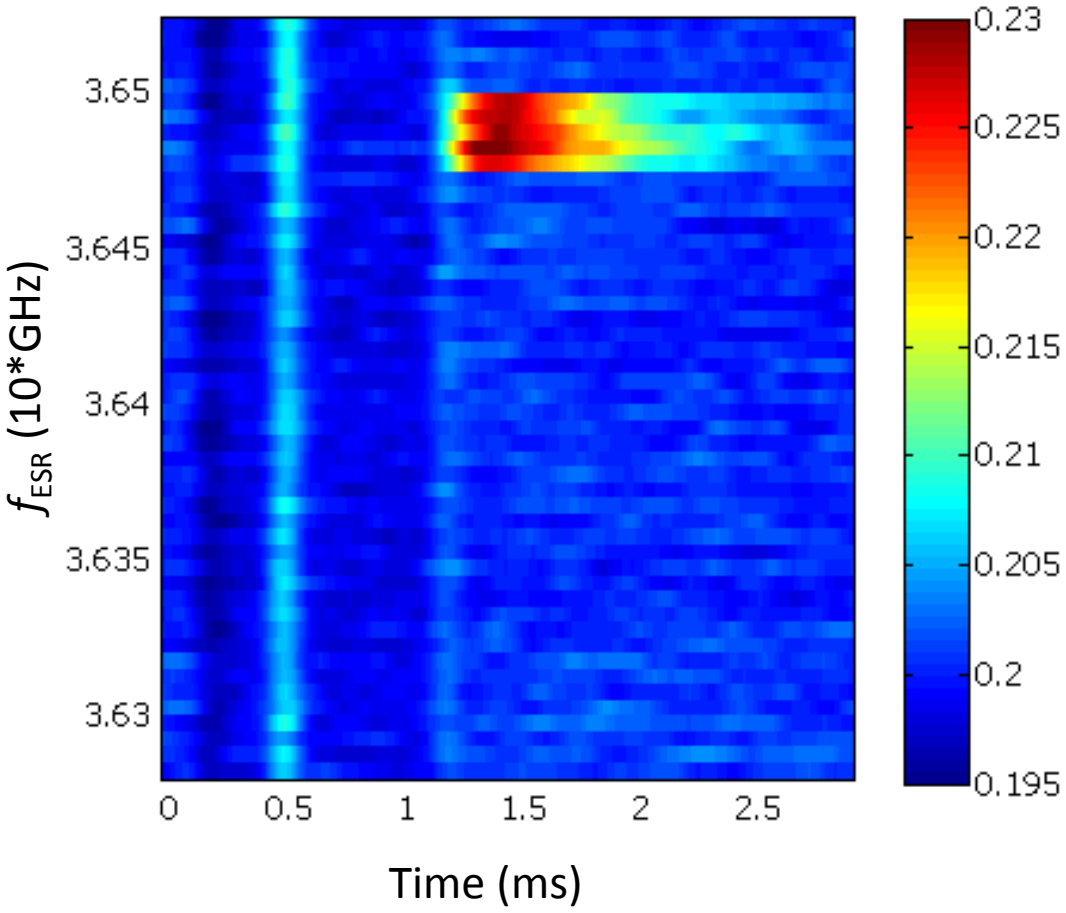


Electron Spin Resonance

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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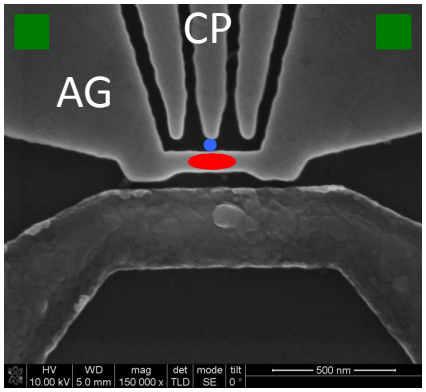
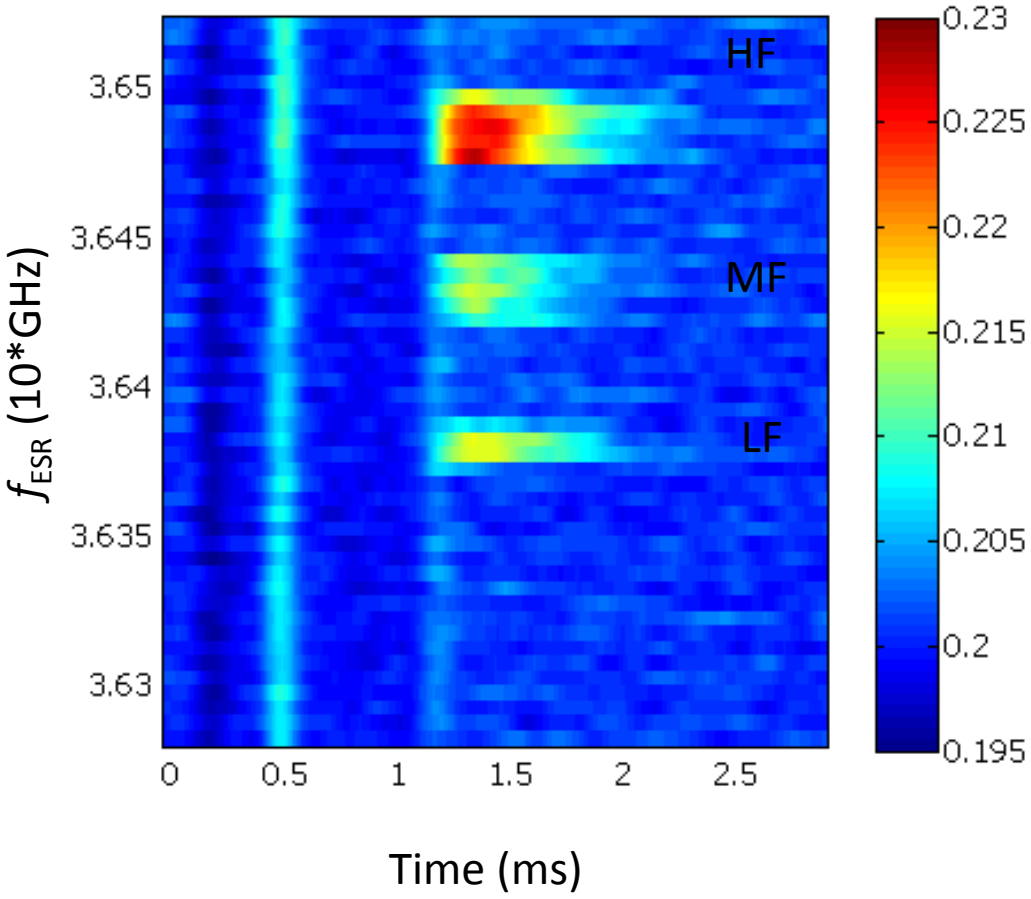
Electron Spin Resonance

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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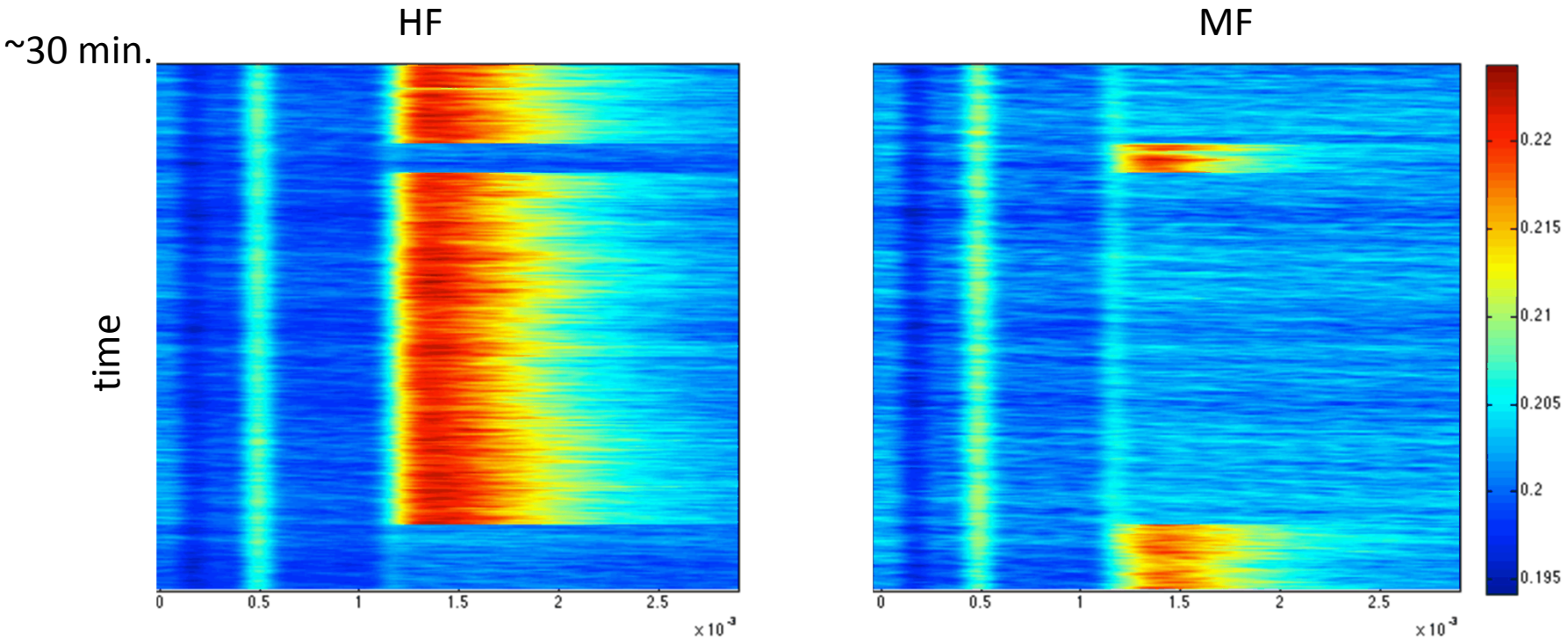
B=1.3 T

Electron Spin Resonance



- 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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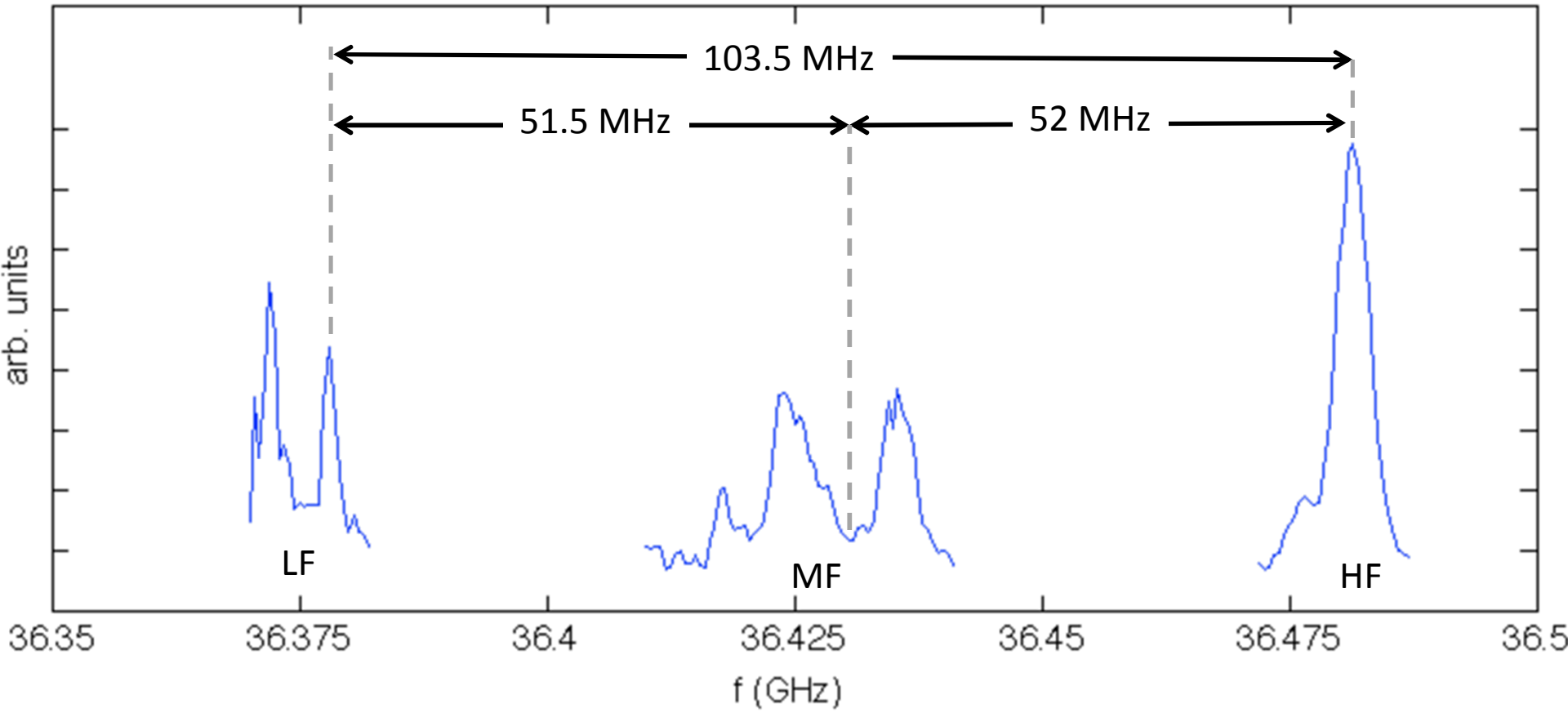
ESR Spectra

B=1.3 T



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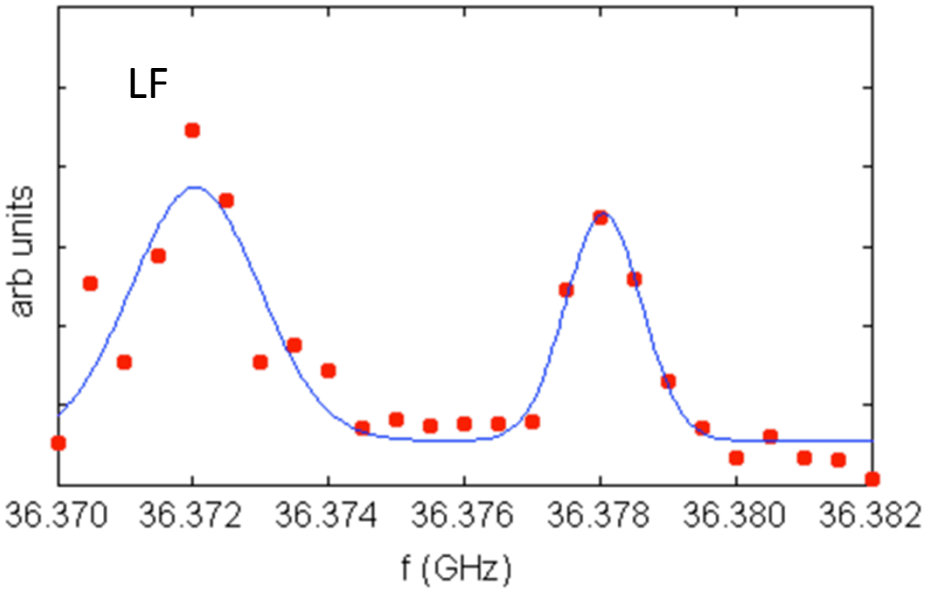
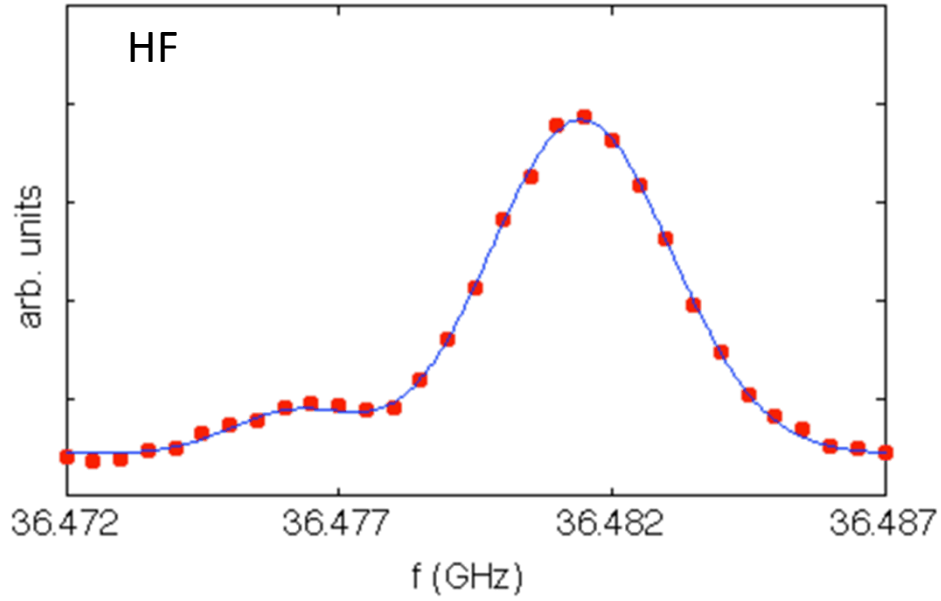
B=1.3 T

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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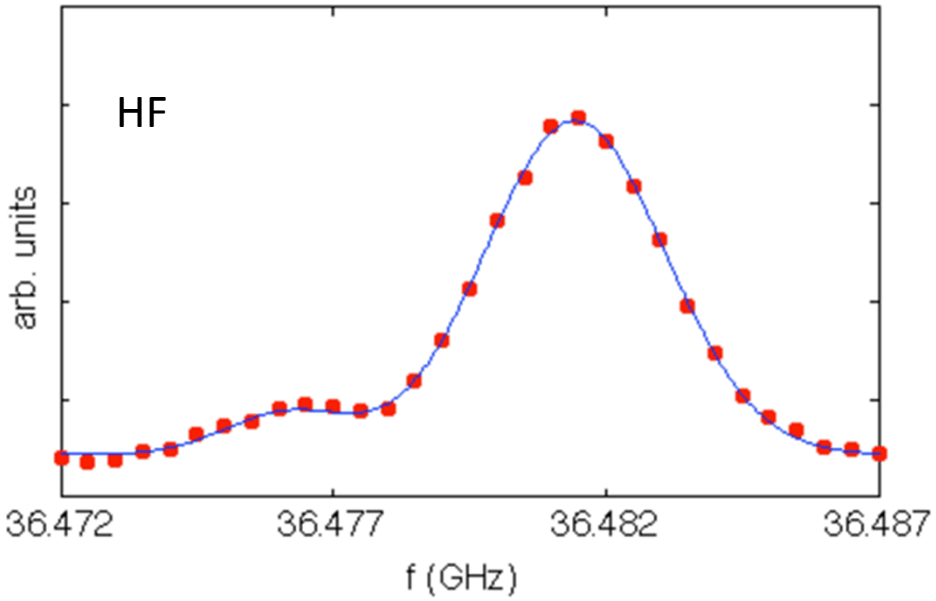
B=1.3 T

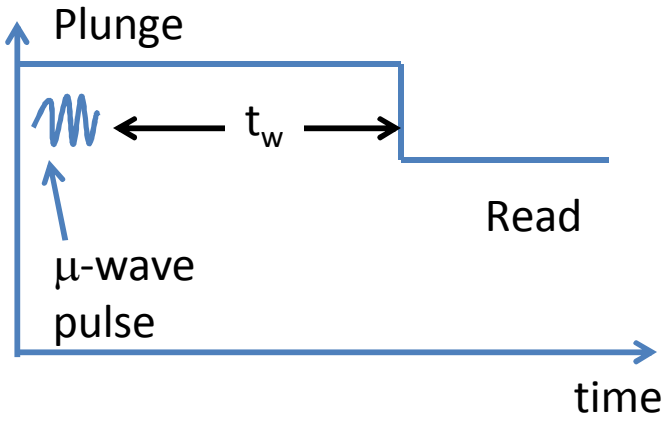
Measurement Sequence

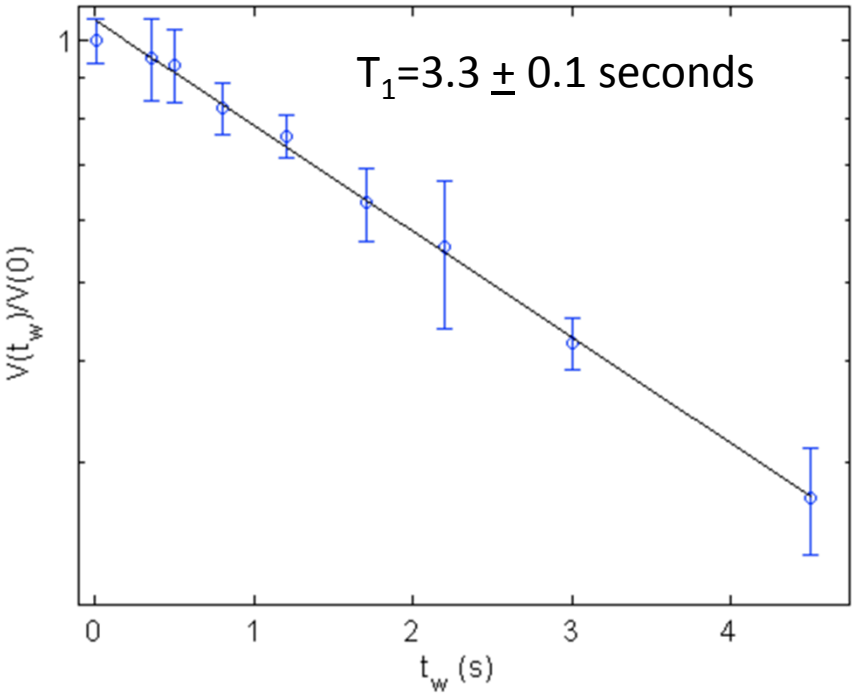


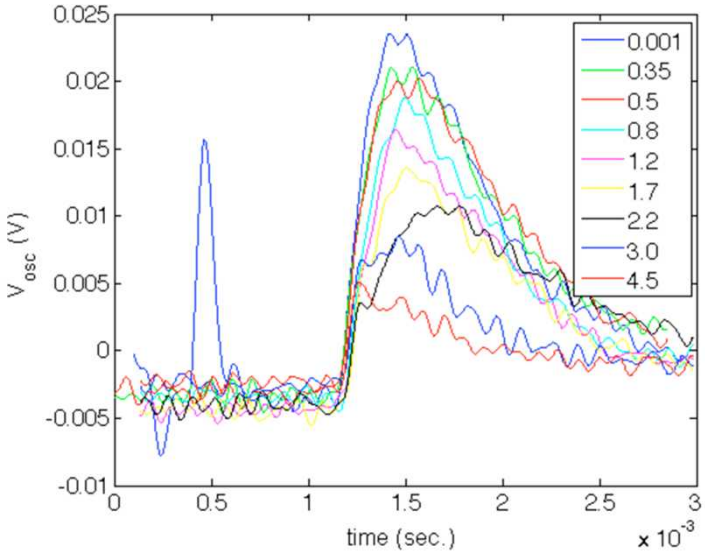
- Apply ESR pulse
- Perform Readout
- Toggle through other states to determine which is occupied
- Reject data when system not in the f=36.482 GHz state

T_1 Measurement

Prepare spin up state with adiabatic sweep across HF







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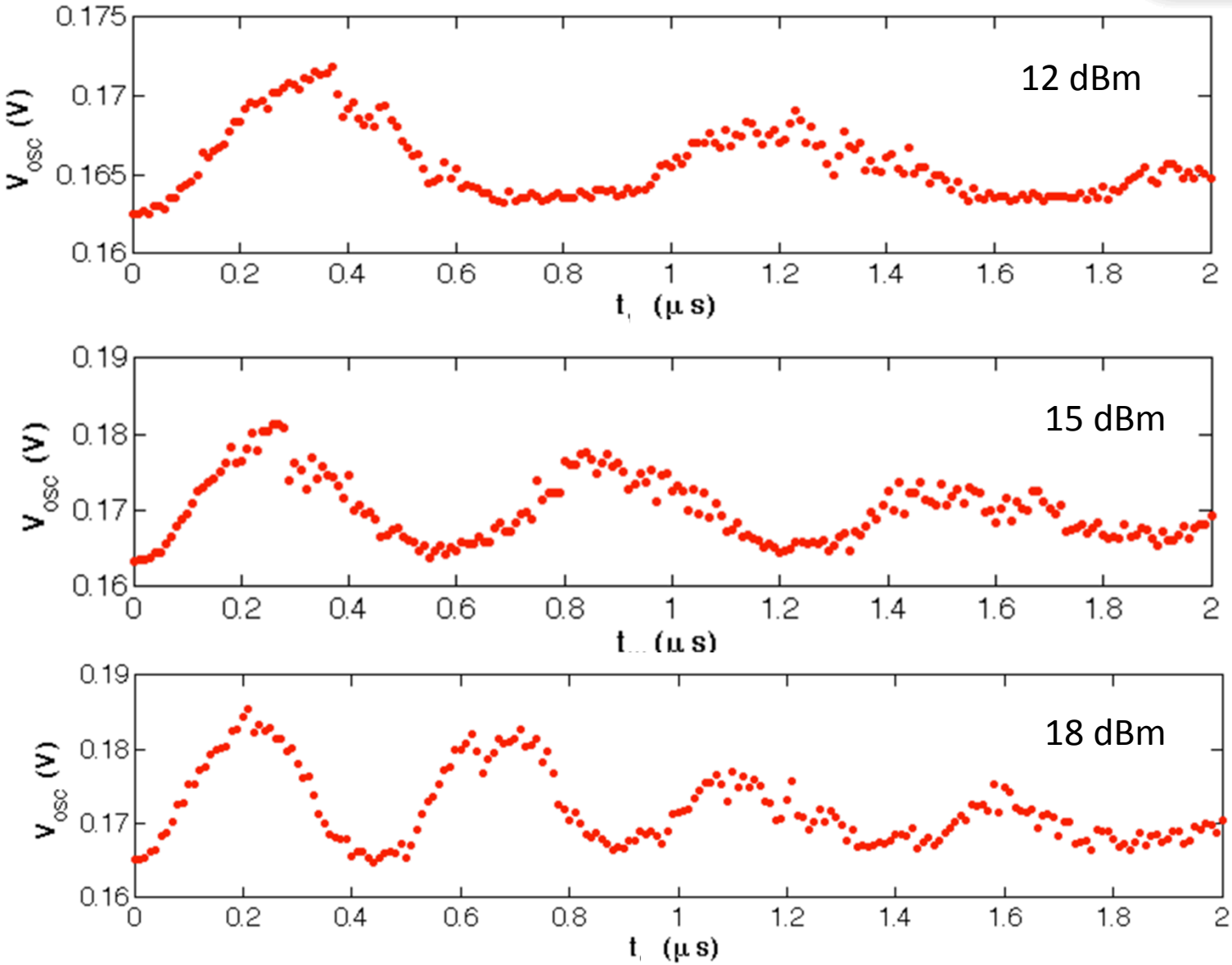
Rabi Oscillations

B=1.3 T



5760 averages

1920 averages

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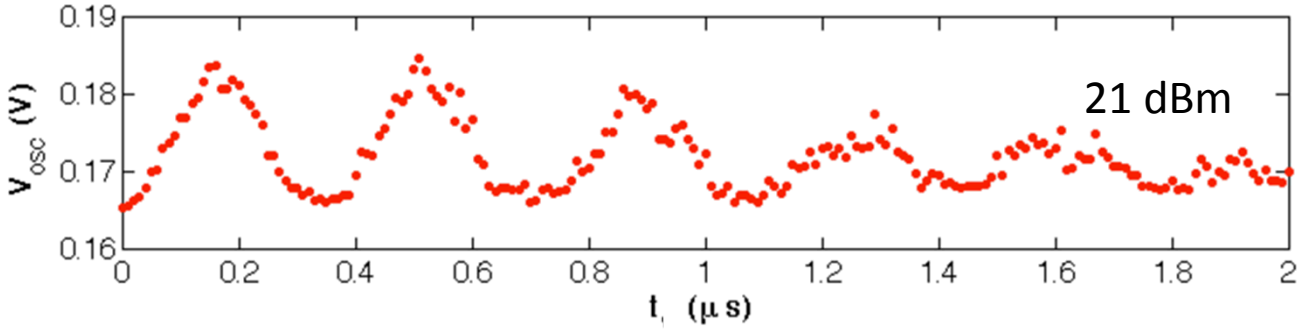
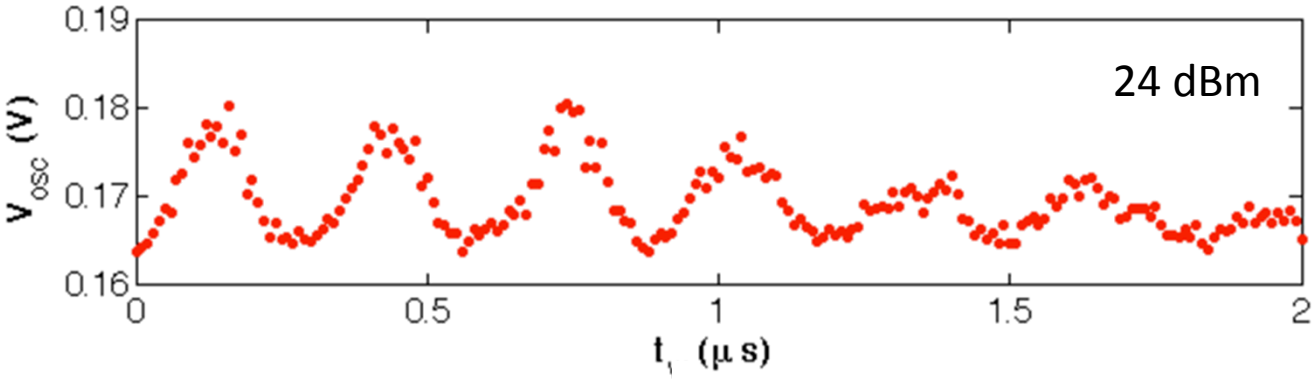
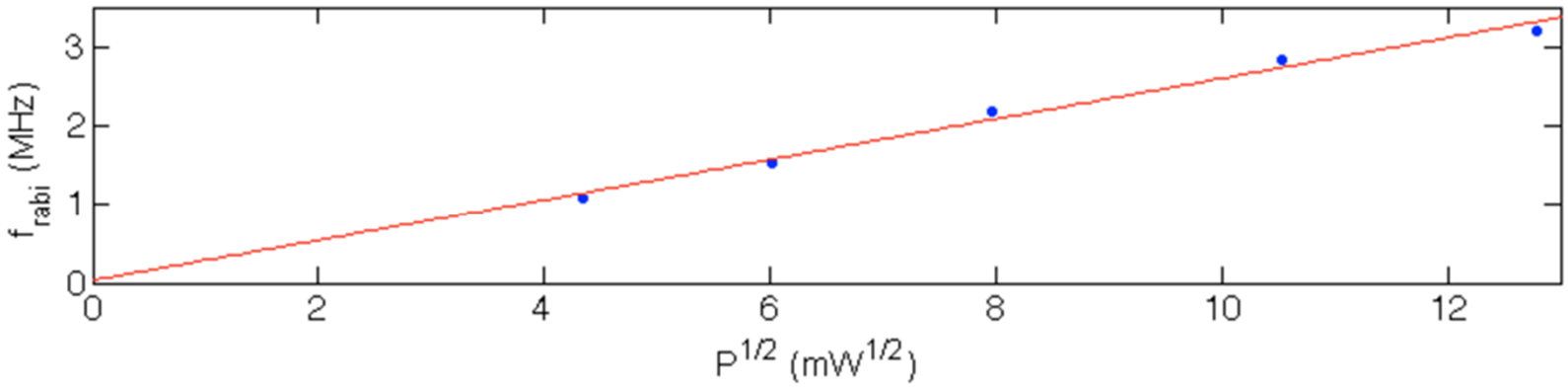
B=1.3 T

Rabi Oscillations

1920 averages







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BIR4-WURST Rabi Oscillations

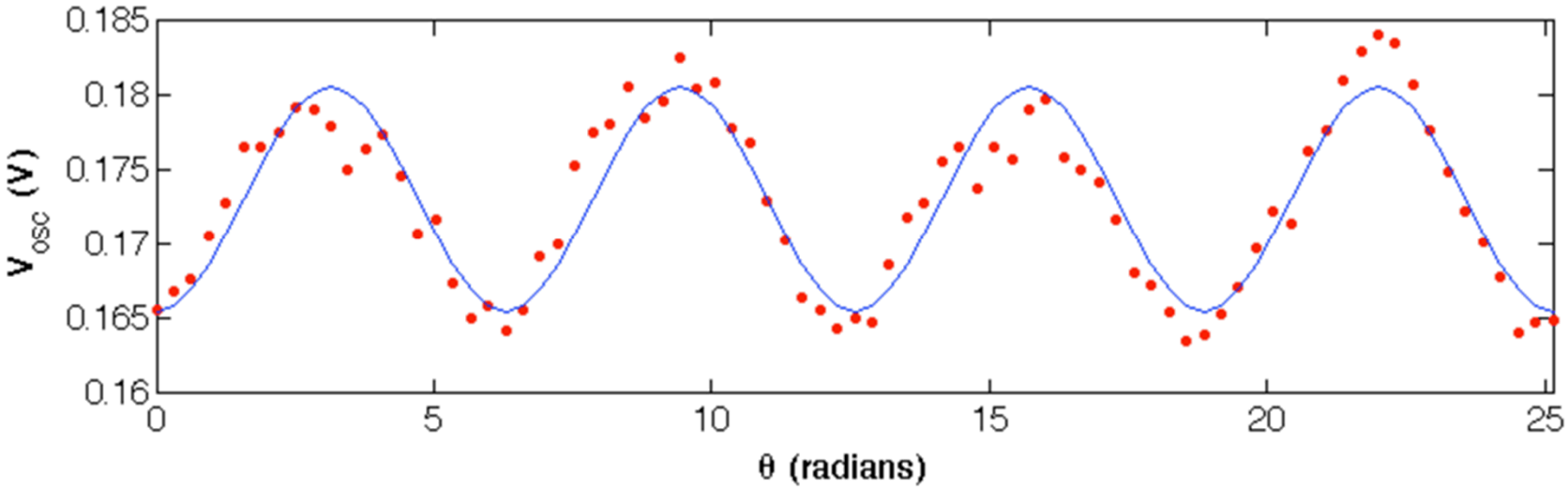
B=1.3 T

15 dBm
2048 averages

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

Line is a fit to

$$f(\theta) = a\sin^2(\theta/2) + c$$



Acknowledgements: S. Lyon

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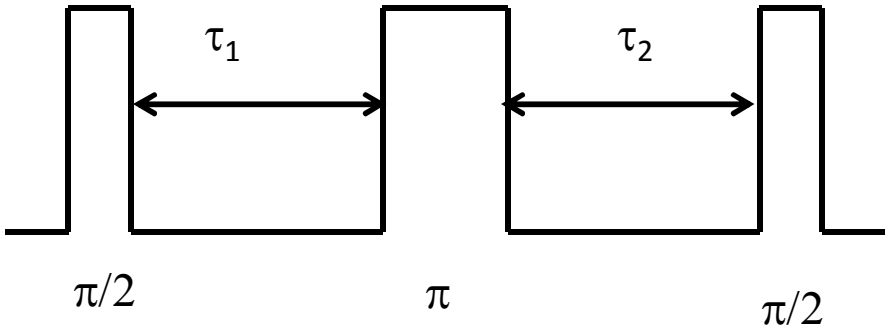
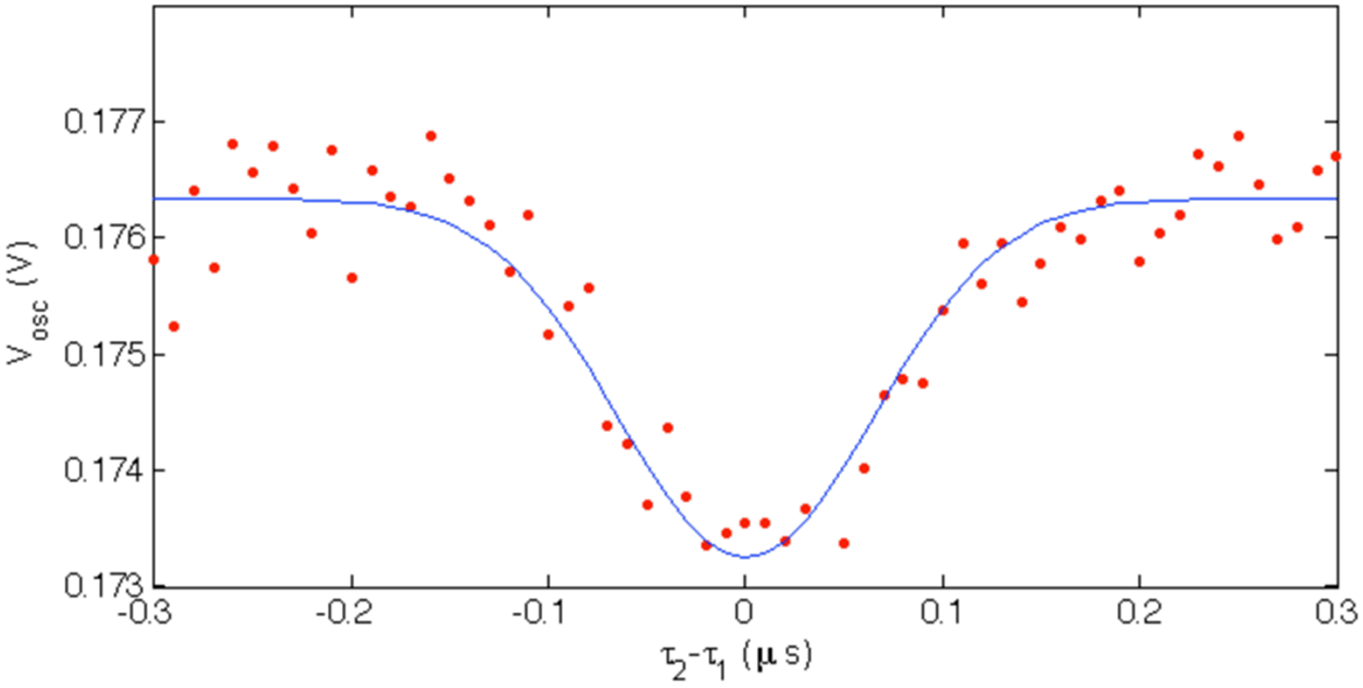
T_2^* Measurement

B=1.3 T

18 dBm

Hahn echo technique:
Vary τ_2 relative to τ_1=10 μs





T_2^*= 77±5 ns

Line is a fit to a Gaussian

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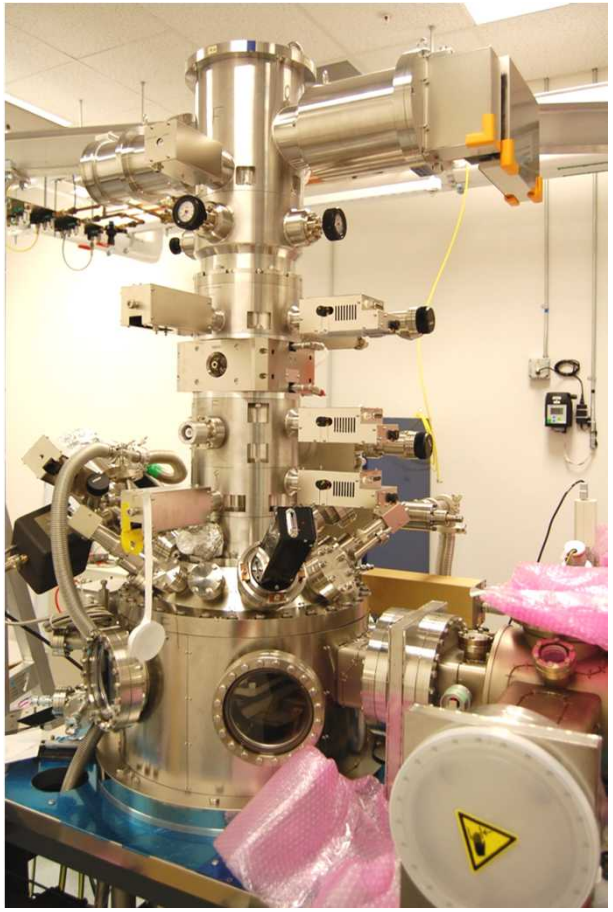
Outline

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

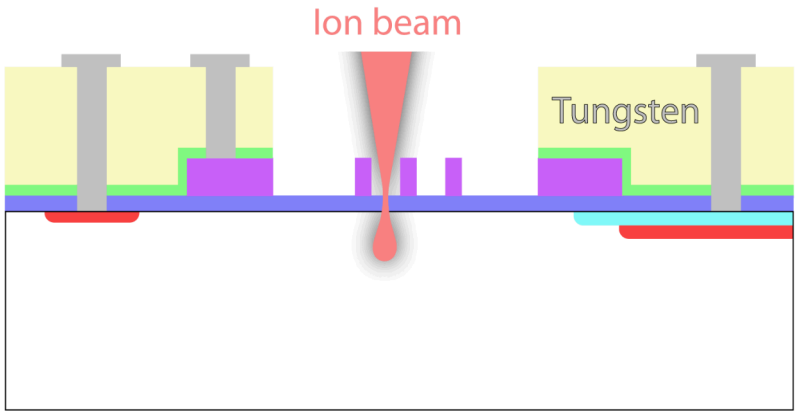
Deterministic implants using ion detection

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



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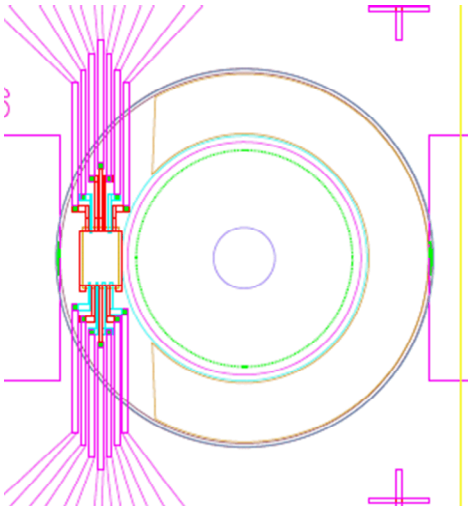
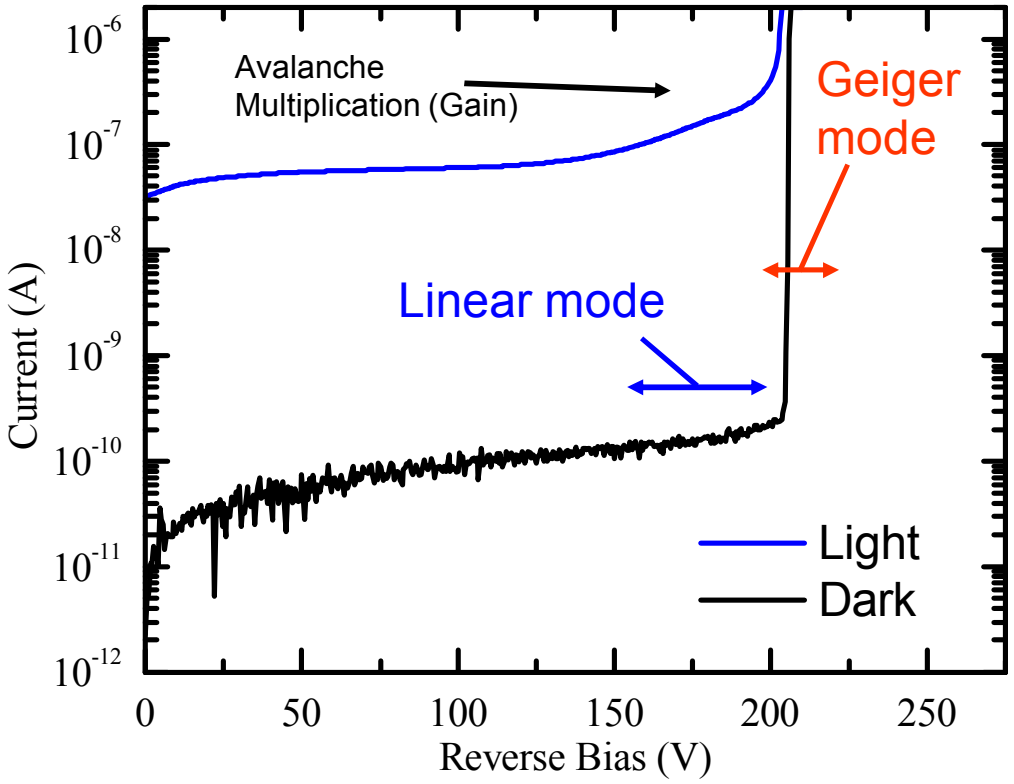
Ion detector operation

CAD for detector and nanostructure construction zone





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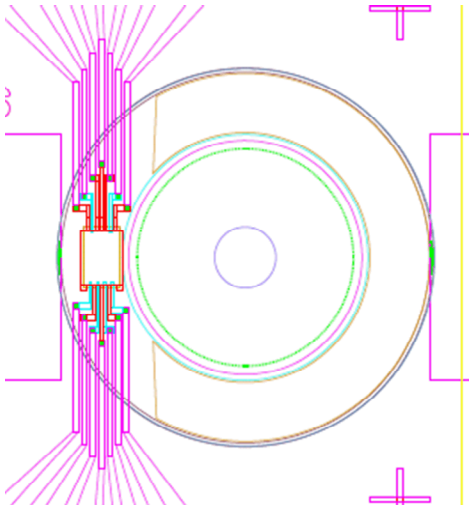
Ion detector operation

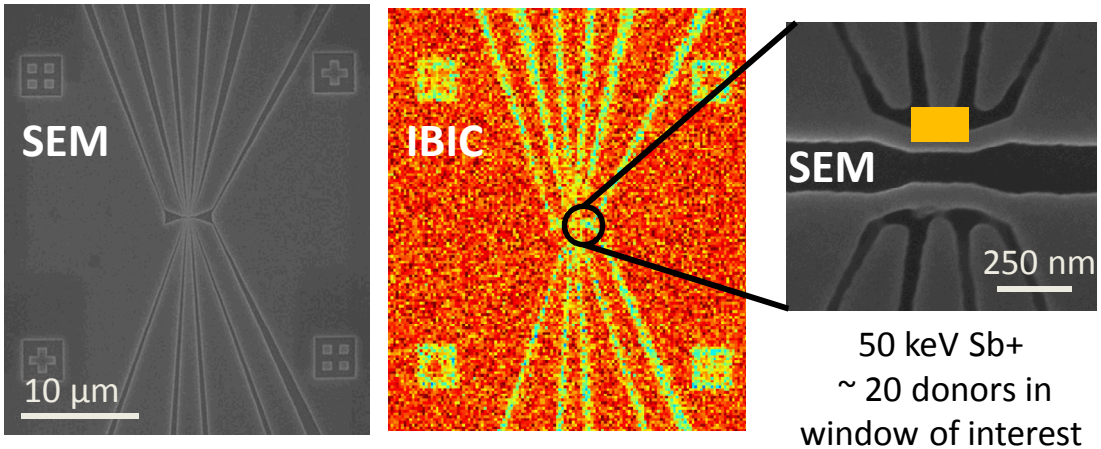
Detected single donor implantation of Sb ions allows multi-donor devices

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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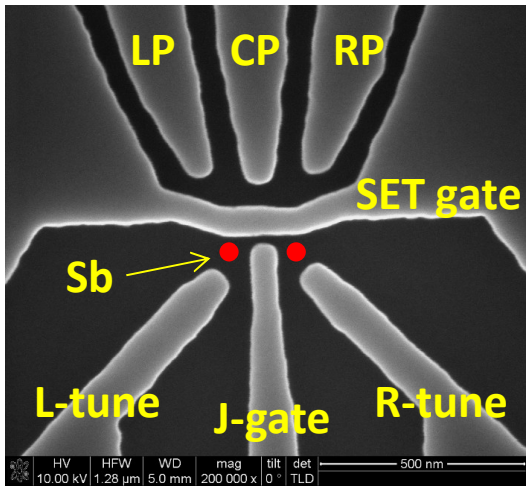
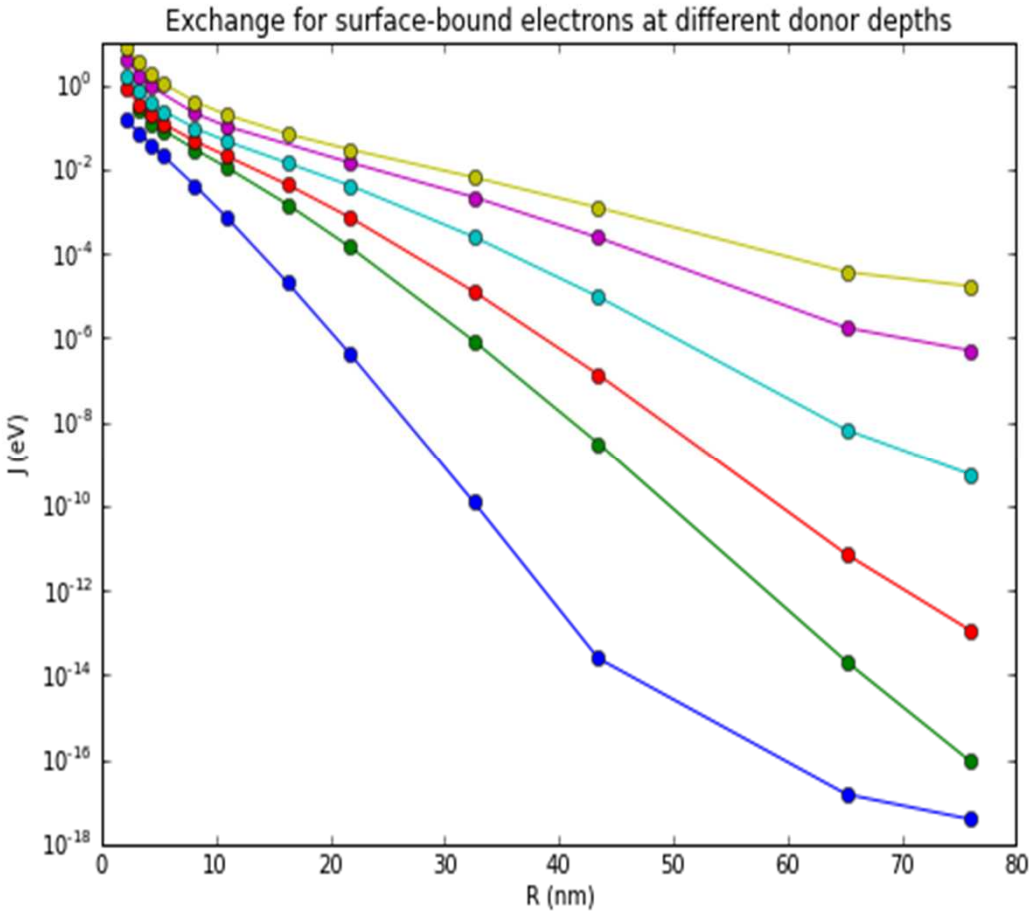
Two qubit structures

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

Exchange interaction device



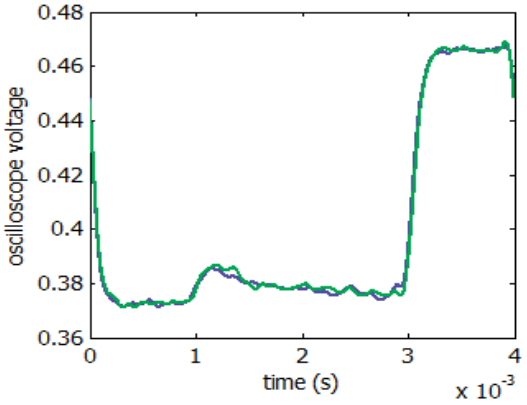


Rick Muller

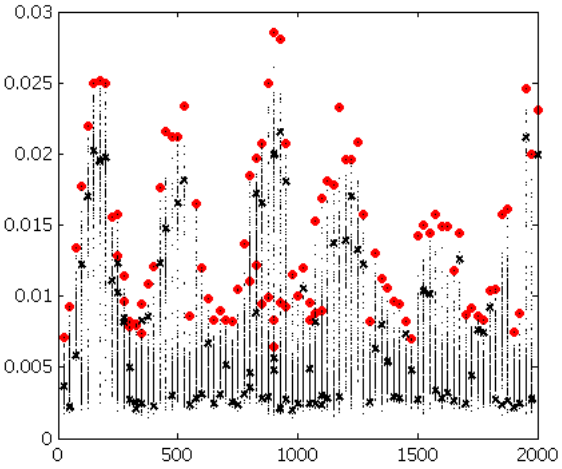
Summary

- 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

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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)