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# ESR Experiments on a Single Donor Electron in Isotopically Enriched Silicon

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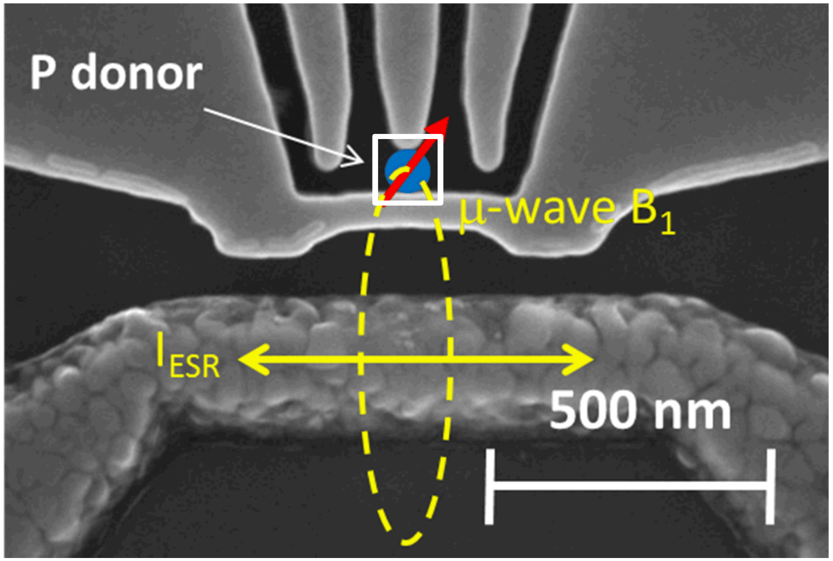
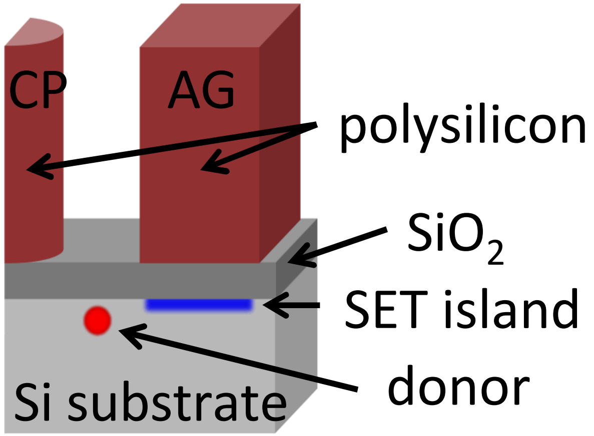
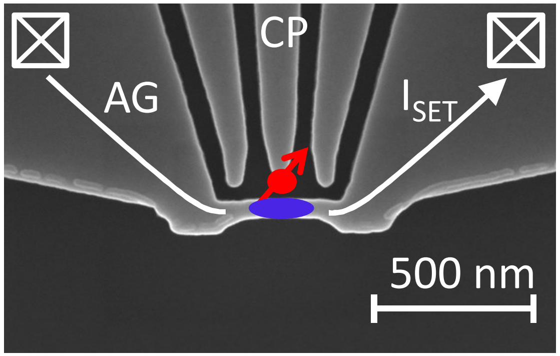
# local ESR device

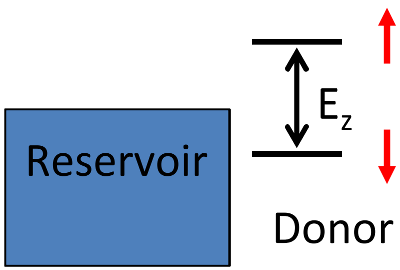
- Timed P implant with PMMA window, self-aligned with polysilicon gates
- 45 keV implant, range ~15 nm below $SiO_2$/Si interface
- 4 – 8 $x10^{11}/cm^{-2}$ dose → ~ 40 - 80 P donors in 100 x 100 $nm^2$ window
- Nearby microwave antenna for local ESR
- Dry dilution refrigerator
  $T_{base}$ = 10 - 20 mK
  $T_{electron}$ = 200 - 300 mK

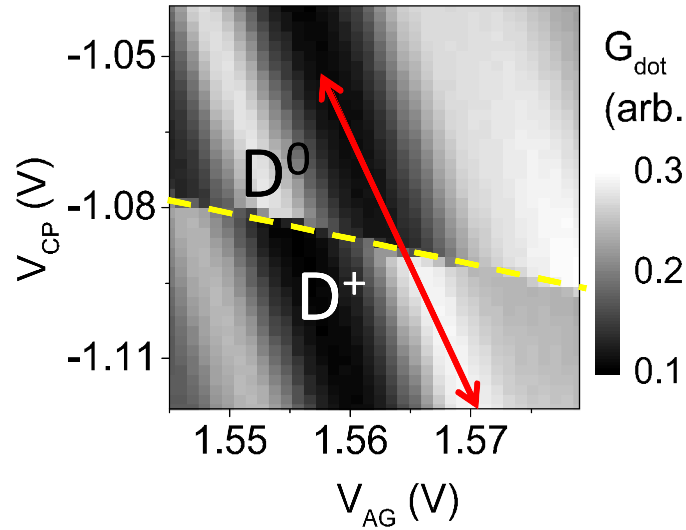


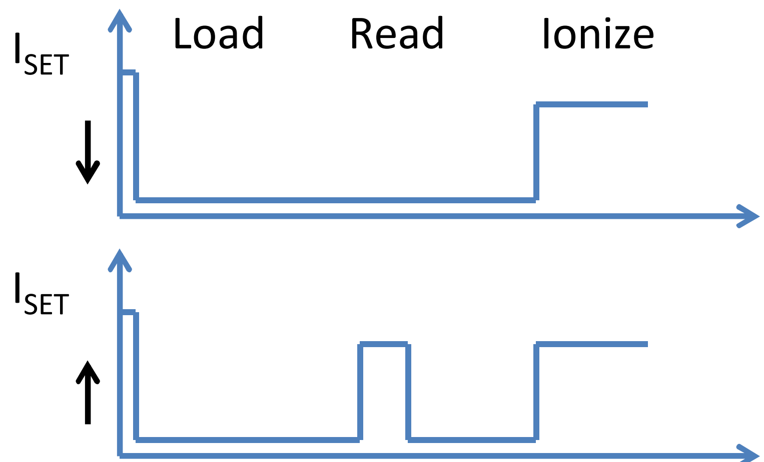
# Single spin readout




- Spin selective tunneling from donor to reservoir in magnetic field
- Used to initialize and read spin
- B = 1.3 T → $E_z$ ~ 1.7 K





J. M. Elzermann *et al.*, Nature **430**, 431 (2004)
A. Morello *et al.*, Nature **467**, 687 (2010)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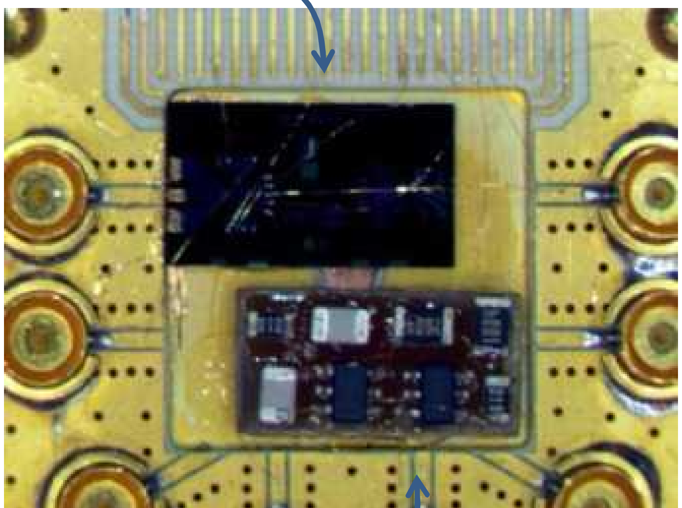
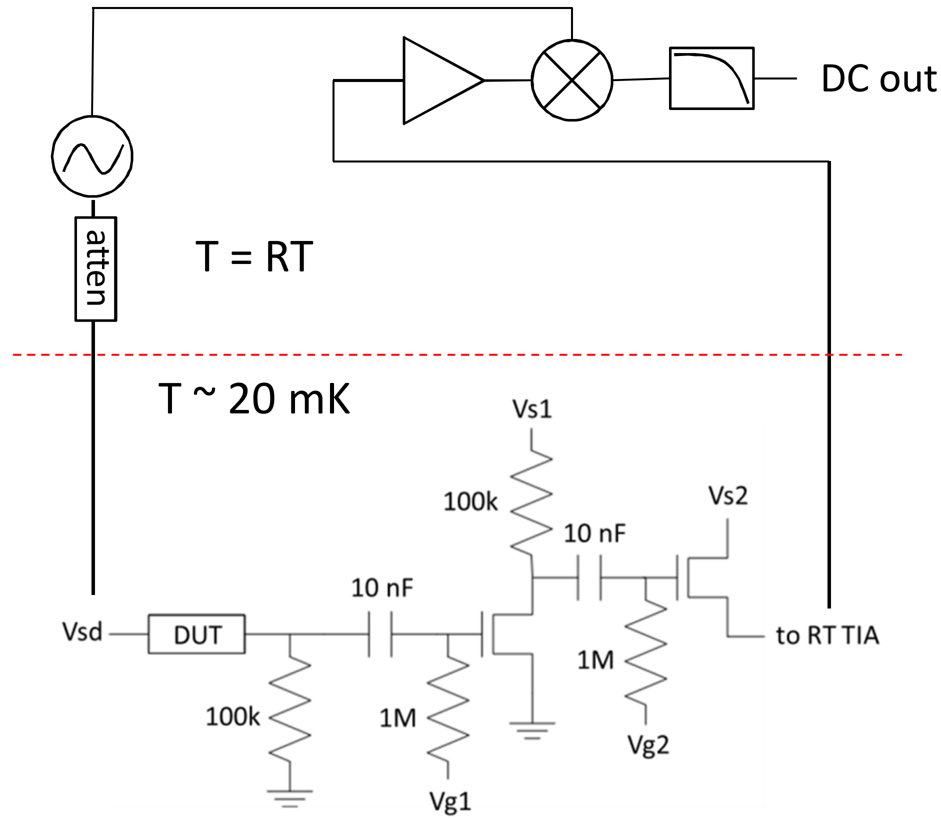
# Read-out circuit with amplification at sample

Si chip

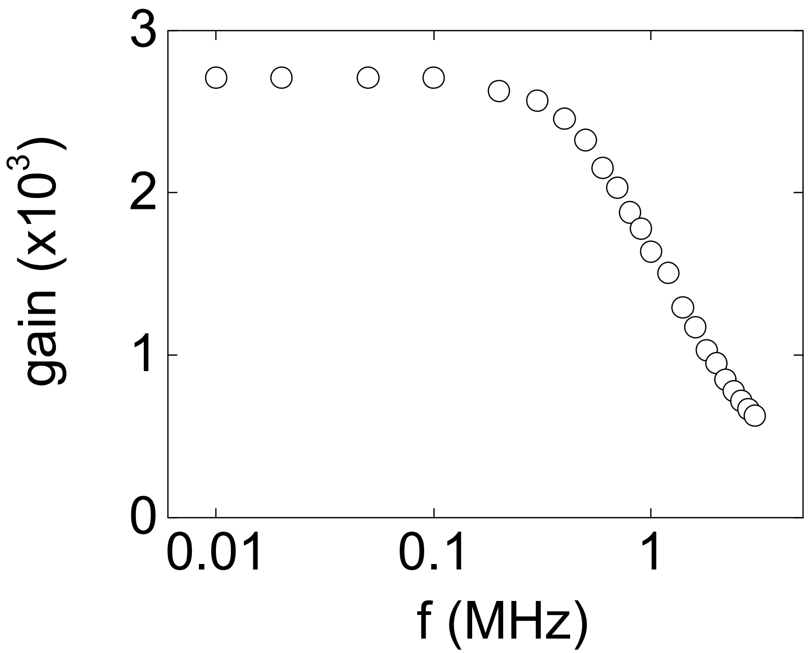


HEMT circuit

- Commercial InGaAs enhancement mode HEMTs

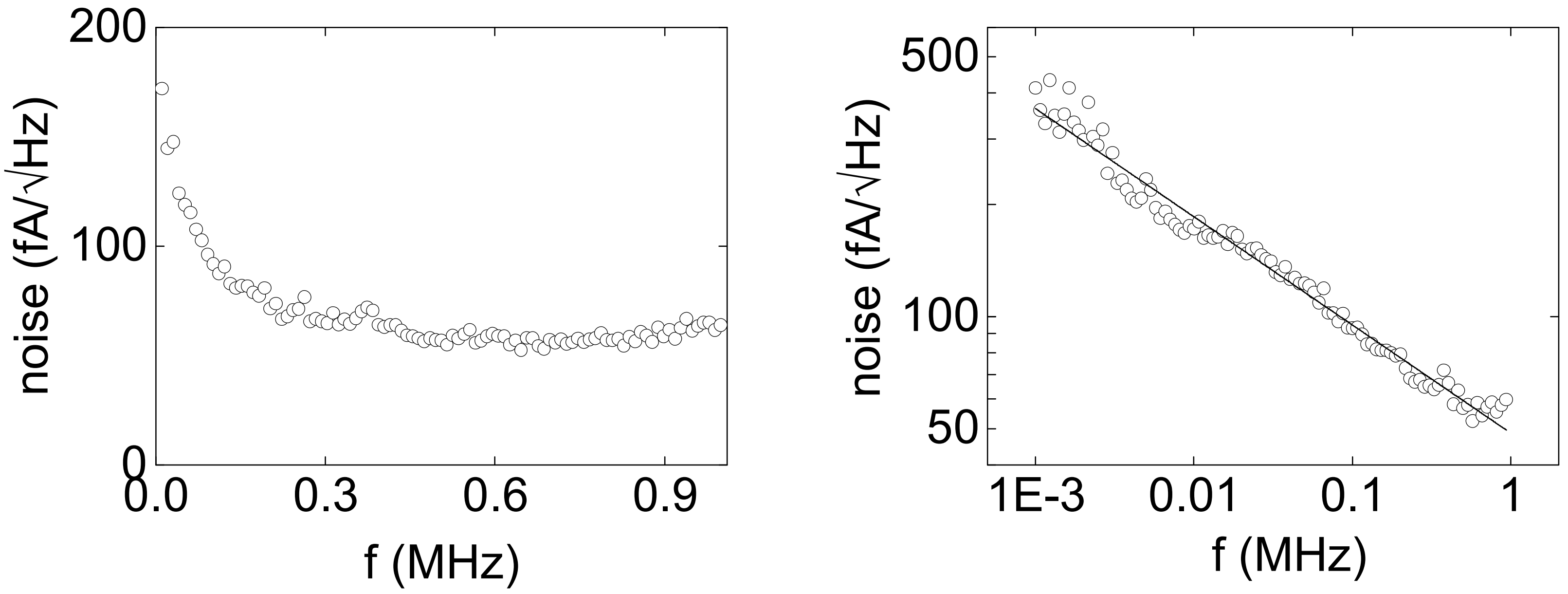


# Gain and bandwidth



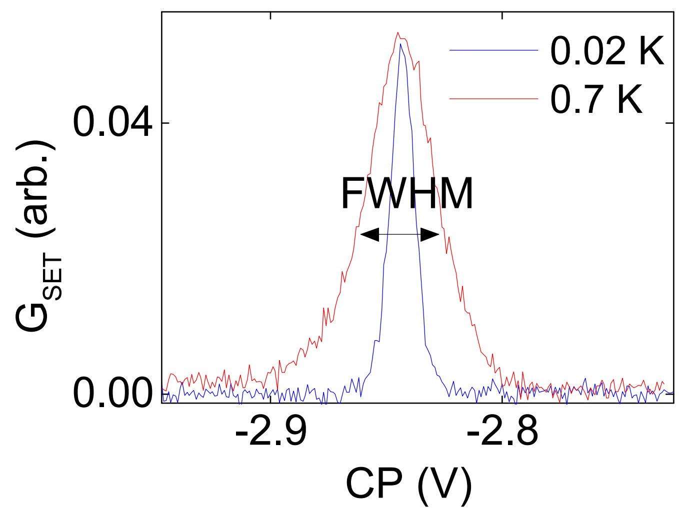

- DUT = 100k resistor
- Meas BW ~ 1.3 MHz
- 1st HEMT: 3 μW, 2nd HEMT 10 μW
  → 13 μW total
- tradeoff gain for power?

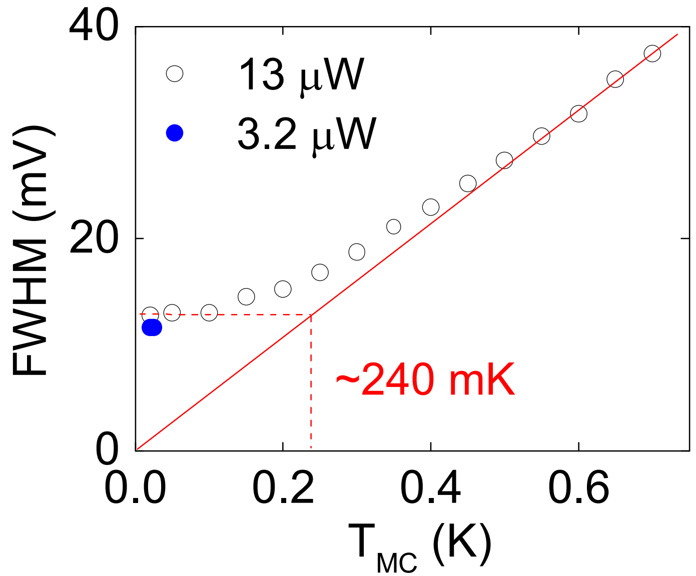
# Noise

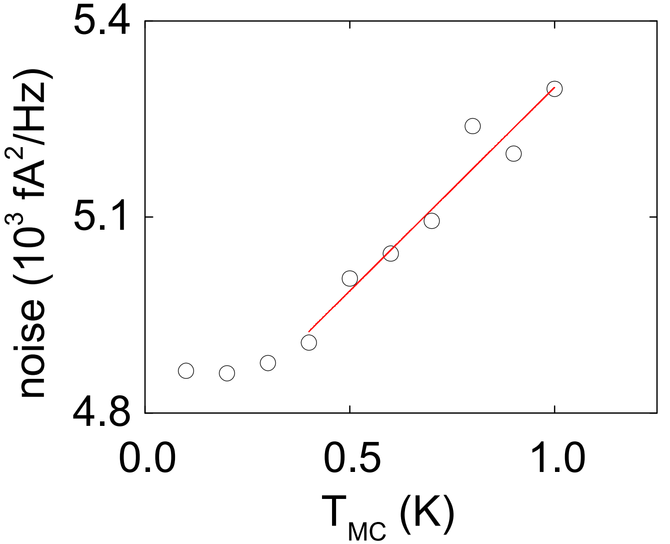



- ~ 70 fA $Hz^{-1/2}$ above 0.3 MHz
- 1/f noise (~ $f^{-0.3}$)

# Temperature



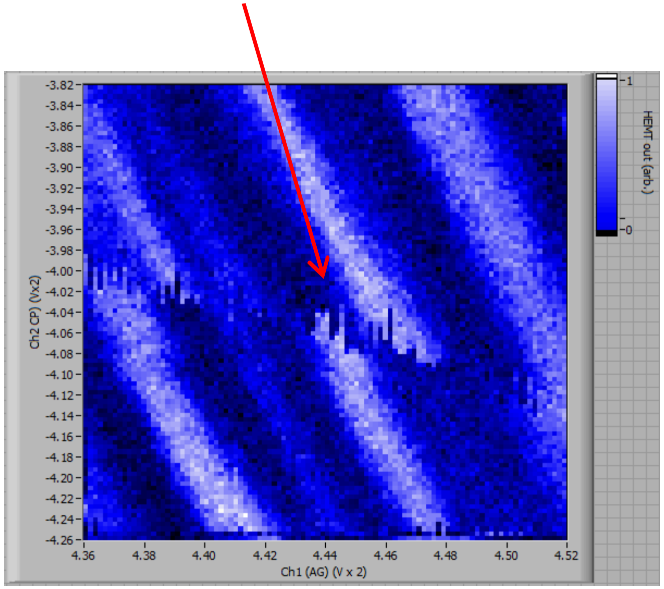



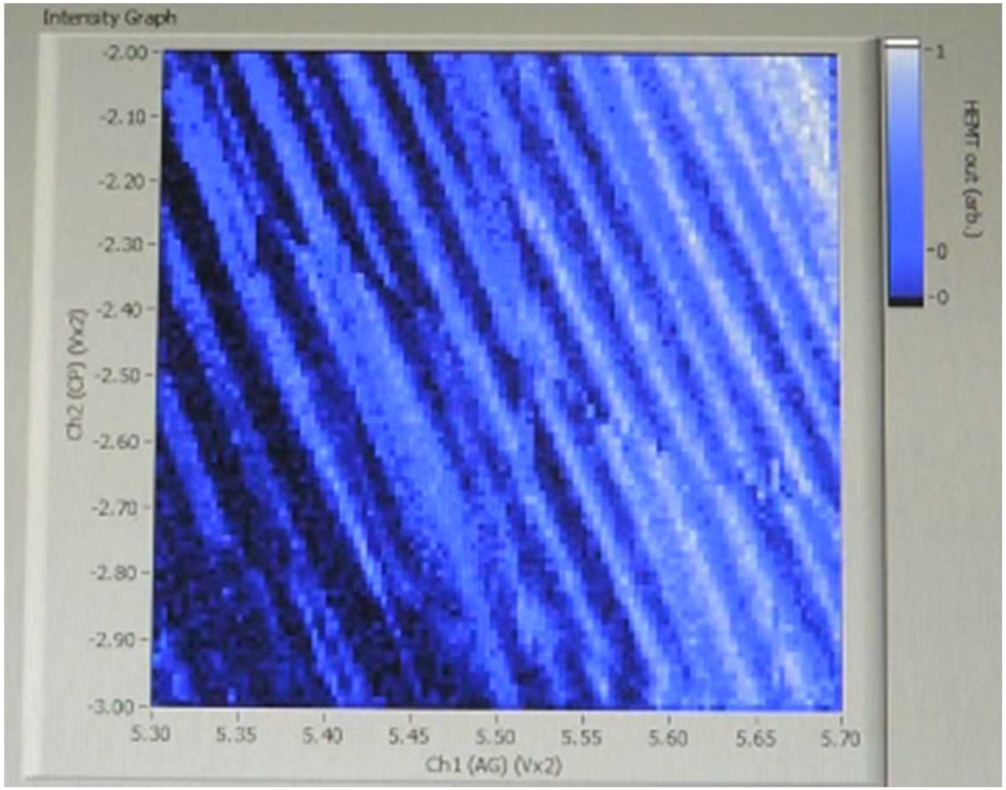

- SET temperature ~ 240 mK at 13 μW
- ~220 mK at 3 μW suggests not dominated by HEMT
- Slope of noise vs. $T_{MC}$ greater than expected for simple Johnson noise
- Knee of noise vs. $T_{MC}$ suggests 1st HEMT ~ 300 mK

# Live SET tuning

- Rapid search for donor charge transitions
- Response rate of offset gives tunnel time estimate

100 x 100 scan, ~3 Hz refresh rate

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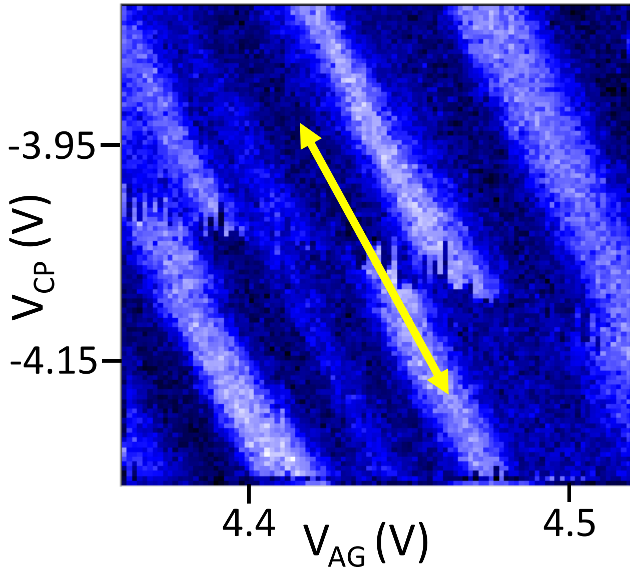
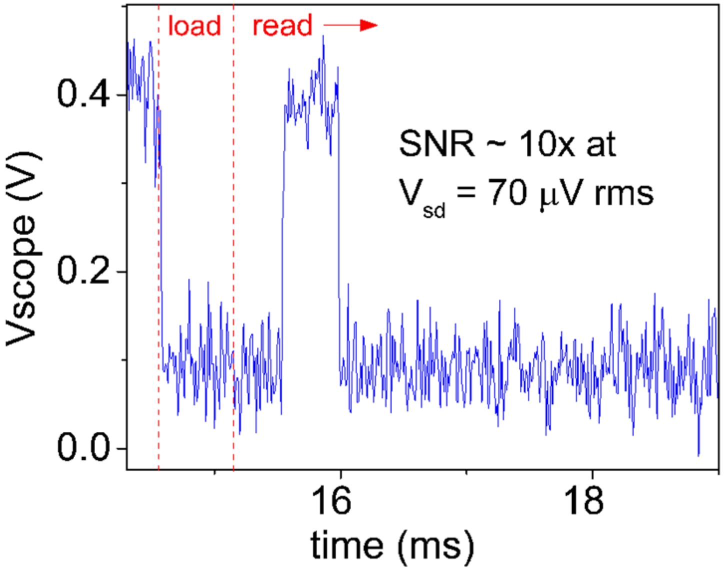
# Single shot spin readout




- Single shot event SNR ~ 10x for Vsd = 70 uV rms
- Effect of dry fridge triboelectric noise reduced by gain before coax and by working at higher frequencies

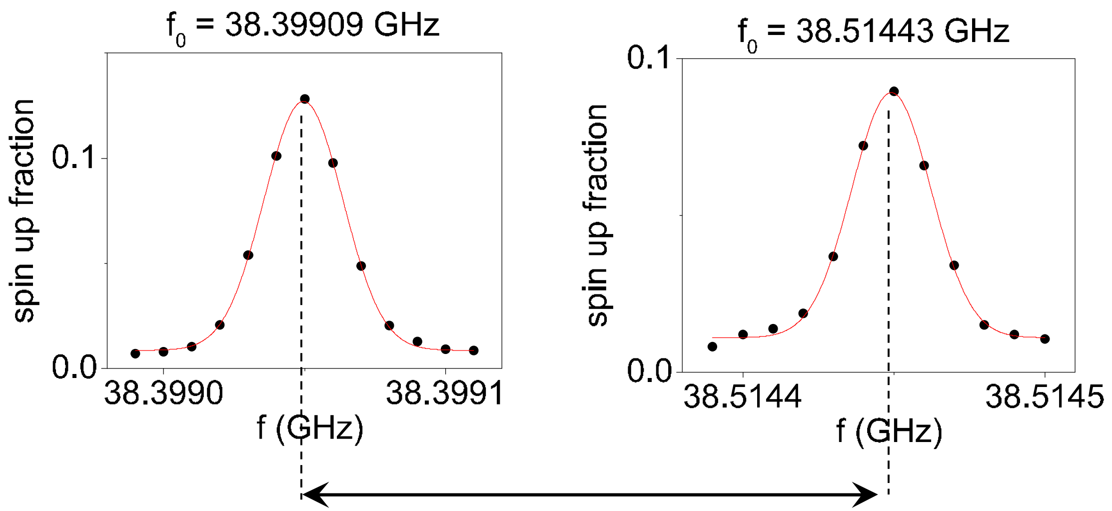
# Enriched $^{28}Si$: P donor ESR line

$^{28}Si$ epilayer

- 2.5 μm thick
- 500 ppm $^{29}Si$ (ToF SIMS)

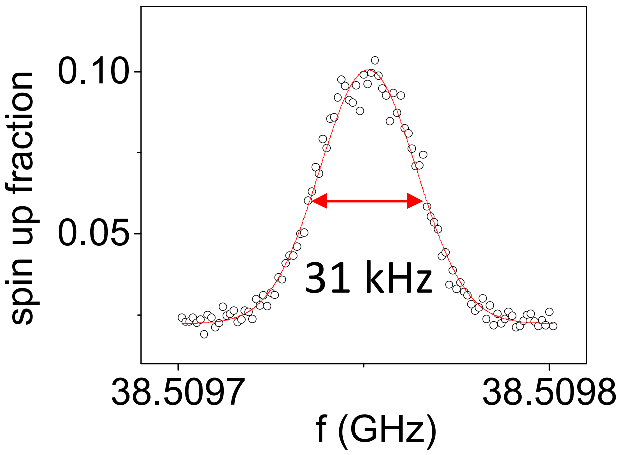
P Implant

- 45 keV implant
- range ~15 nm below $SiO_2$/Si interface
- Fluence: $4 \times 10^{11}$ $cm^{-2}$




P hyperfine: $\Delta f_0$ = 115.3 MHz

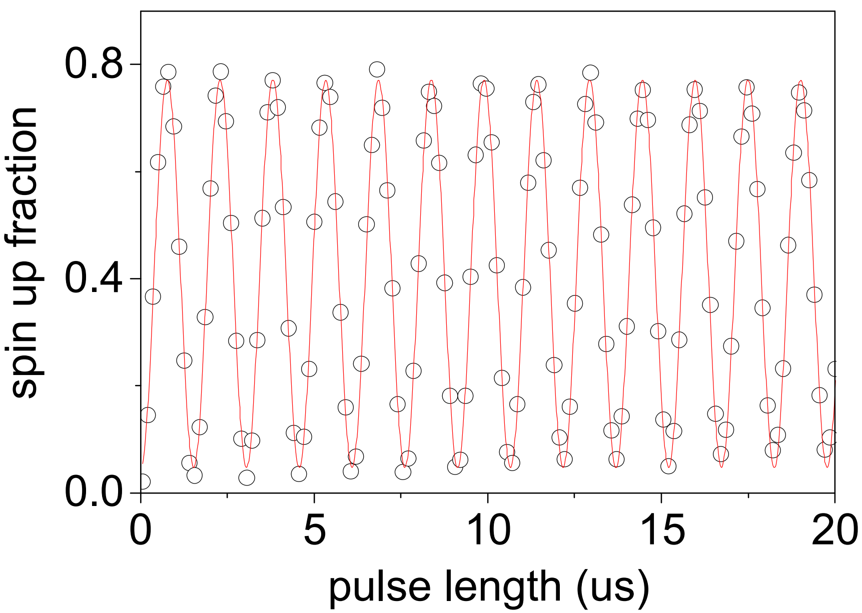
low power linewidth



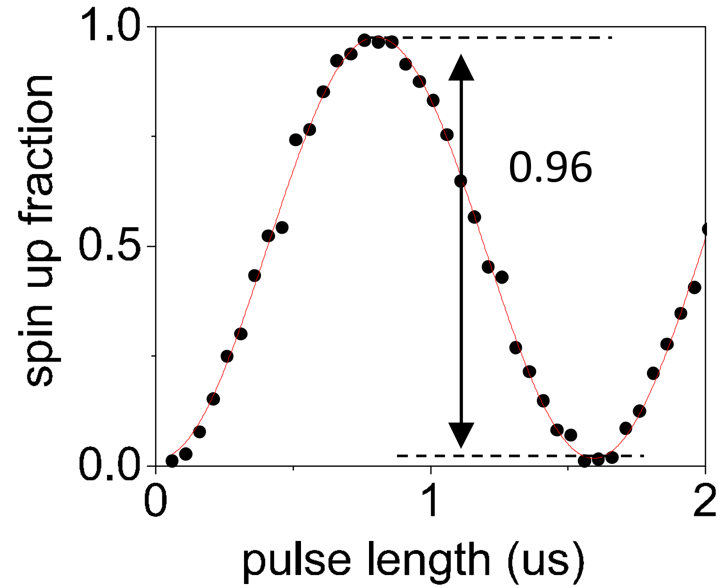

- Similar lines seen in two $^{28}Si$ ESR devices (115 – 116 MHz hyperfine w/ ~30 kHz linewidth)
- FWHM = 31 kHz → $T_2^*$ = 10 us

# Rabi oscillations

10 kHz BW

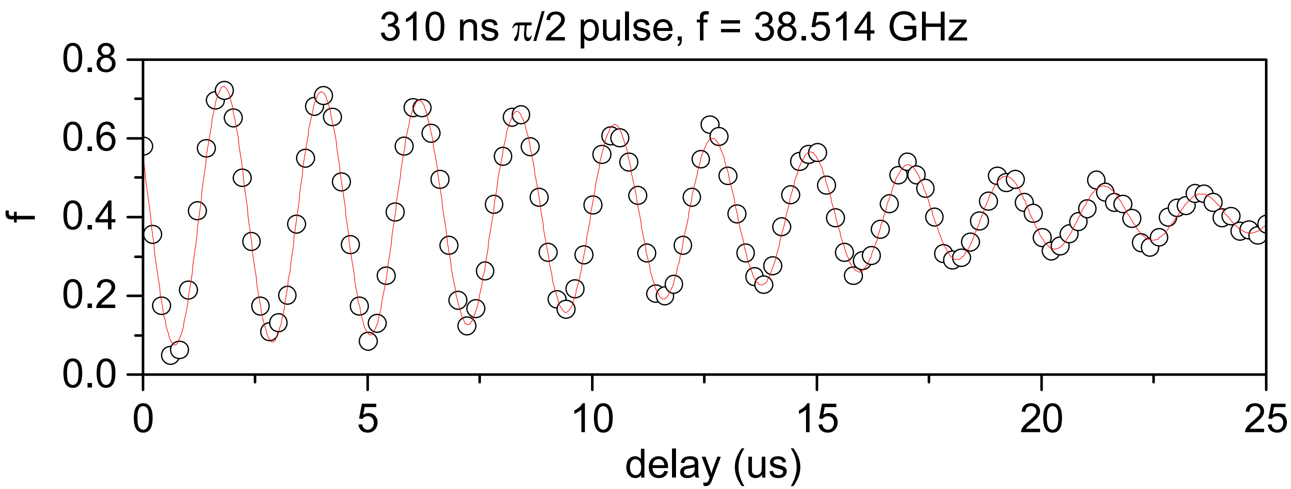



100 kHz BW



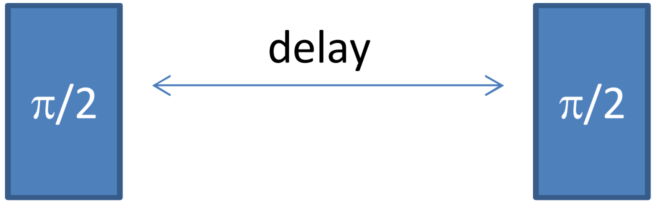

- Long lived Rabi oscillations
- Visibility reduced because readout BW was not optimized (~ 10 kHz)
  For example, fast spin-up tunneling events can be missed.
- Visibility ~ 96% (readout & initialization)

# Ramsey fringes




Fit envelope: $f = P_0 exp[-(t/T_2{}^*)^2] + P_\infty$

→ $T_2{}^*$ ~ 18 us




- ~ 0.5 MHz detuning from resonance
- $T_2{}^*$ value in same ballpark as linewidth estimate, but slightly longer (~18 us vs. 10 us)
- $T_2{}^*$ = 18 us shorter than meas $T_2{}^*$ = 270 μs of J. T. Muhonen *et al.*, Nat. Nano (2014) in 800 ppm $^{28}Si$.

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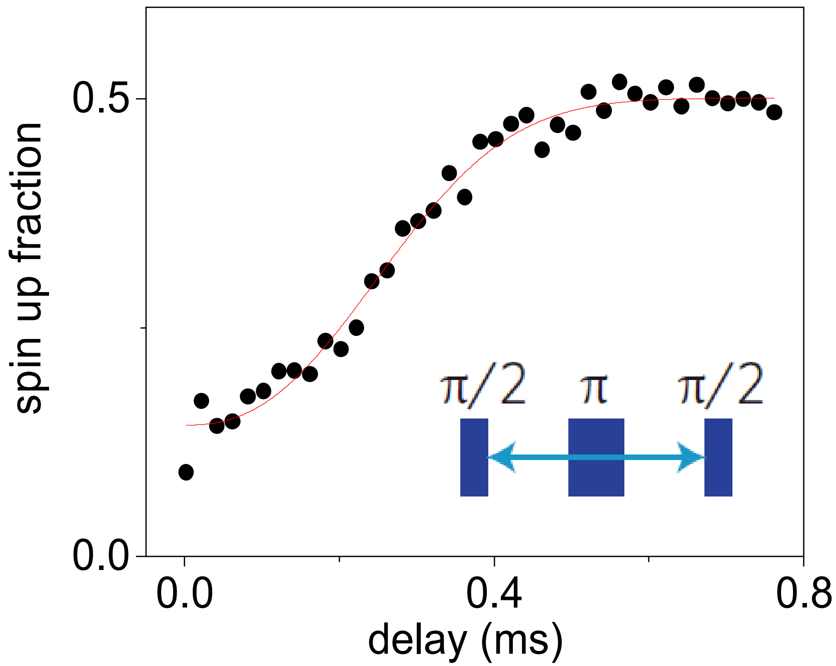
# Hahn Echo




- Echo $T_2$ in ballpark of previous meas of 0.95 ms, n = 3.5 (J. T. Muhonen et al., Nature Nano (2012))
- Exponent n = 2.4, for 1/f noise n = 2

Fit: $f = P_0 exp[-(t/T_2)^n] + P_\infty$

→ $T_2$ = 0.31 ms, n = 2.4

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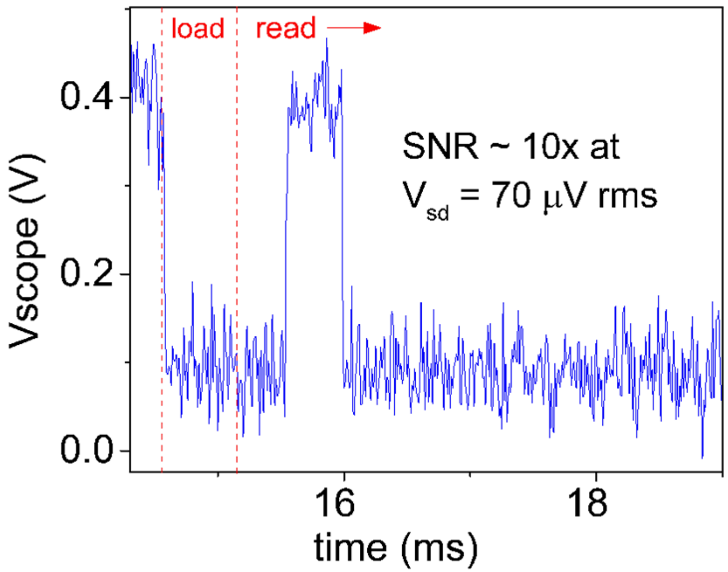
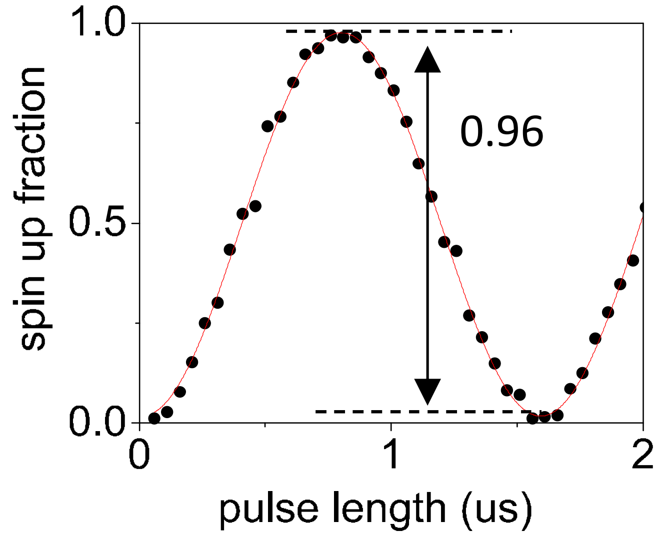
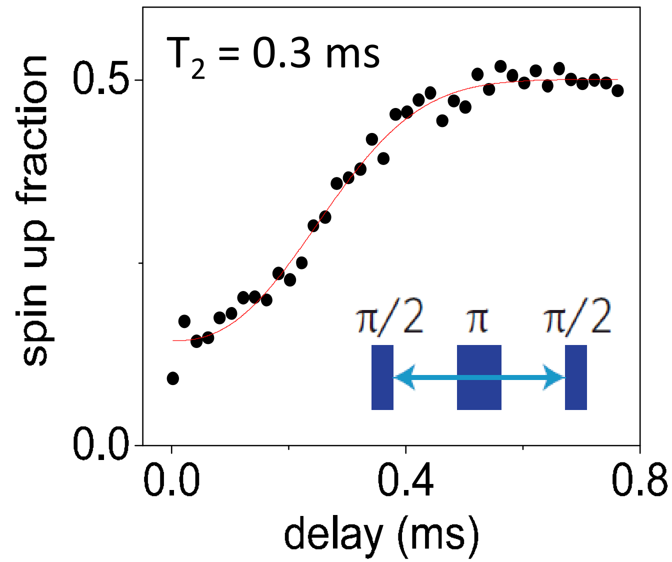
# Conclusions




- 100 kHz BW, 10x SNR spin readout with HEMT amplifier
- Rabi Visibility 96%
- Coherence:
  - $T_2^*$ = 18 μs
  - $T_2$ = 0.3 ms (Hahn Echo)

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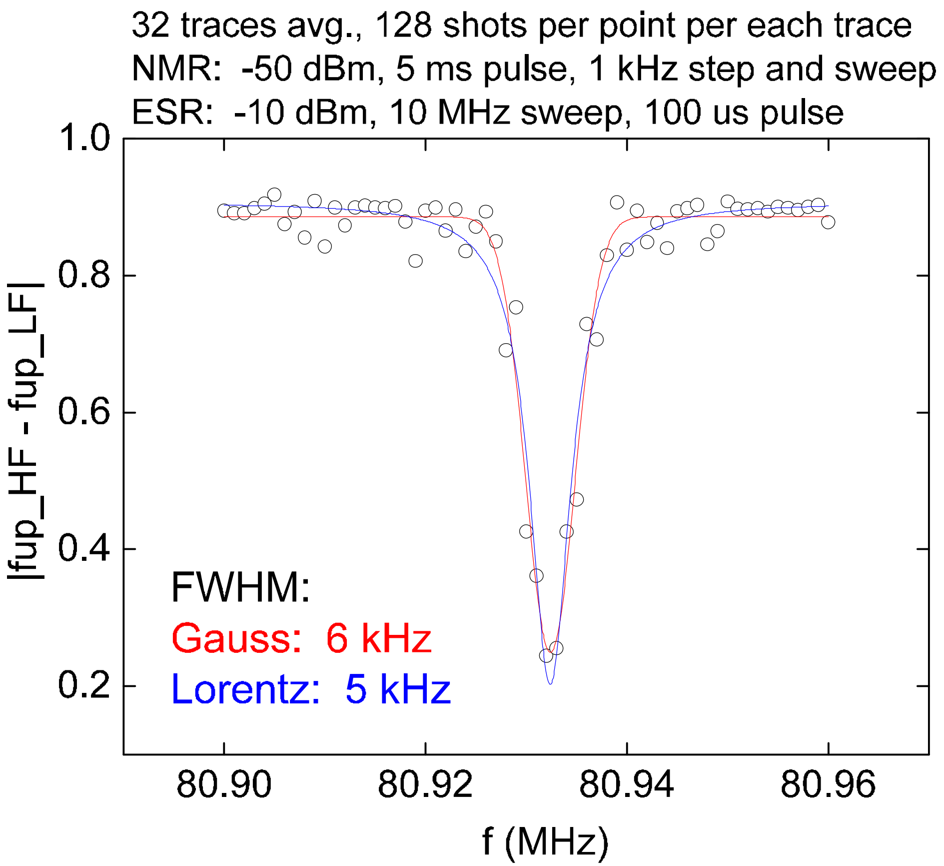
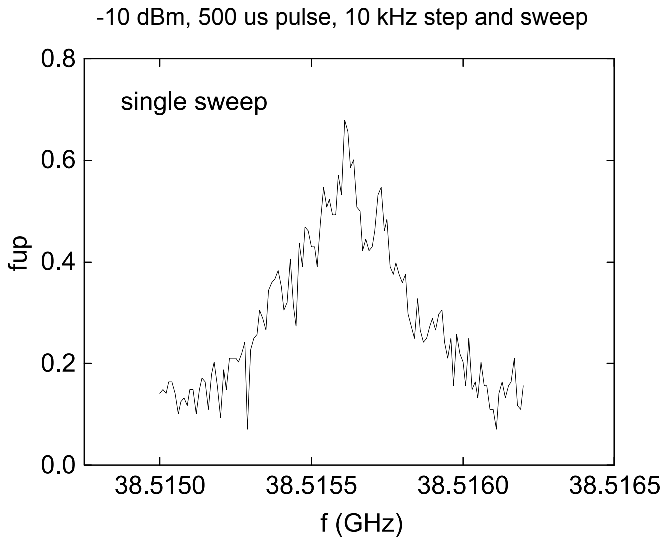
# Auxiliary slides

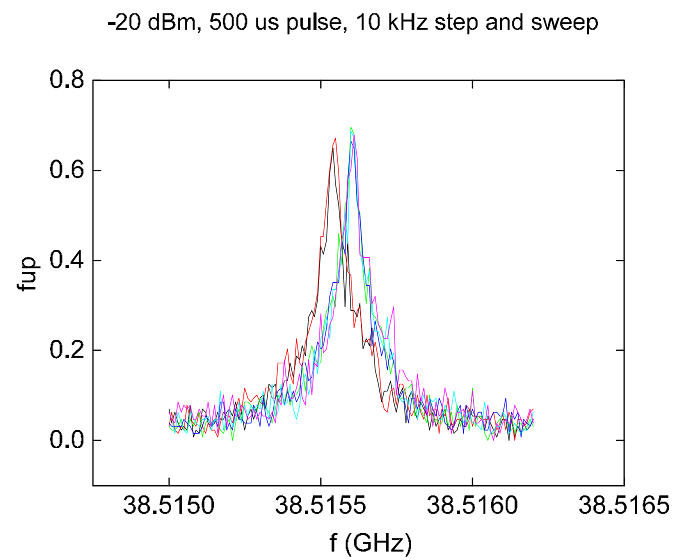
# Lower power NMR sweep



# High power ESR sweeps




repeats of single sweep

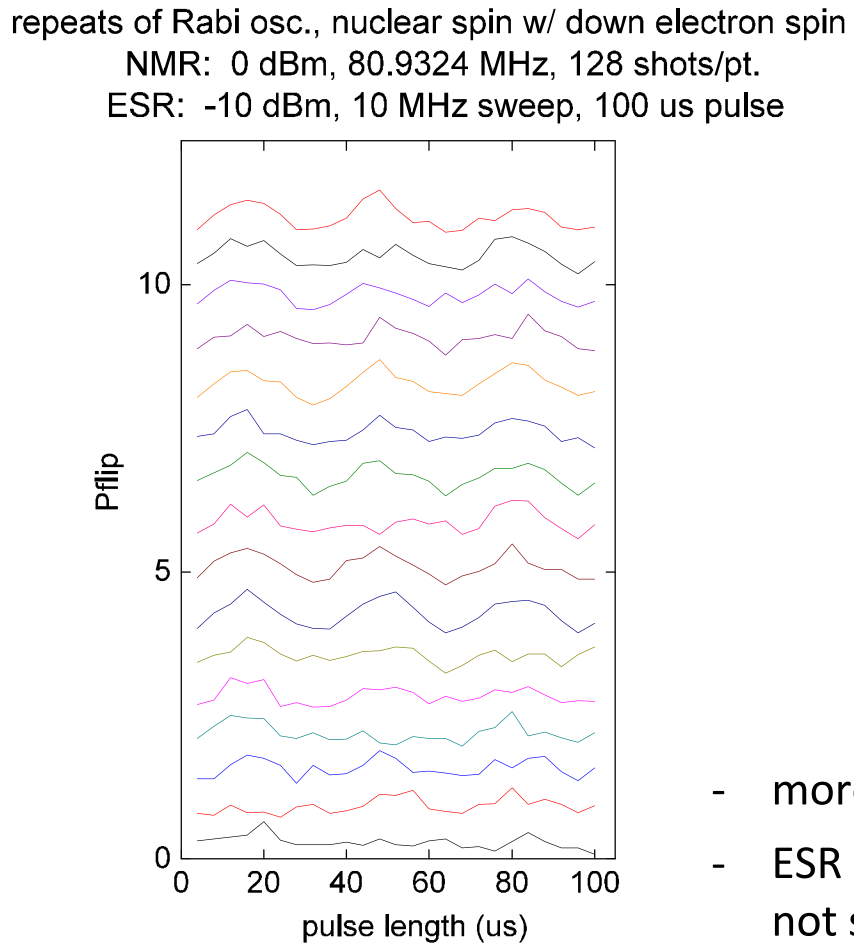


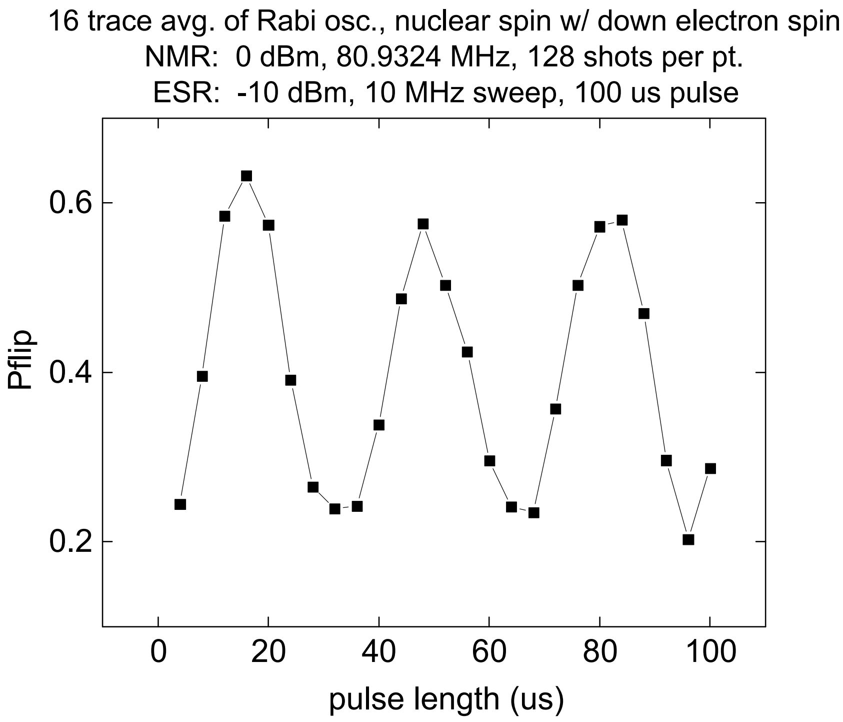

~10 min per trace

jump ~ 60 kHz
similar to jump in slide 12

Ramsey beat frequency was ~ 200 kHz

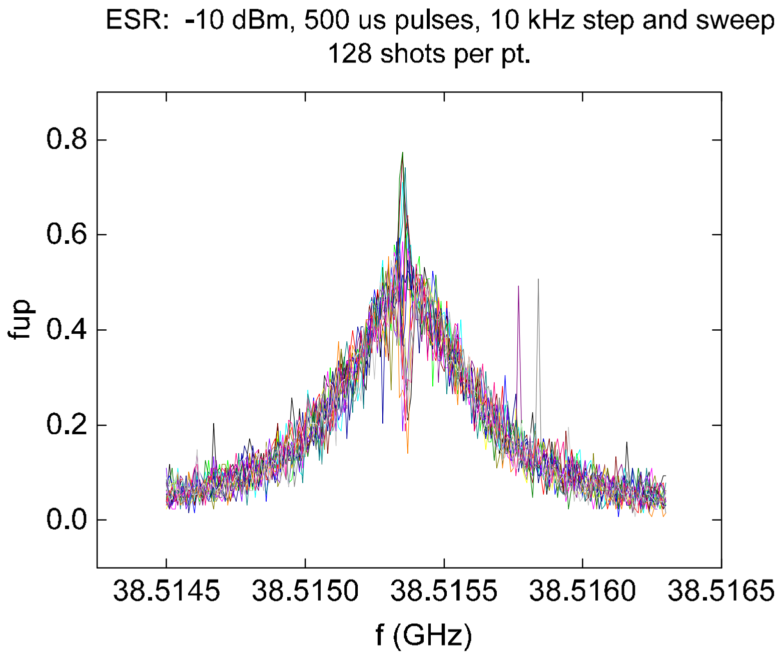
# Nuclear Rabi Osc. (electron down spin loaded on donor)

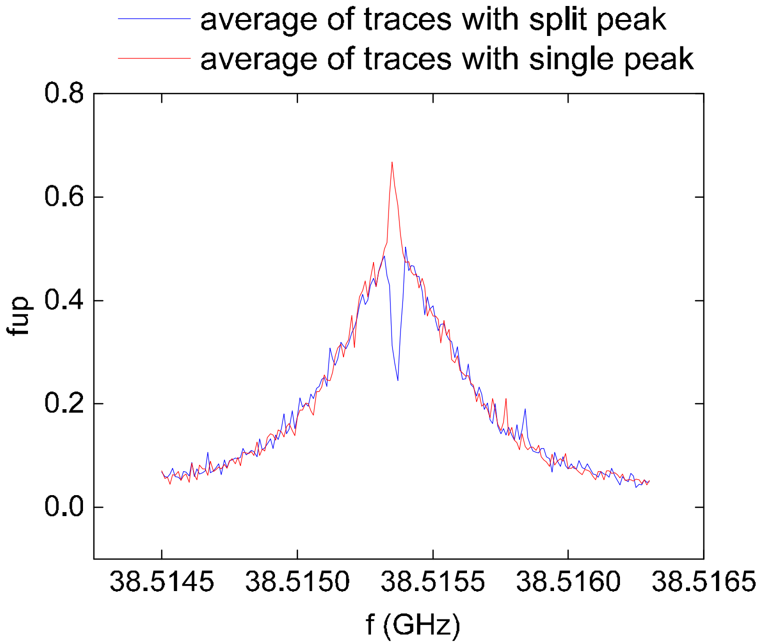



- more power reaching sample than I expected
- ESR adiabatic flip and readout should be ~ 0 to 0.9, not sure why Pflip contrast for nuclear flip is low (oscillations noisy)
- Info about charge noise?

# High power ESR sweep to flip neighboring P electron spins

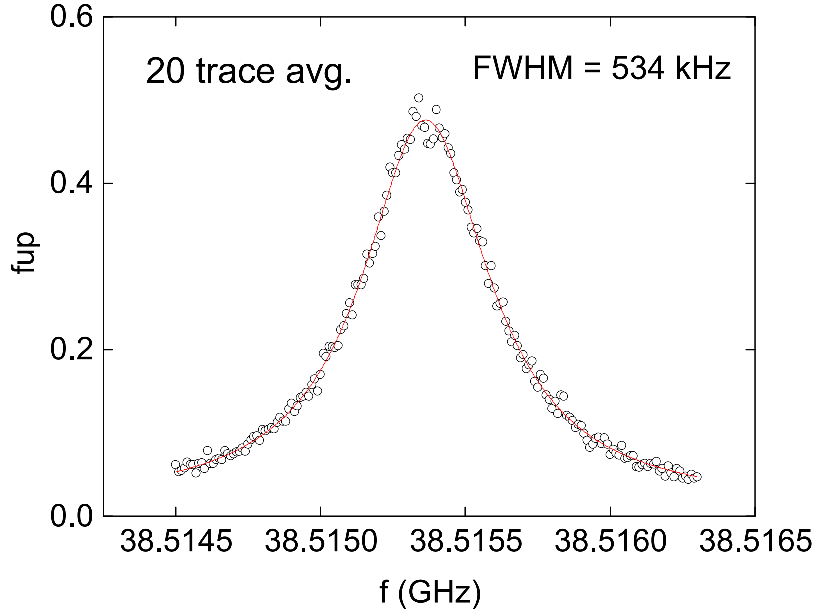


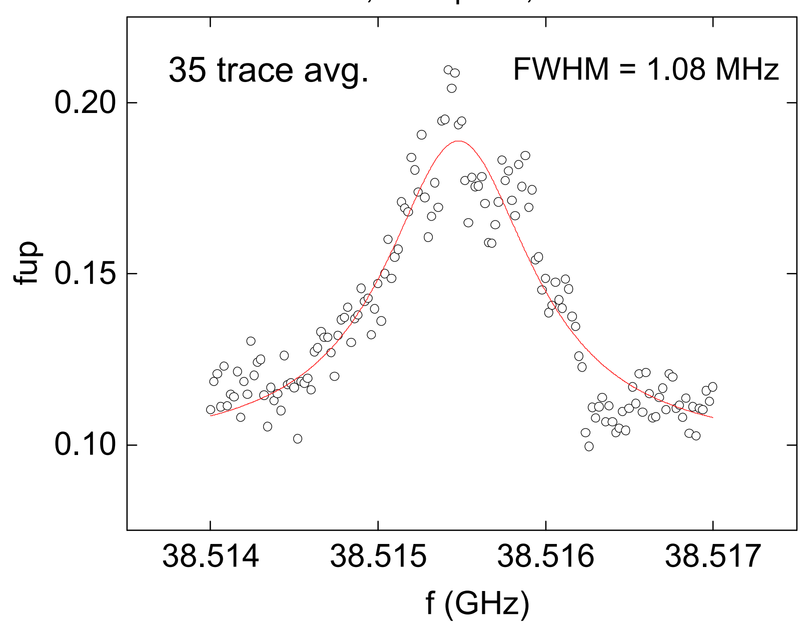

Could this be this neighbor P nuclear spin up vs. down?

# ESR sweep with P NMR pulse

No NMR



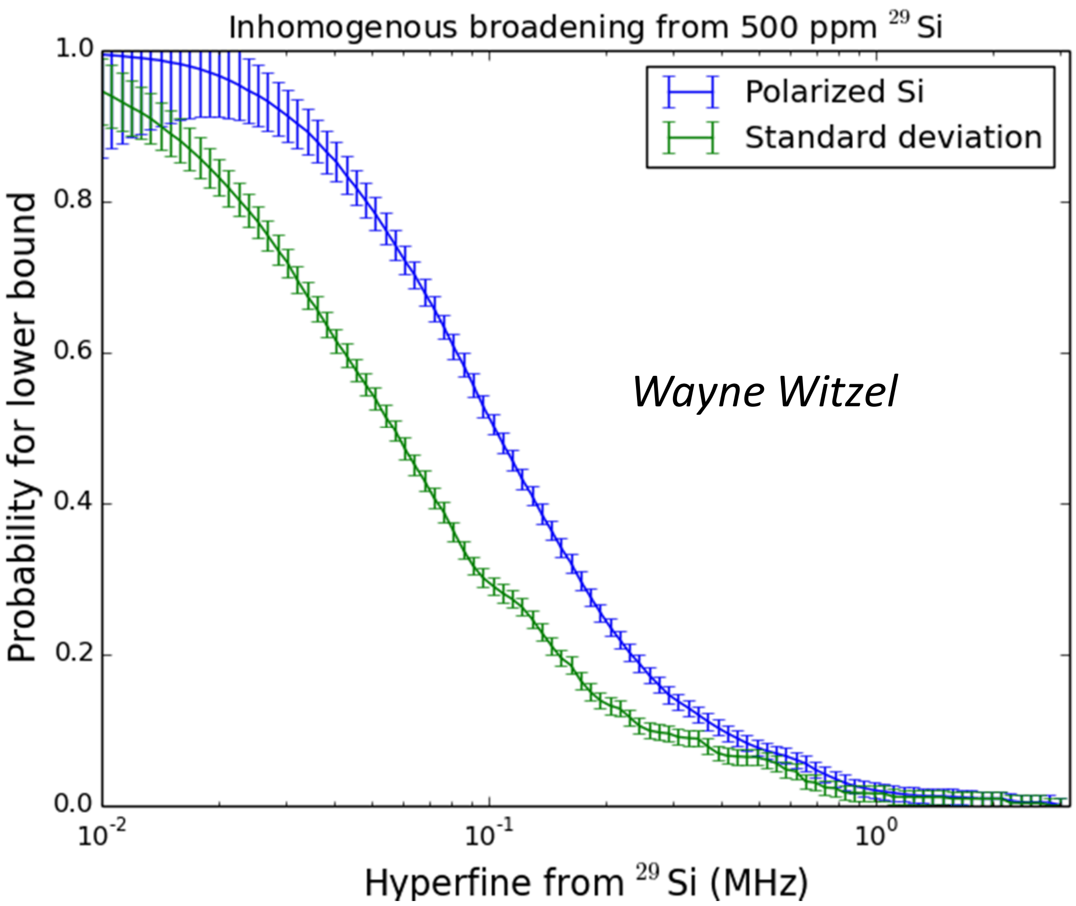

P NMR & ESR sweep
ESR: -10 dBm, 20 kHz step and sweep, 500 us pulse
NMR: -3 dBm, 5 ms pulse, 79 to 83 MHz




ESR peak width increase with 4 MHz P nuclear sweep?

# Hyperfine shifts from $^{29}$Si?

W. Witzel




- Every sample will have different $^{29}$Si constellation.
- 30 kHz linewidth seems reasonable, but it is suspicious that is occurred in two samples.
- Dynamics? How are background spins changing during measurement?

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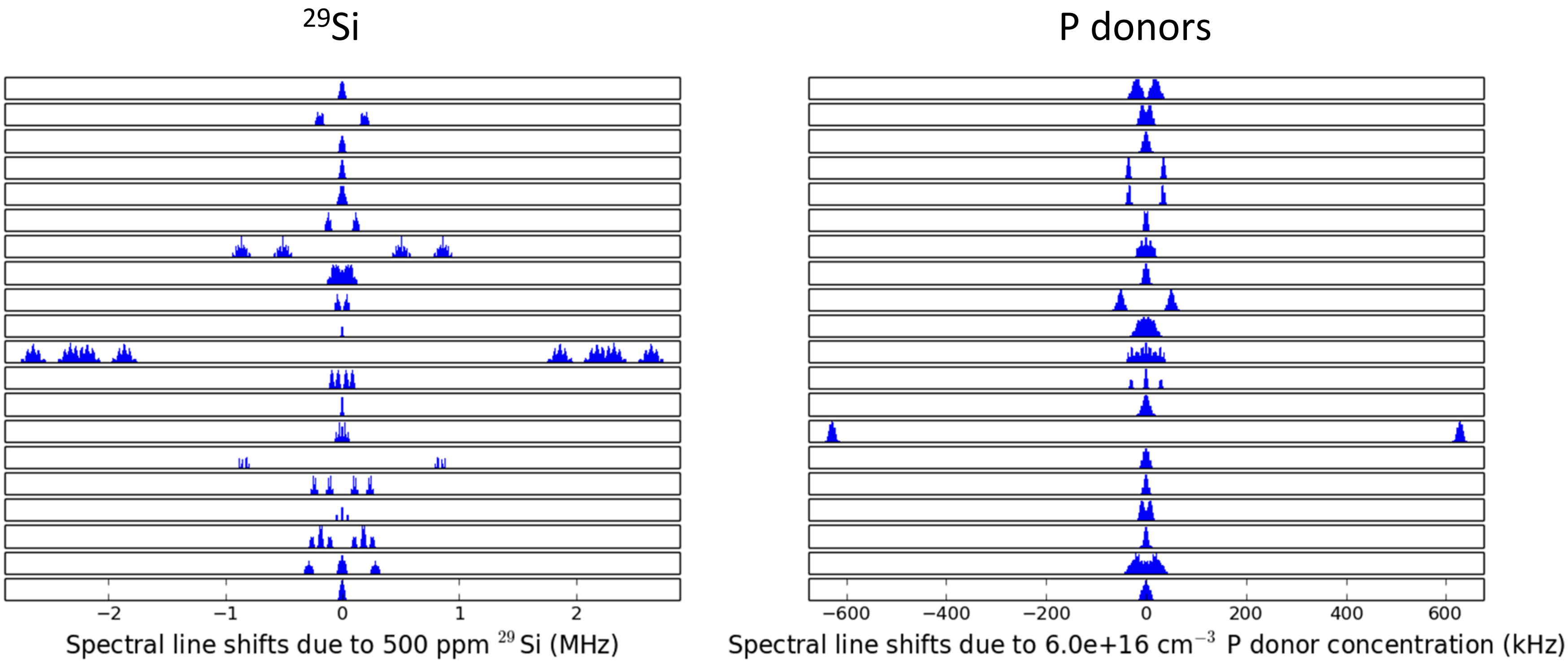
W. Witzel

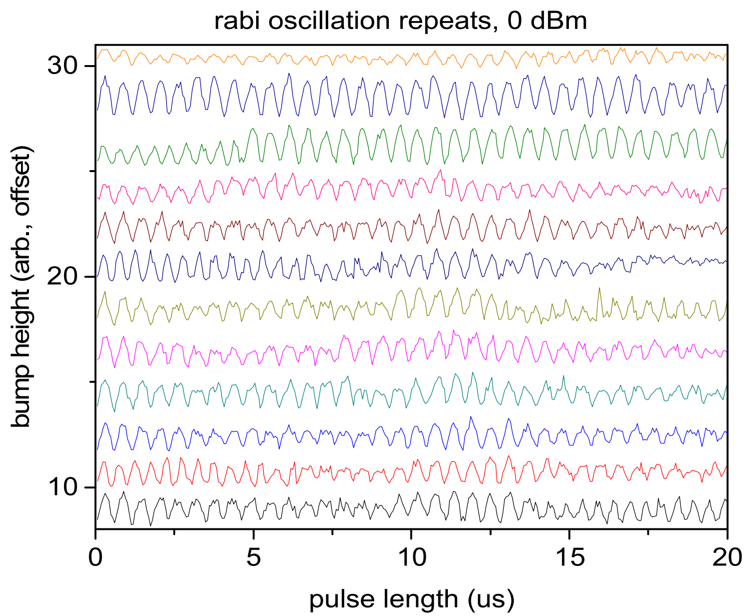
# Calculated ESR line shapes




- Each row: different possible spectra for a given constellation of neighboring spins
- From experiment: P density 6x10$^{16}$/cm$^{3}$, 500 ppm $^{29}$Si

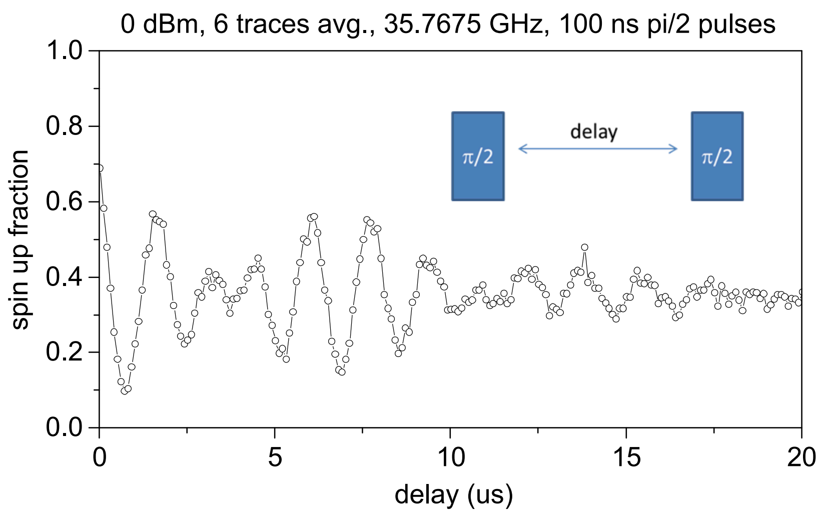
# Beating in Rabi oscillations

Each trace identical repeat




0 dBm
128 averages

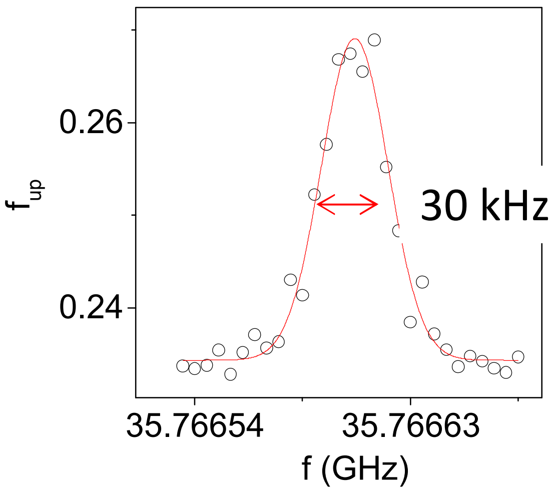
Ramsey Fringes



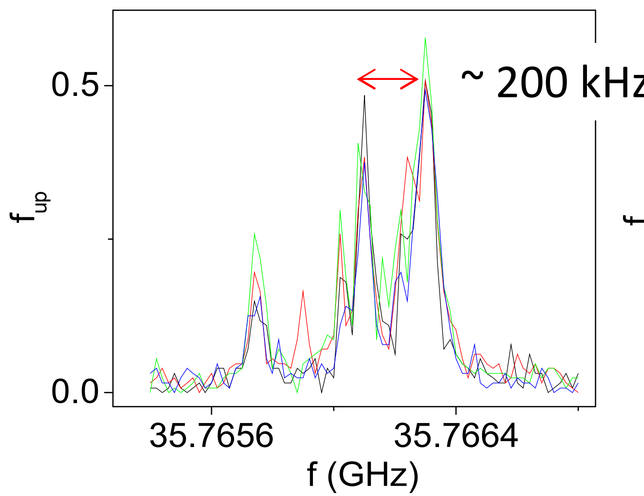

Beat frequency ~ 200 kHz

# Complex line structure

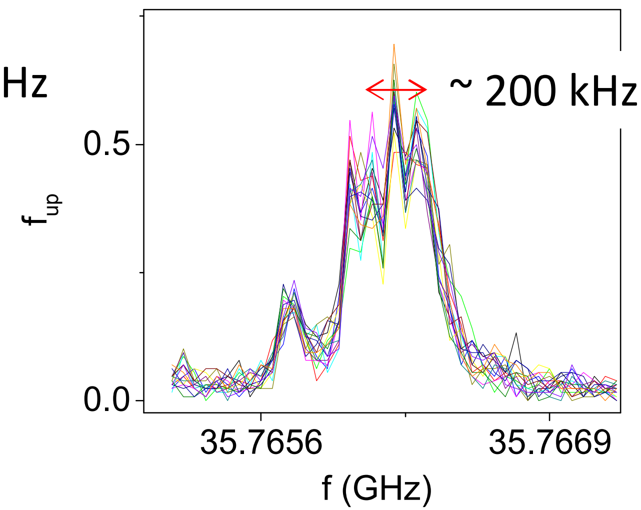
-50 dBm



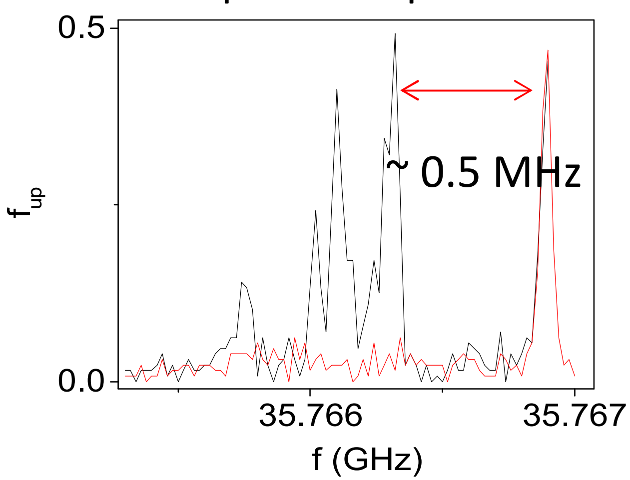

-40 dBm




-30 dBm




Jumps in line position




- Additional transitions apparent at higher microwave power
- Discrete jumps in position of line over hour long time scales

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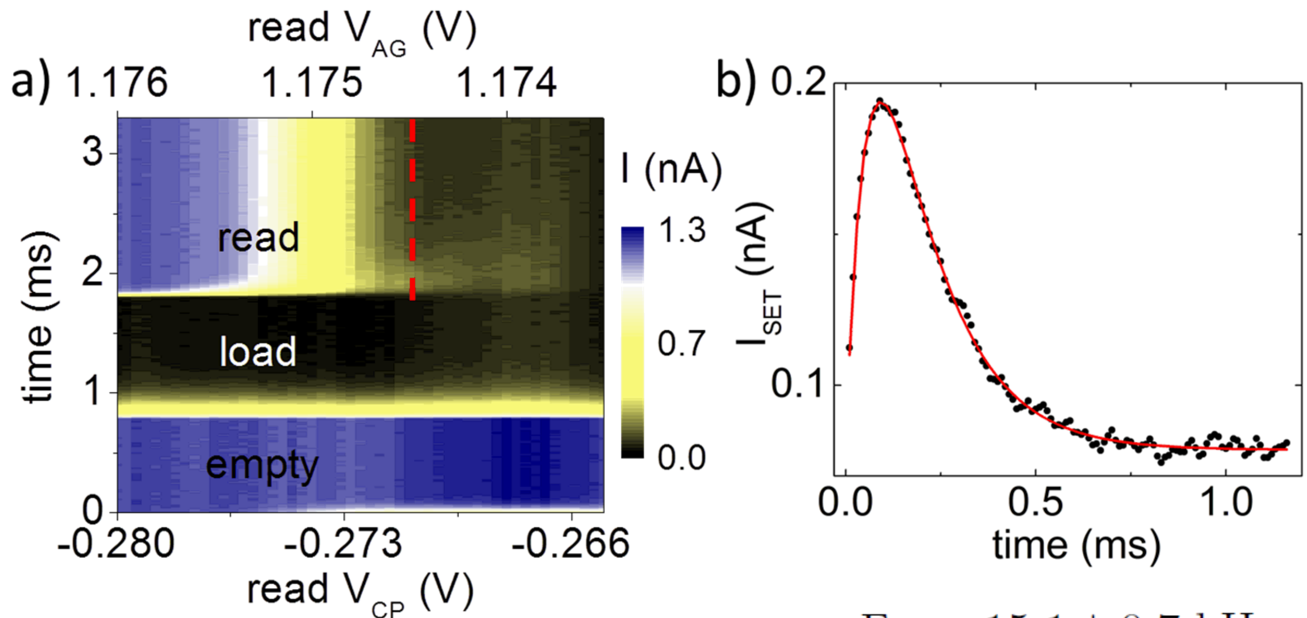
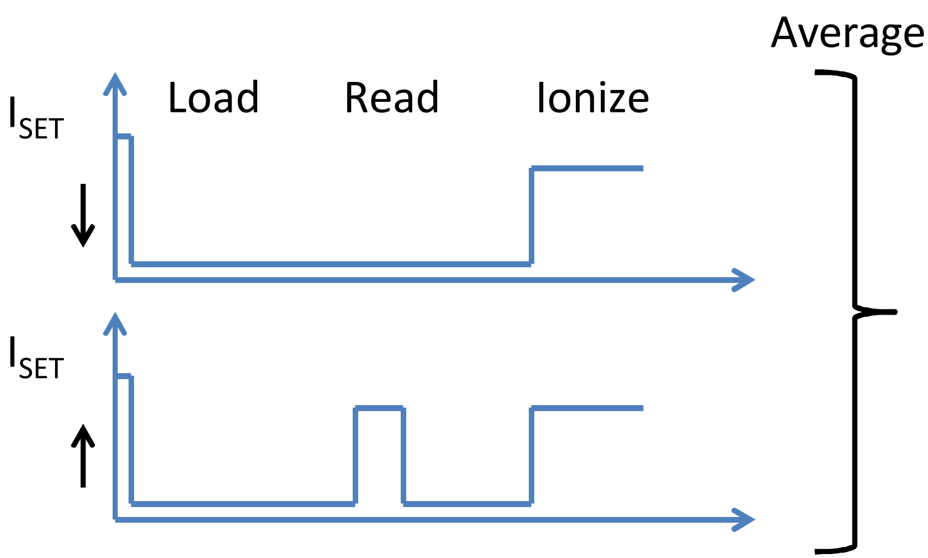
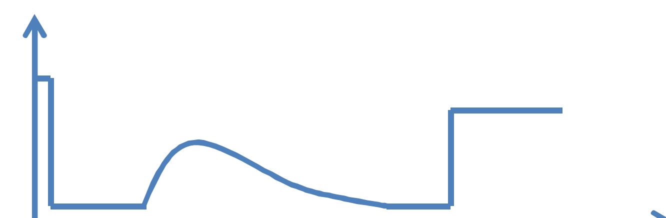
# Tuning read level




$$\Gamma_{\downarrow l} = 15.1 \pm 0.7 \text{ kHz}$$
$$\Gamma_{\uparrow u} = 6.8 \pm 0.2 \text{ kHz}$$




BW for high fidelity single shot readout?

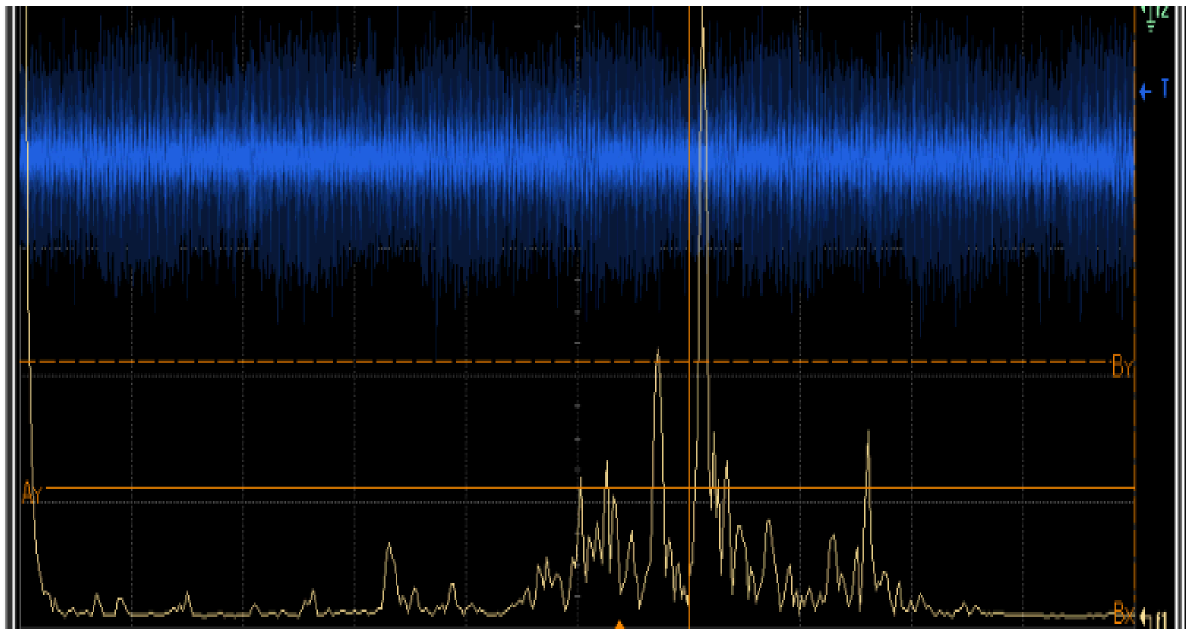


averaged readout

# Dilution refrigerator acoustic noise (pulse tube)

Voltage from pickup coil at sample position

FFT



0 1 2

f (kHz)

Rough estimate: ~ 10 um of vibration, ~100 kHz linewidth

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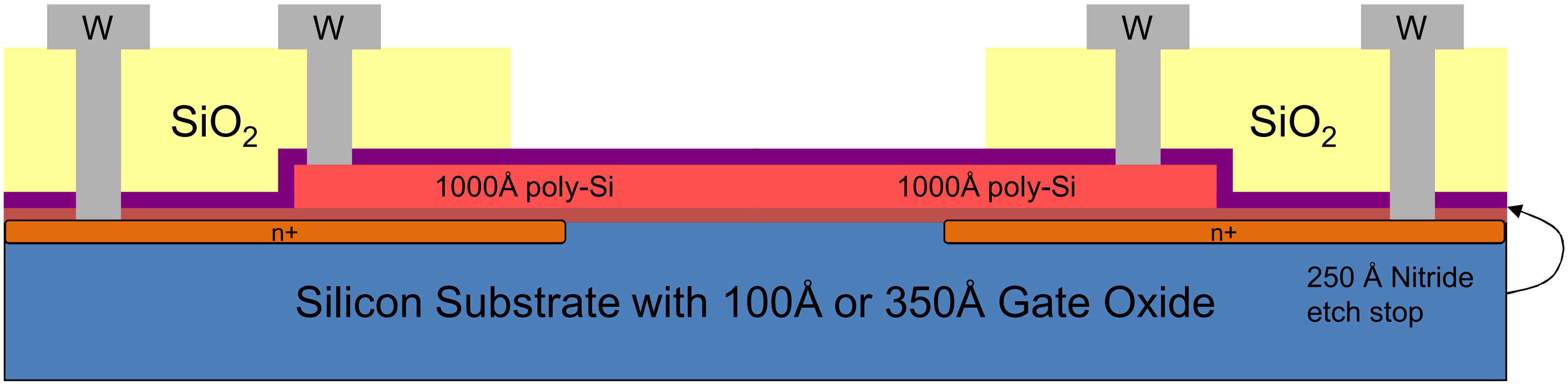
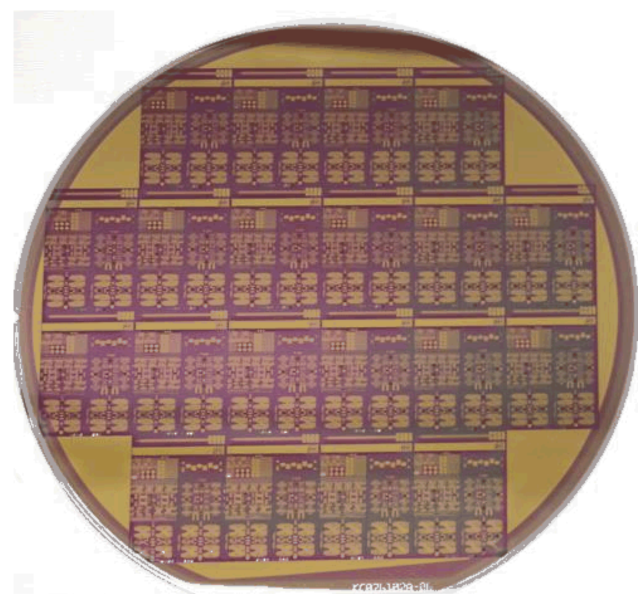
# Si donor qubit fabrication – SNL Si foundry

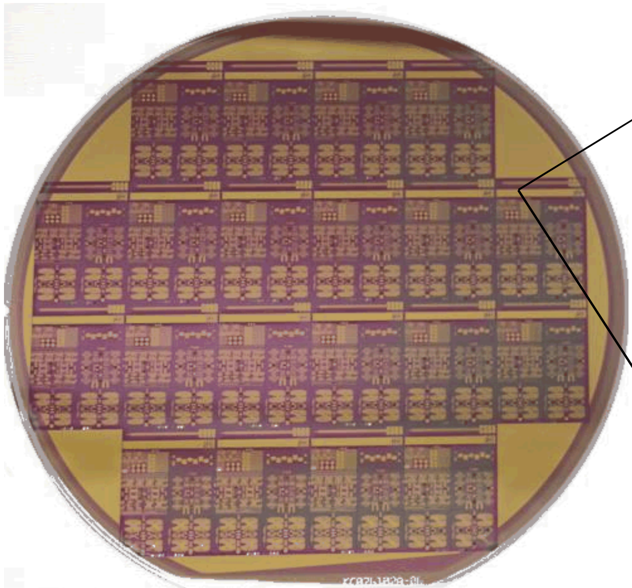


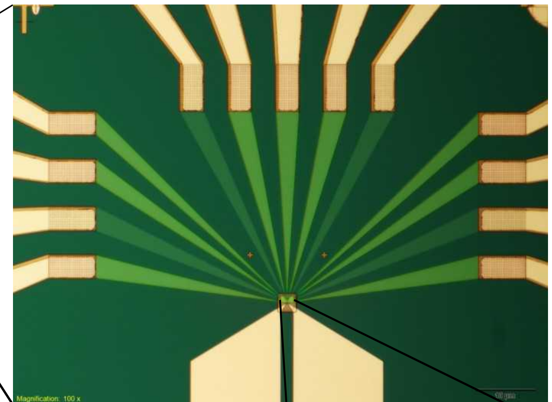

<u>**MOS Stack from Si fab**</u>
**Many electron QDs possible with 0.18 μm litho**
**Structures fabricated for external community**
**(NIST, LBNL, CQC2T, U. Princeton)**
**7,500 – 15,000 4K mobility**

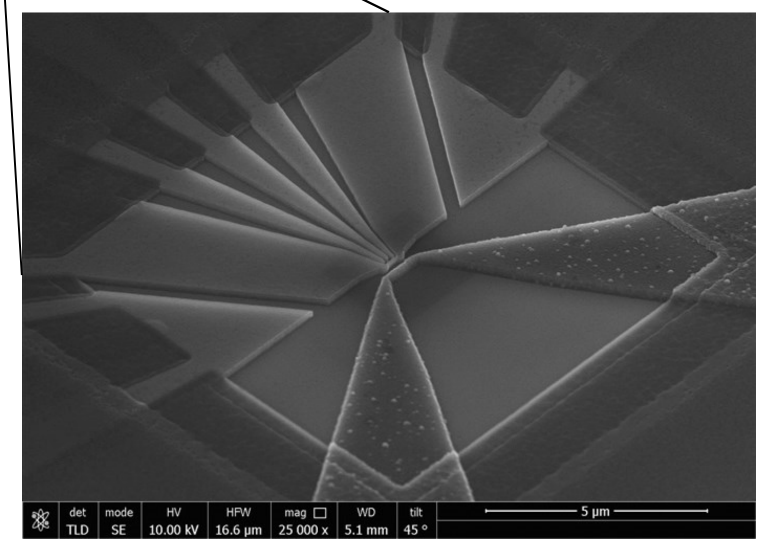


**T. Pluym, G. A. Ten Eyck, N. Bishop,**

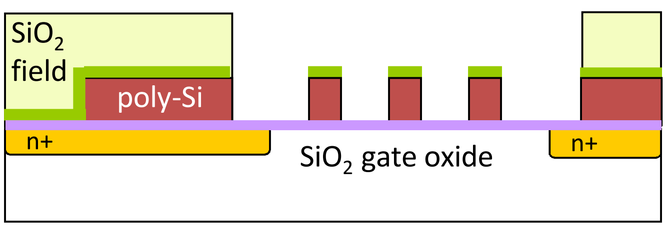
# Nanostructure fabrication






EBL and poly etch to define nanostructure gates





**G. A. Ten Eyck, J. R. Wendt, J. Dominguez, B. Silva, N. Bishop,**

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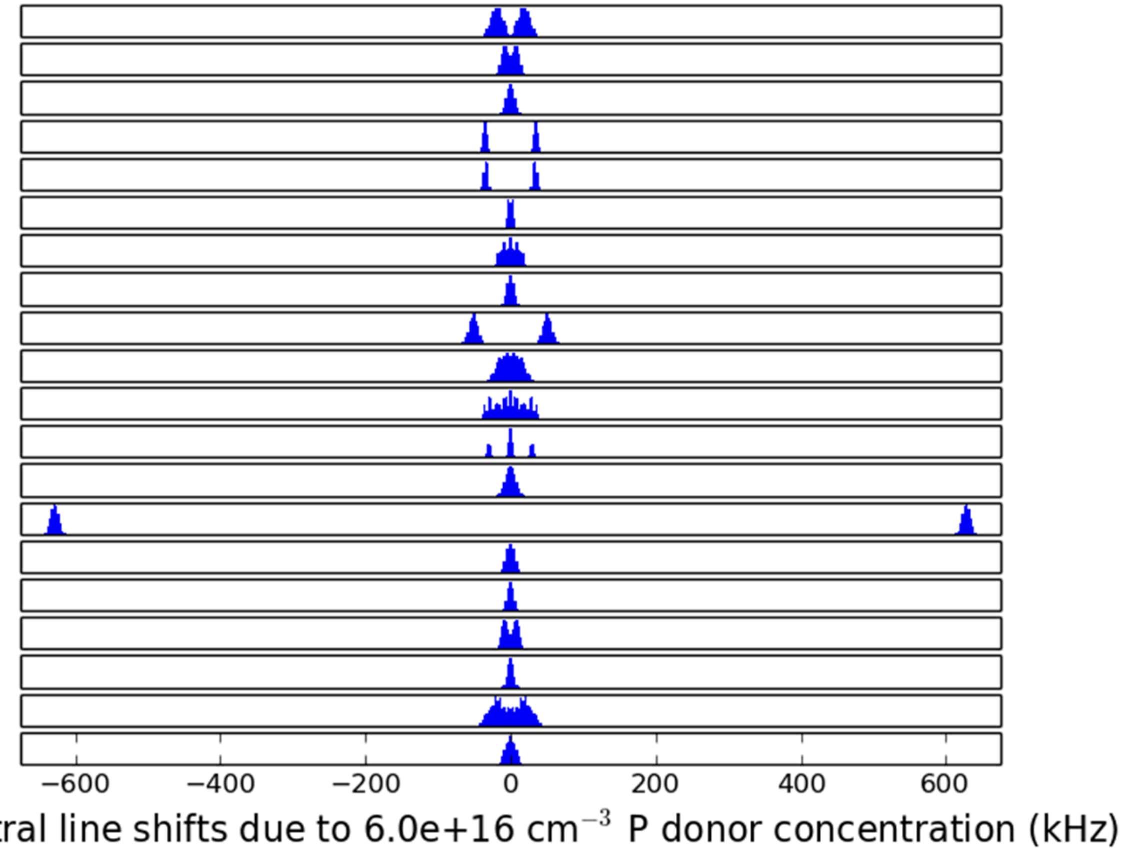
Quantum Information S&T

W. Witzel

# Calculated ESR line shapes




- Each row: different possible spectra for a given constellation of neighboring spins
- Dynamics?

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R. Blume-Kohout, E. Nielsen

# Gate Set Tomography

| Operator | Hilbert-Schmidt vector (Pauli basis) | Matrix |
|---|---|---|
| $\rho_0$ | 0.7206<br>−0.0168<br>−0.0185<br>0.6741 | $\begin{pmatrix} 0.9862 & 0.0177e^{i2.3} \\ 0.0177e^{-i2.3} & 0.0328 \end{pmatrix}$ |
| $E_0$ | 0.6929<br>0.0328<br>−0.0029<br>−0.6516 | $\begin{pmatrix} 0.0292 & 0.0233e^{i0.1} \\ 0.0233e^{-i0.1} & 0.9507 \end{pmatrix}$ |

Table 5: **The GST estimate of the SPAM operations.** Compare to Table 1.

| Gate | Superoperator (Pauli basis) |
|---|---|
| Gi | $\begin{pmatrix} 0.9992 & -0.0007 & 0.006 & 0.004 \\ -0.002 & 0.953 & 0.0227 & 0.0008 \\ 0.0114 & -0.0115 & 0.9361 & 0.0065 \\ 0.0027 & -0.0009 & -0.0061 & 1.0047 \end{pmatrix}$ |
| Gx | $\begin{pmatrix} 1.0003 & 0.0087 & -0.0354 & -0.0027 \\ -0.0048 & 0.9352 & 0.1054 & 0.0869 \\ 0.0089 & 0.1197 & -0.0091 & -0.9284 \\ 0.0051 & -0.1363 & 0.9467 & -0.0346 \end{pmatrix}$ |
| Gy | $\begin{pmatrix} 0.999 & 0.0496 & -0.008 & -0.0219 \\ 0.0014 & -0.0115 & 0.099 & 0.9425 \\ -0.0072 & 0.1273 & 0.929 & -0.1308 \\ 0.0145 & -0.9091 & 0.0914 & -0.0356 \end{pmatrix}$ |

Table 6: **The GST estimate of the logic gate operations.** Compare to Table 2.

- Gate set tomography (GST) was used to characterize qubit. Maximum length base sequence L = 8.
- State preparation and measurement error (SPAM) is ~6%
- Idle gate error is ~2.5%.
- X and Y rotation errors ~5%. Looks like phase error between X and Y. Possibly instrumental error which can be improved.