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Quantum Control of Single Spins

Phosphorous Donors in Silicon

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CINT Quantum Materials Forum
April 28, 2017

Outline

- Control of a Single Electron and Nuclear Spin in Donor Qubits
- New Ideas
  - Spin Physics of Holes in Germanium
  - Ultra-Sensitive Ensemble ESR

Control of Single Electron and Nuclear Spins in Donor Qubits

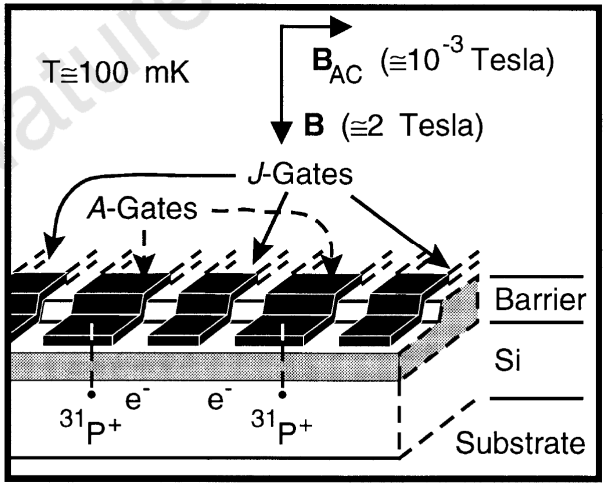
With Lisa Tracy

Motivation—Donor Based Qubit

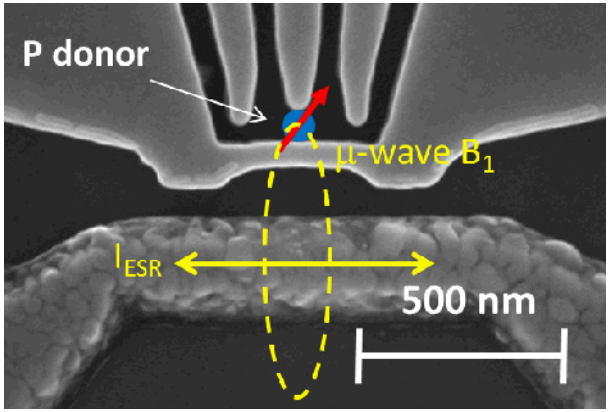
Donors in silicon are relatively uncoupled from the environment while allowing control.

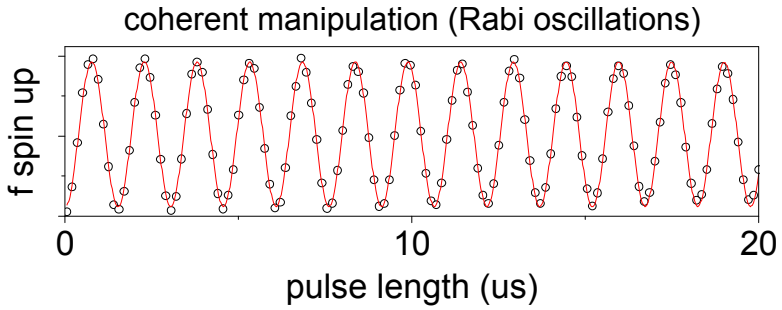
Kane architecture

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



Coherent Quantum Control of Electron Spin with Electron Spin Resonance

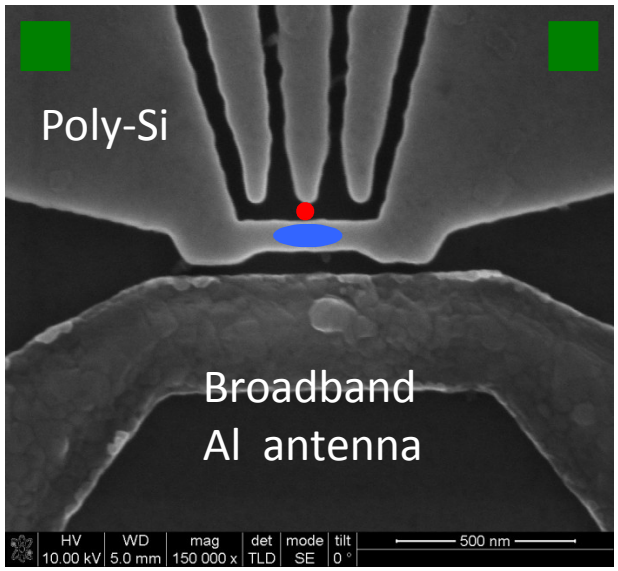




Donor Device Design

- Poly-Si gated nanostructures
- 45 kev P Donor implants: 4e11 cm^{-2}
- T=20 mK

Typical Device

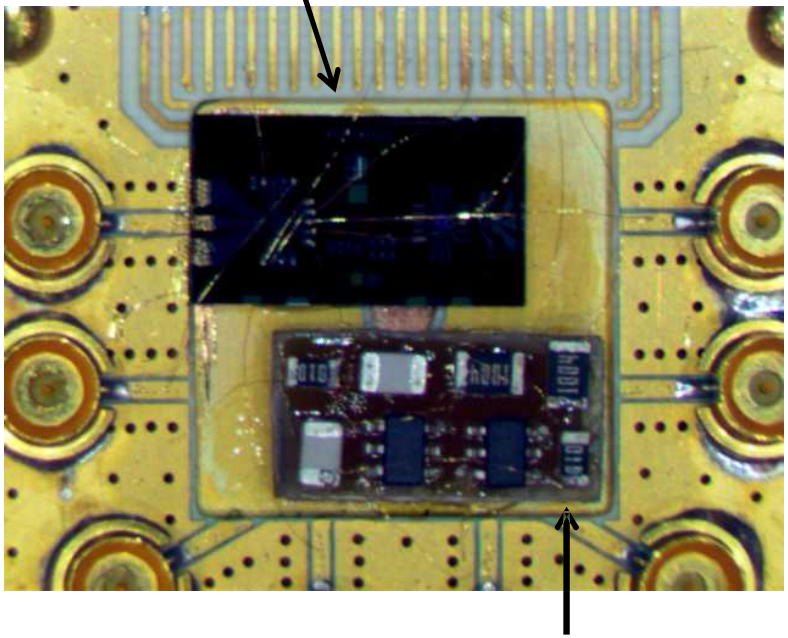


Ohmics

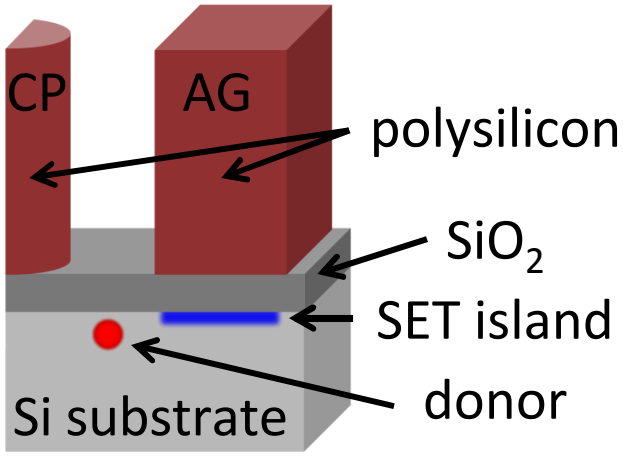
Donor

Quantum Dot

Qubit Sample

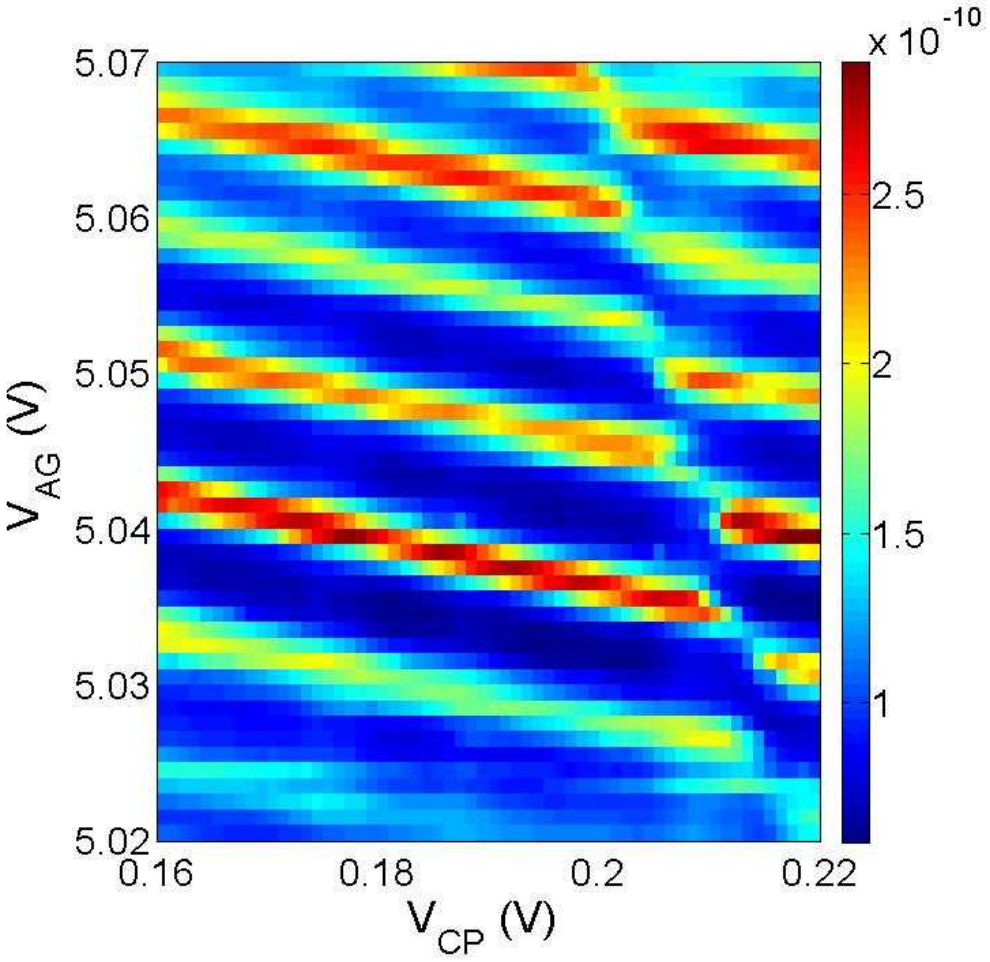


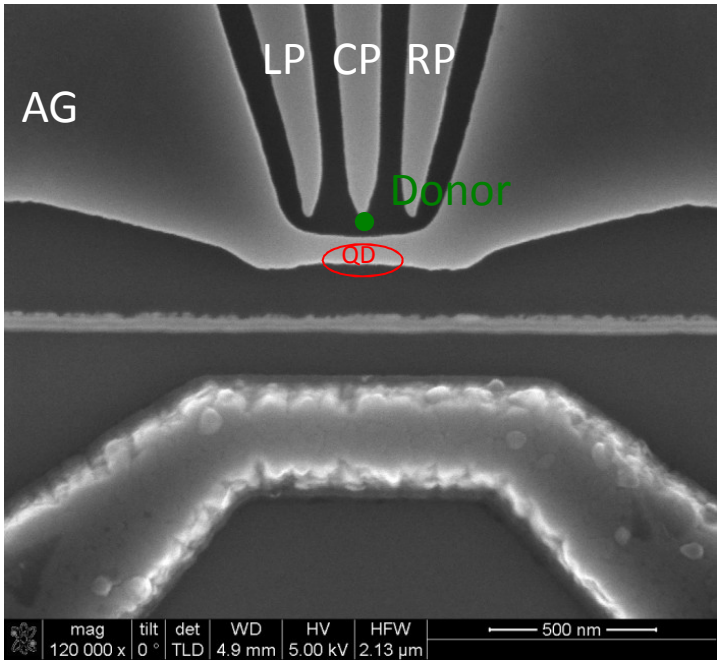
Two-Stage HEMT amplifier stage



Transport Through Quantum Dot

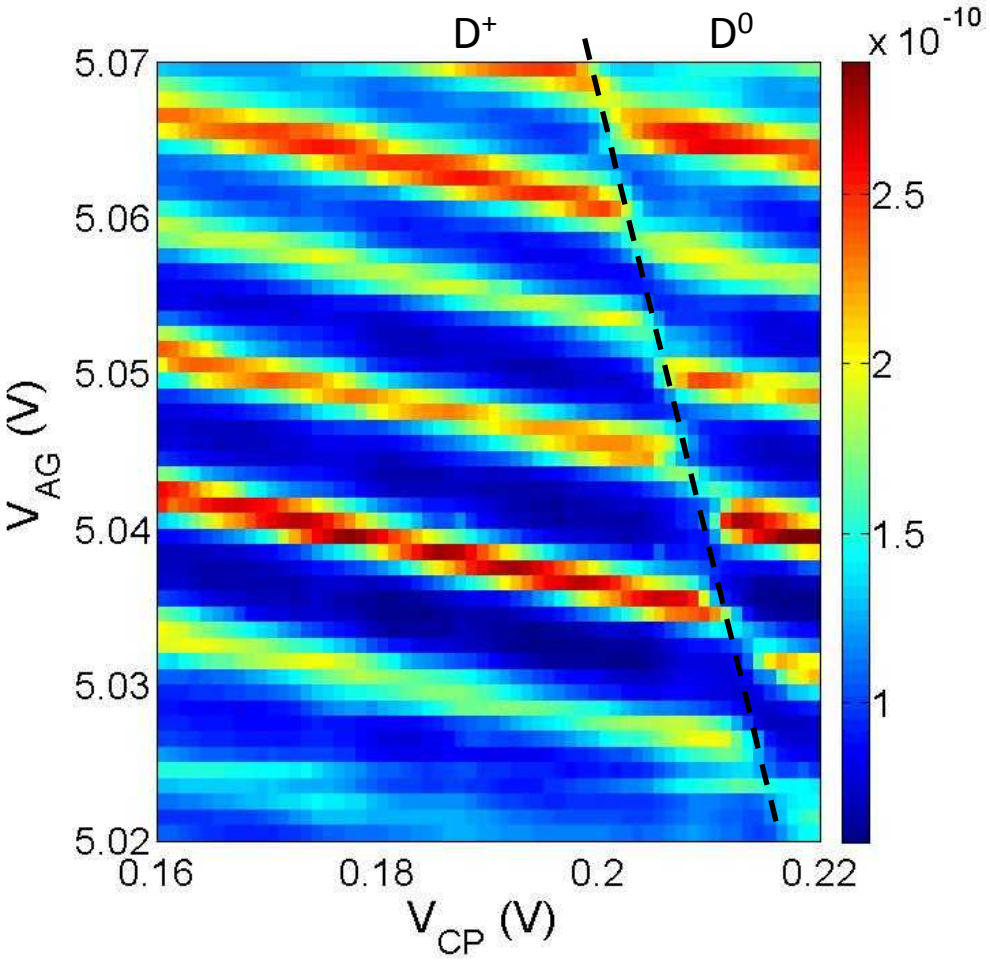
Transport Through Quantum Dot



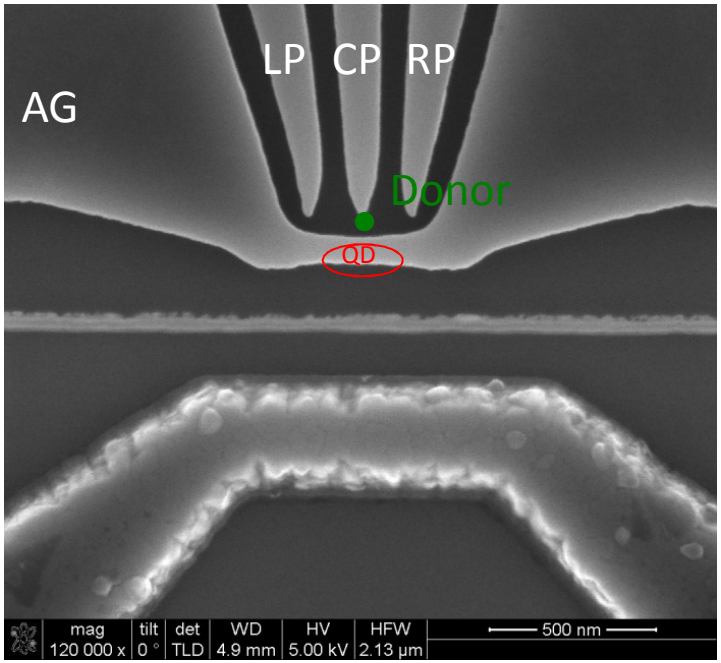


T~15 mK

Transport Through Quantum Dot

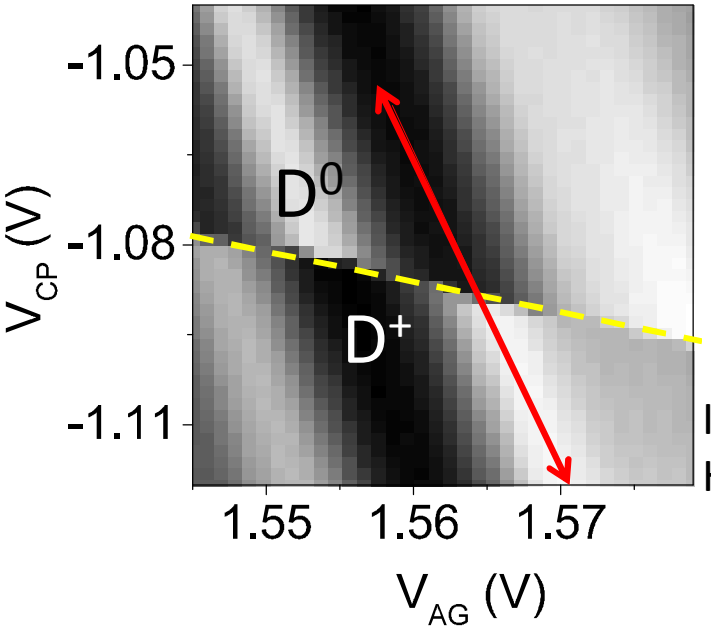


T~15 mK



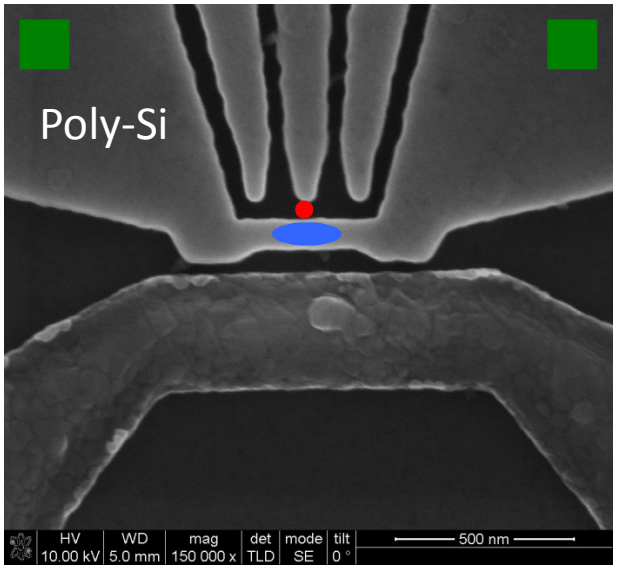
Dot transport can be used as a sensor for donor occupancy

Spin Readout



Neutral:
Low Current

Ionized:
High Current



Ohmics

Donor

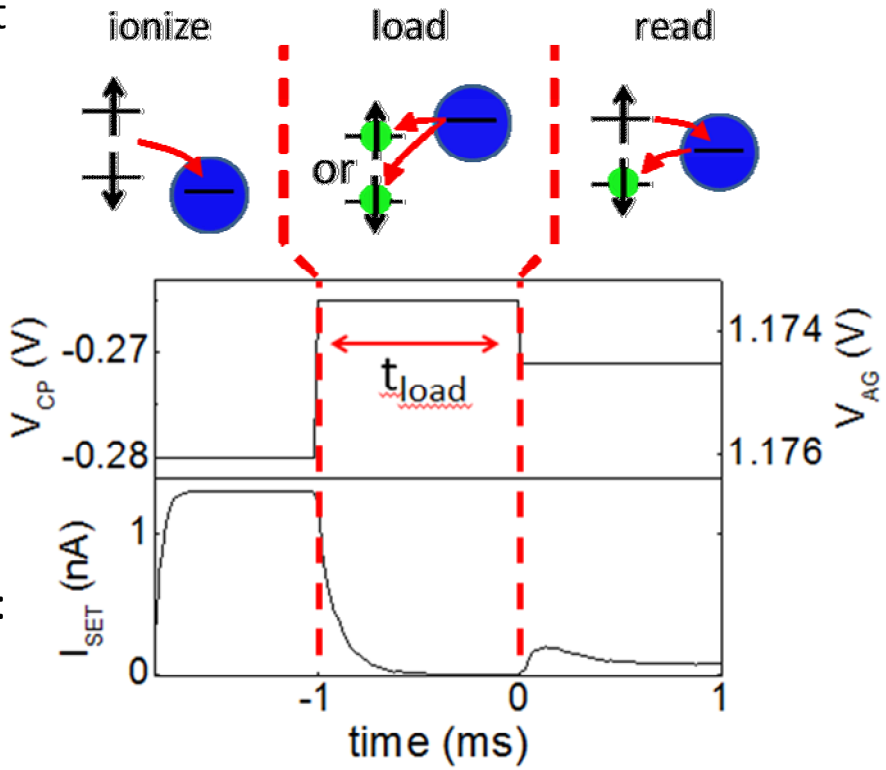
Quantu
Dot

Al
stripline

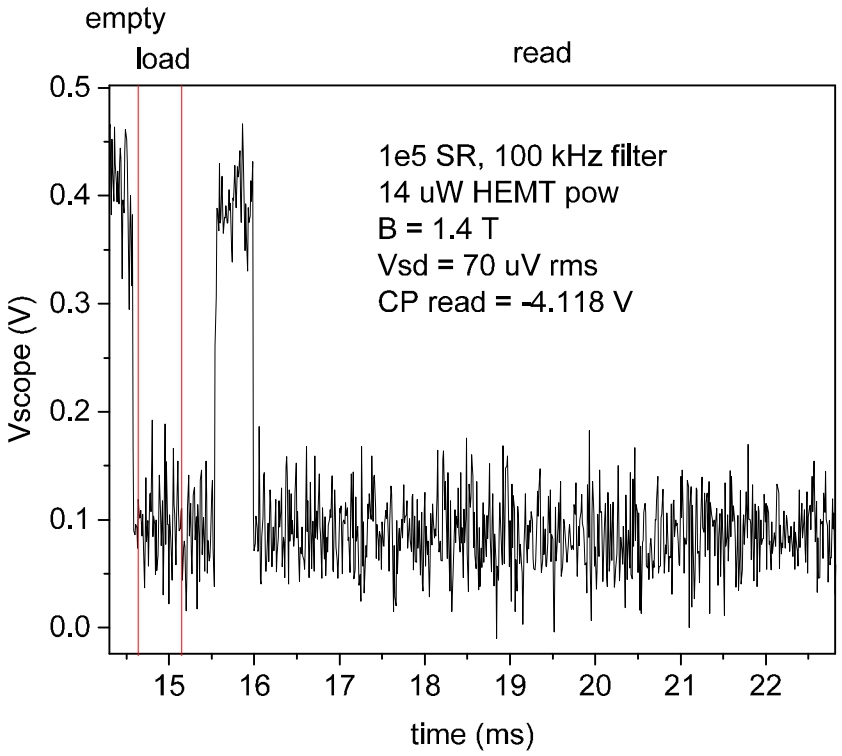
Pulse across donor transition.

In large B-field, electron on donor will exhibit spin dependent tunneling.

Average of many sequences:



Single Shot Readout



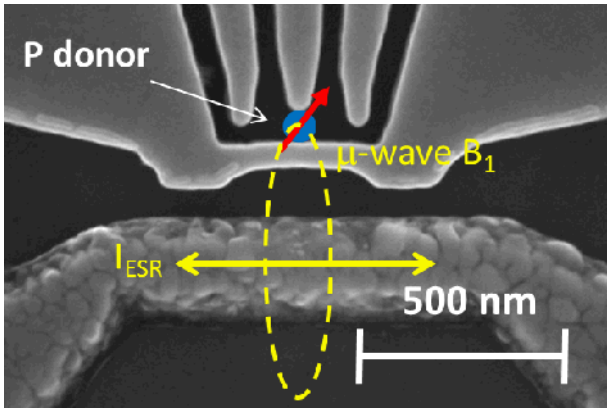
Detection of a single spin-up electron

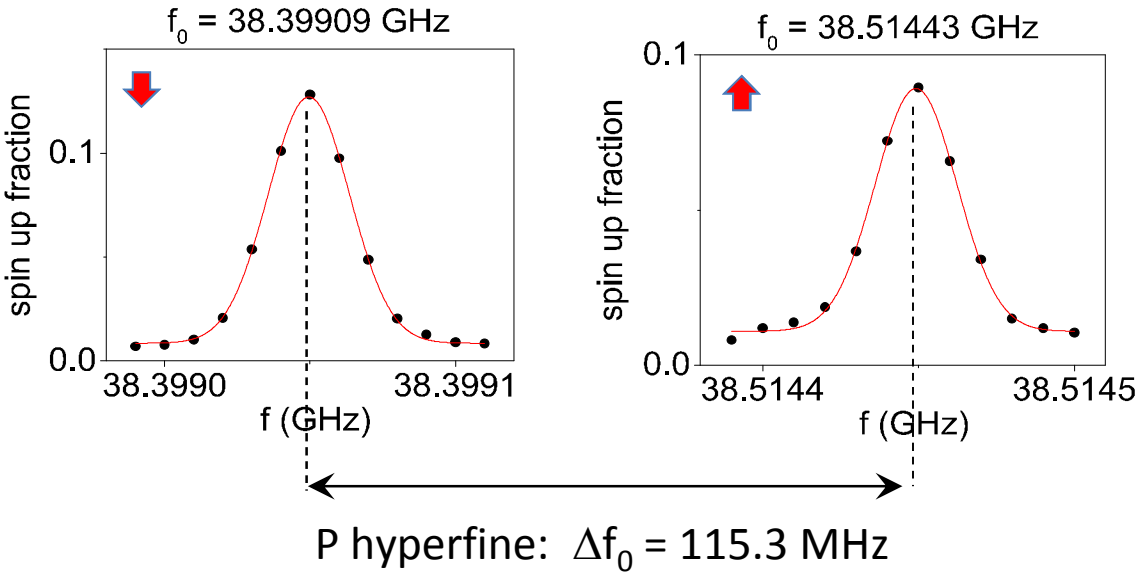
The donor has a spin down electron at the end of the readout cycle.

ESR of a Single Spin

Measurement Steps:

- Initialize Spin Down
- Manipulate Spin with Microwaves
- Readout Spin





P hyperfine: Δf_0 = 115.3 MHz

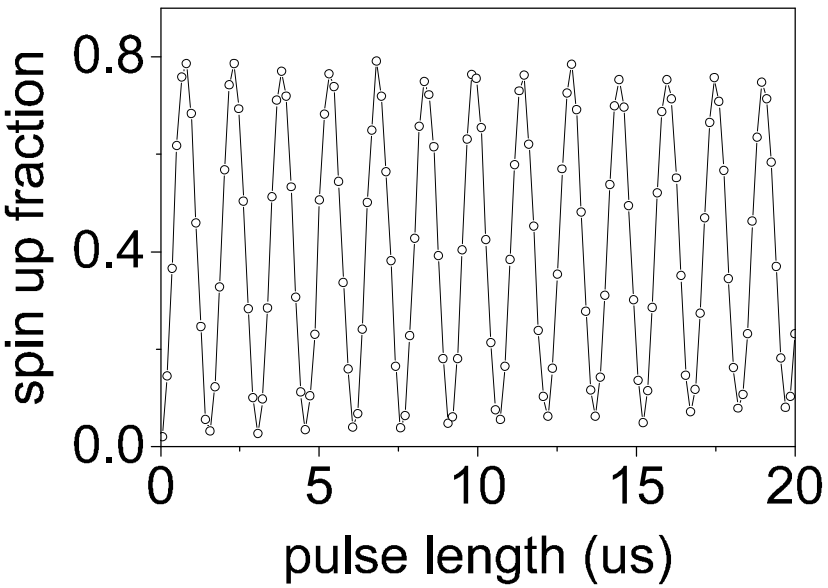
Hyperfine splitting consistent with Phosphorous

$$f_{ESR} = \gamma B \pm A/2$$

Expect two resonance lines: Nuclear spin up and Nuclear spin down

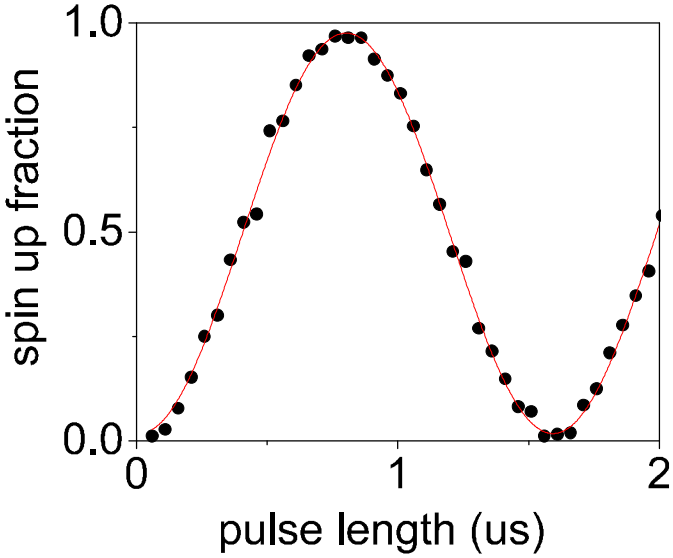
Coherent Control of an Electron Single Spin

Rabi Oscillations

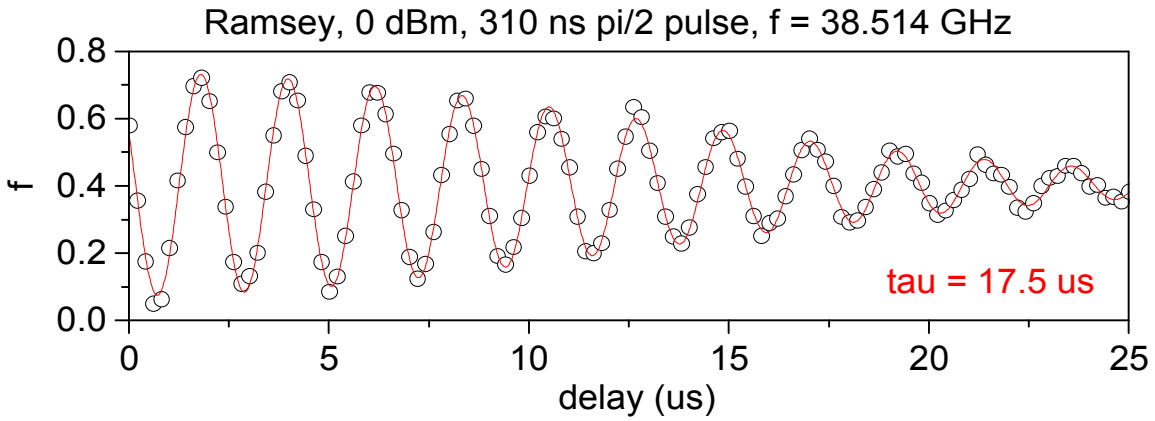


Optimized Readout: 96% visibility

Bandwidth: 100 kHz



Ramsey Fringes:

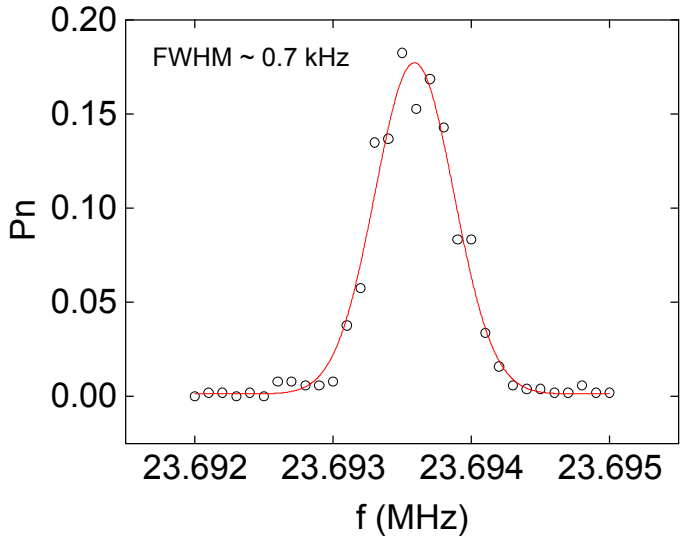


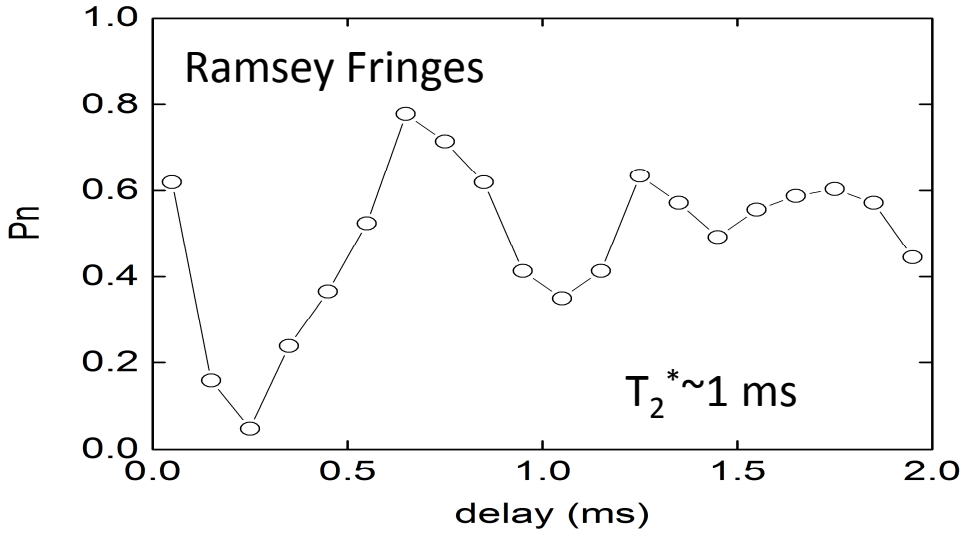
$T_2^* = 17.5\ \mu s$

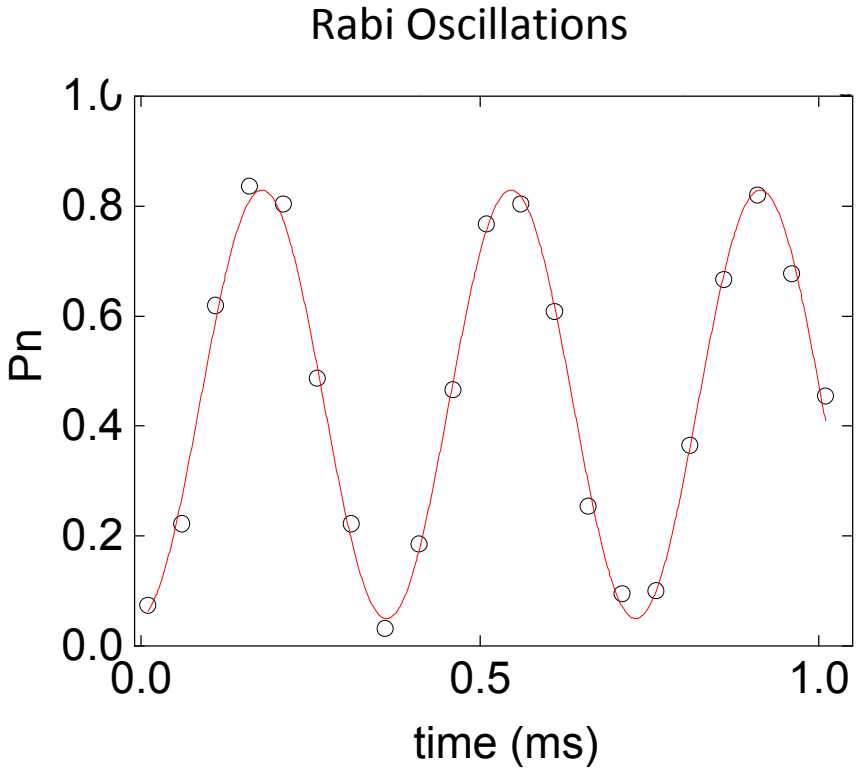
$T_{2\ HE} = 310\ \mu s$

Coherent Control of Nuclear Spin

Readout Nuclear Spin through ESR Frequency of electron spin



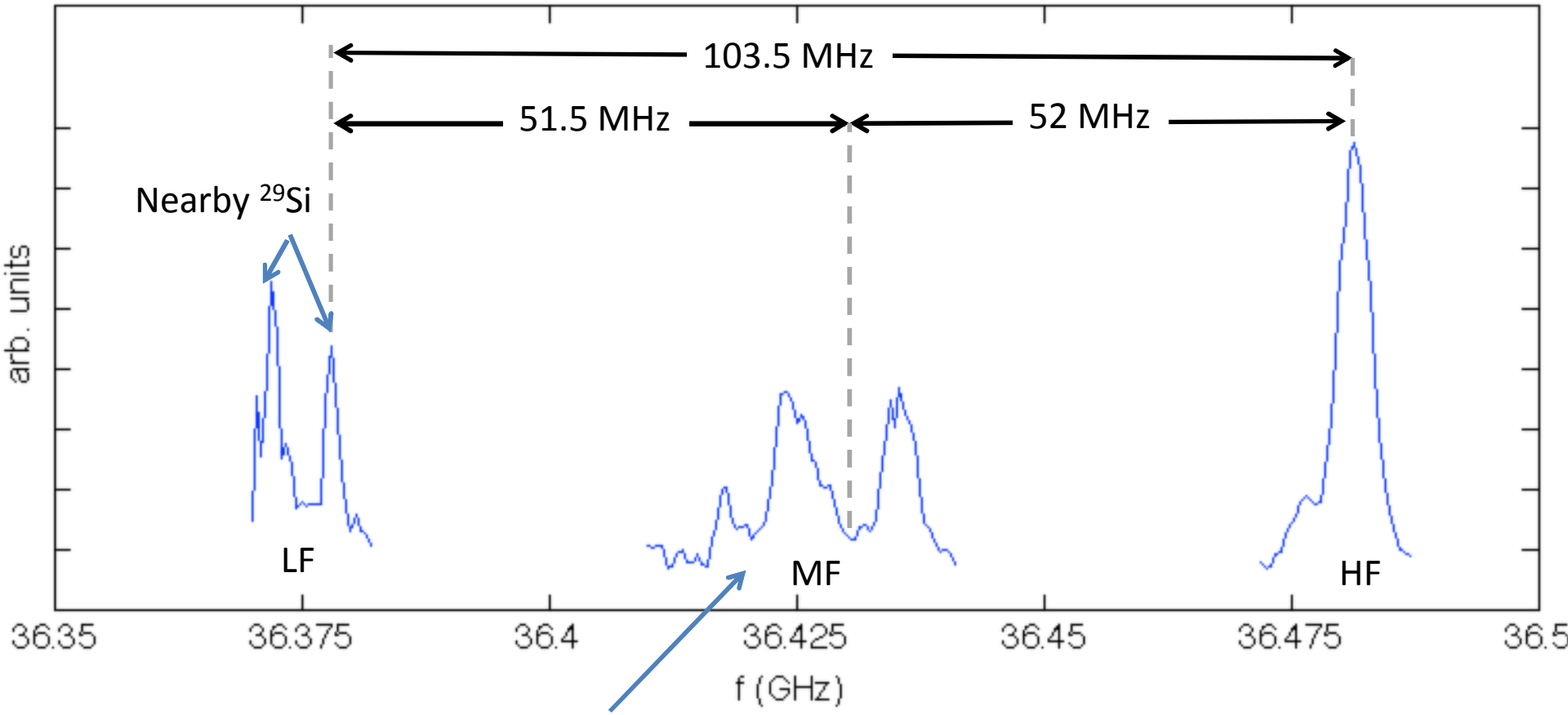




Nuclear Spin of P donor
Implanted in Silicon

B=1.3 T

ESR Spectrum of P2 Dimer



Indicates nuclear spin anti-aligned state

ESR Spectrum and coherence times provide information about the material and environment

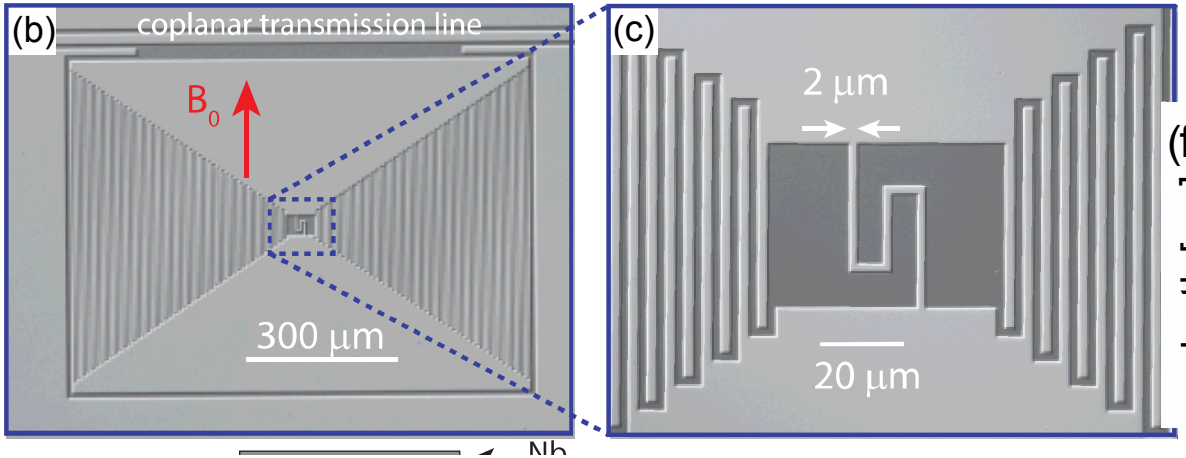
Possible New Directions

- Ultra-Sensitive Ensemble ESR (with Lisa Tracy)
- Holes in Ge Nanostructures (with Tzu-Ming Lu)

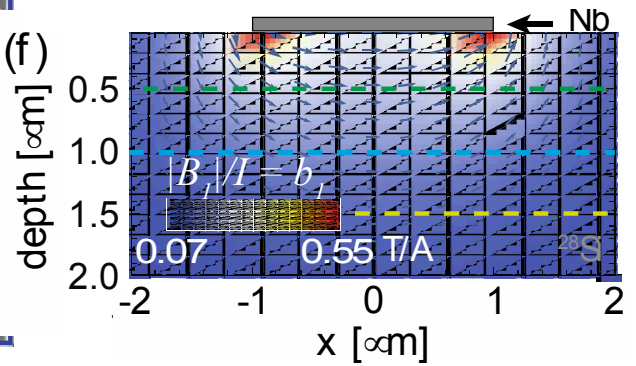
Ultra Sensitive Ensemble ESR

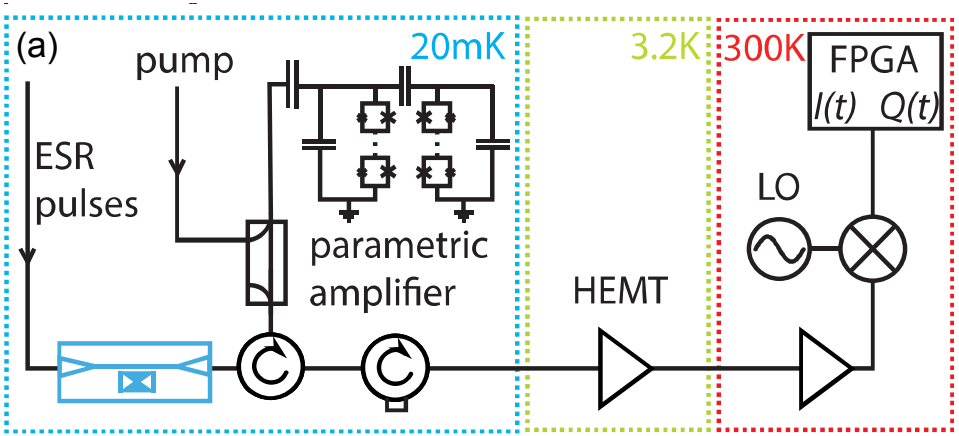
Induction Detection

Superconducting Resonator with Parametric Amplifier output



Eichler, et al. (2016)





- Perform ESR at the nano-scopic scale
- Small Number of Spins
- Material Characterization
  - Defects
  - Chemical Composition

A Versatile Platform

Large Trade Space with regards to temperature, magnetic field, sensitivity, applications, etc.

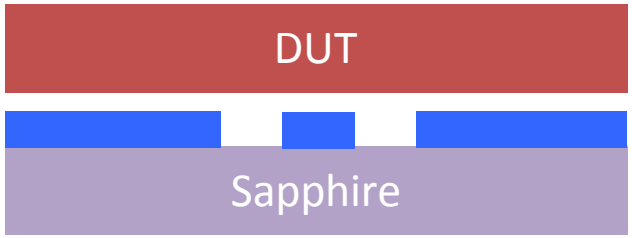
Spatial mapping possible through magnetic field gradients

Possible NMR through ENDOR

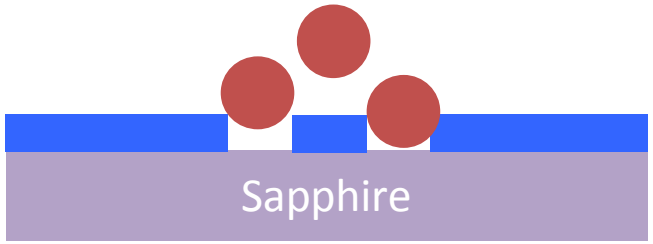
Multiple Geometries

Direct

Non invasive



Nanoparticles/molecules

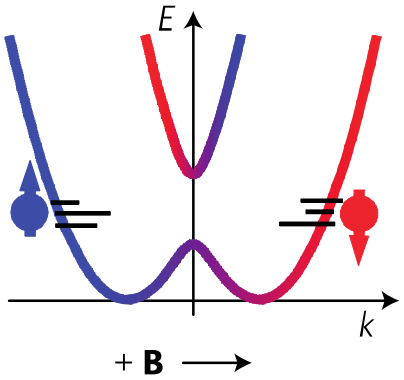


Use technique to explore a variety of material systems

Strained Ge Quantum Wells

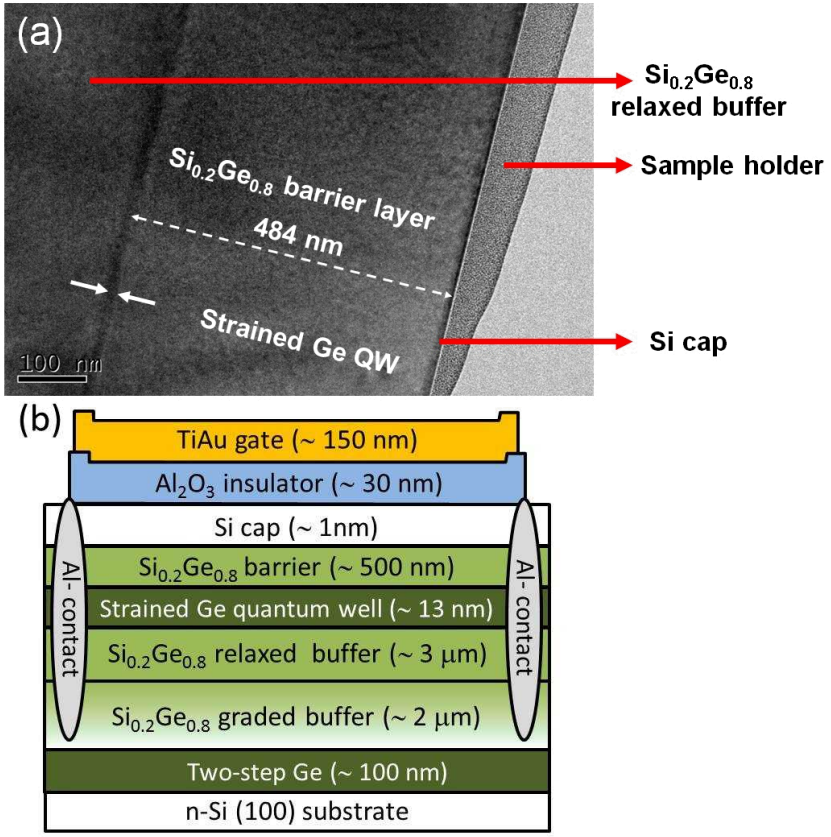
- p-type
- Undoped Structures
- Low Disorder with tunable density
- Large g-factor anisotropy
- Large Spin Orbit Coupling

$$H_{SO} = \alpha\vec{\sigma} \cdot \underbrace{\vec{k} \times \vec{E}}_{B_{SO}}$$



Spin Momentum Locking in 1D with External B

Quay et al. Nat. Phys. (2010)



Laroche, Lu, et al. Appl. Phys. Lett. (2016)

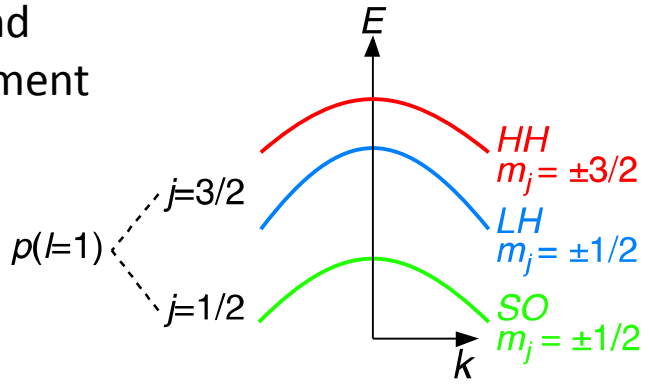
Control of a Single Hole Spin in Ge

Carriers are heavy holes with J=3/2 and $m_j = \pm 3/2$

Confine single hole to a lithographically defined quantum dot. Single Spin Readout

Splitting due to strain and Confinement

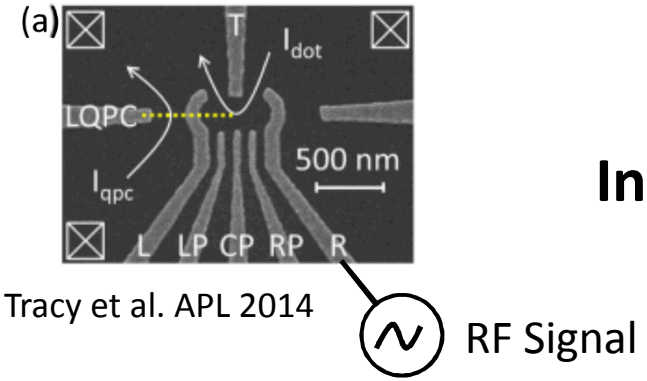
Band Structure:



Moriya et al. PRL (2014)

Control Spin through Electric Dipole Spin Resonance by applying RF signal to a confinement gate.

Concept from GaAs Device



Tracy et al. APL 2014

Interesting Topological, Spin and Qubit Physics

Conclusion

- Single electron and nuclear readout
- Coherent single electron control with ESR
- Coherent single nuclear control with NMR
- New Directions
  - Ultra-sensitive Ensemble ESR for material characterization in the small spin limit
  - New Material System: Strained Ge Quantum Wells
    - Single hole spin control