Exceptional service in the national interest

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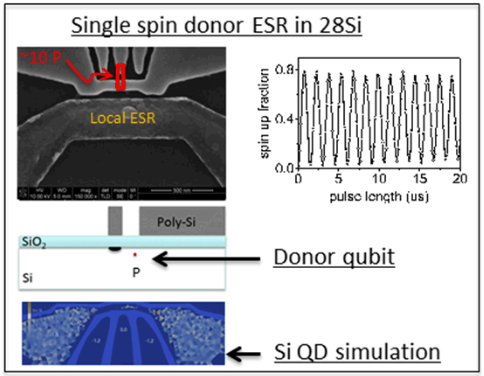
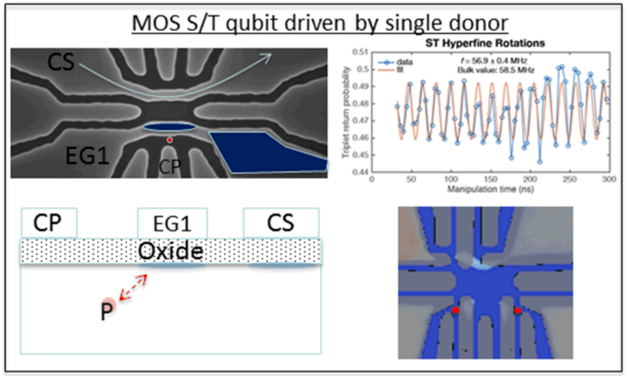
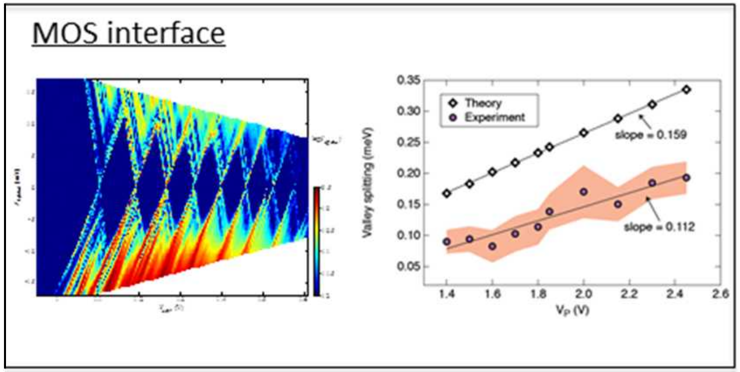
Sandia National Laboratories







Fabrication of MOS based qubits

Malcolm Carroll & **QIST team**

Sandia National Labs, Albuquerque, NM 87185

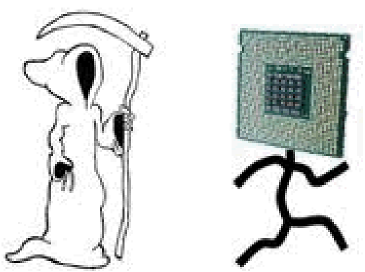
May 31, 2016

Outline

- Introduction to qubits & sources of infidelity
- Fabrication steps
- MOS nanostructures and qubits
- Special donor fabrication techniques
- Summary

Motivations for silicon quantum computing

- End of Moore's law & special purpose speed-ups (e.g., quantum simulation, search)
- Qubits decohere in short times leading to errors (T2)
- Require error correction (QEC)
- Higher fidelity qubit requires less QEC
- Silicon offers promise of realizing higher fidelity & less QEC



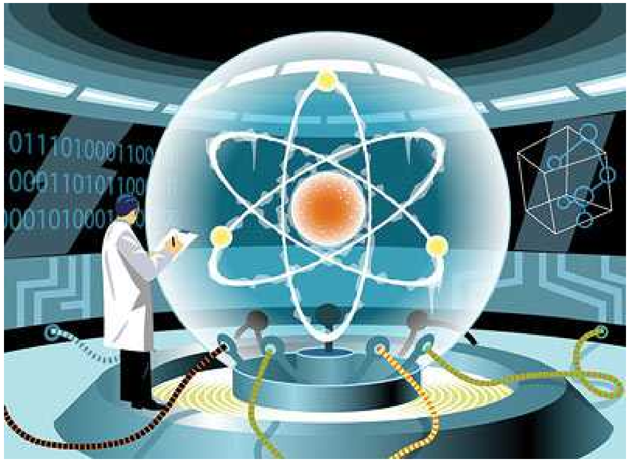
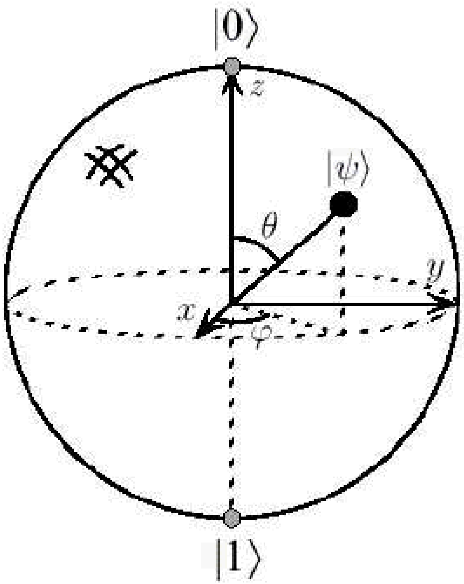


Image from Economist

Companies investing in QC

1. IBM
2. Google
3. Microsoft
4. Intel
5. Lockheed Martin
6. D-Wave
7. … and others including start-ups

Introduction to qubits and single qubit gates



Bit

Identity: x → [ ] → x

IN	OUT
0	0
1	1

NOT: x → [¬] → $x \oplus 1$

IN	OUT
0	1
1	0

Qubit

NOT

$|0\rangle \rightarrow |1\rangle$

$|1\rangle \rightarrow |0\rangle$

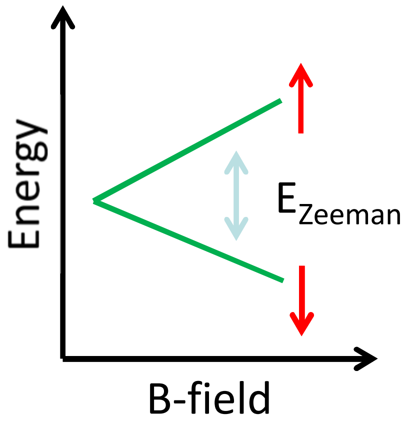
H

$|0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$

$|1\rangle \rightarrow (|1\rangle - |0\rangle)/\sqrt{2}$

- The QC information is described with a | 0 > and | 1 > basis
- A quantum bit can be any system that has two energy levels
  - Electron spin, excited states of an ion or left/right position of a charge in a molecule
- A non-classical feature of two-level systems is superposition states
- QC compute advantage is more related to the utility of non-classical correlations due to entanglement of these qubits (beyond scope of this talk)

An example two level system: single spin qubits

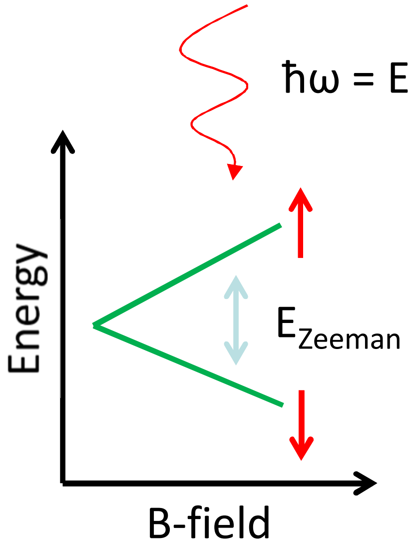


Up spin

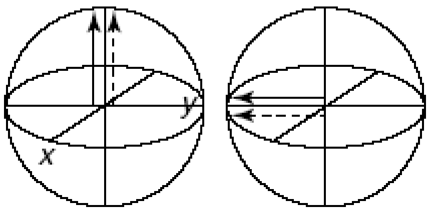
Down spin

- Electron or nuclear spins used for qubits in Si
- Spins can be very decoupled from environment – good qubit
- ESR is a good example
  - electron spin processes in static Bz field
  - Microwaves applied to rotate between down to up (X-axis)
- Errors caused by non-idealities like stray magnetic dipoles

Single spin qubits



90° X
Rotation



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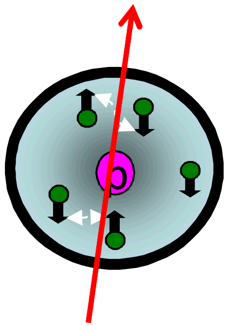
Decoherence (error) in single spin qubits

Electron spin

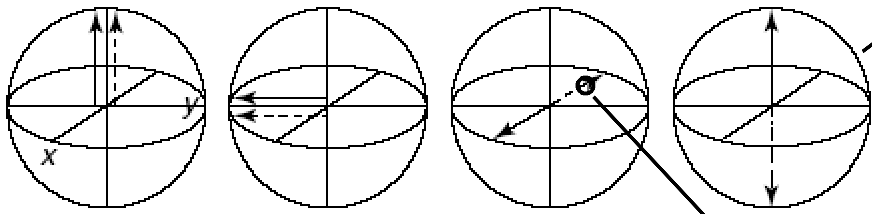


Nuclear spins in crystal
Source of error

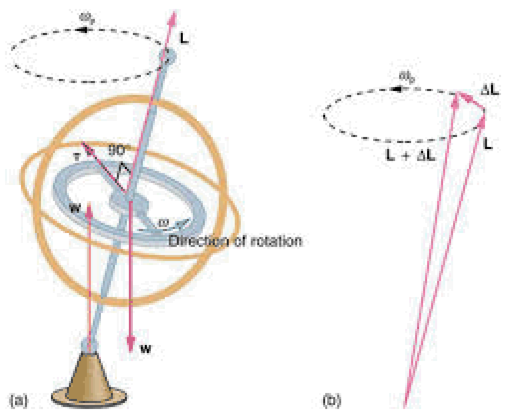
90° X
Rotation

90° Rotation

Spin up/down result "randomized" due to decoherence



Dashed spin evolves slower due to different local bath



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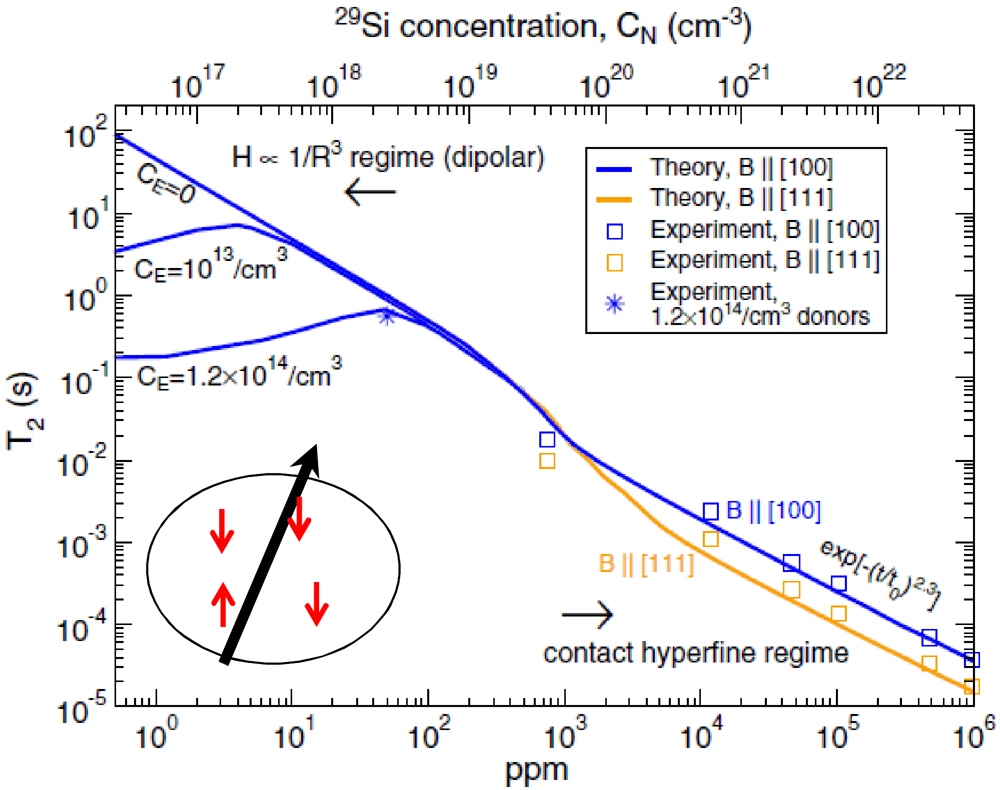
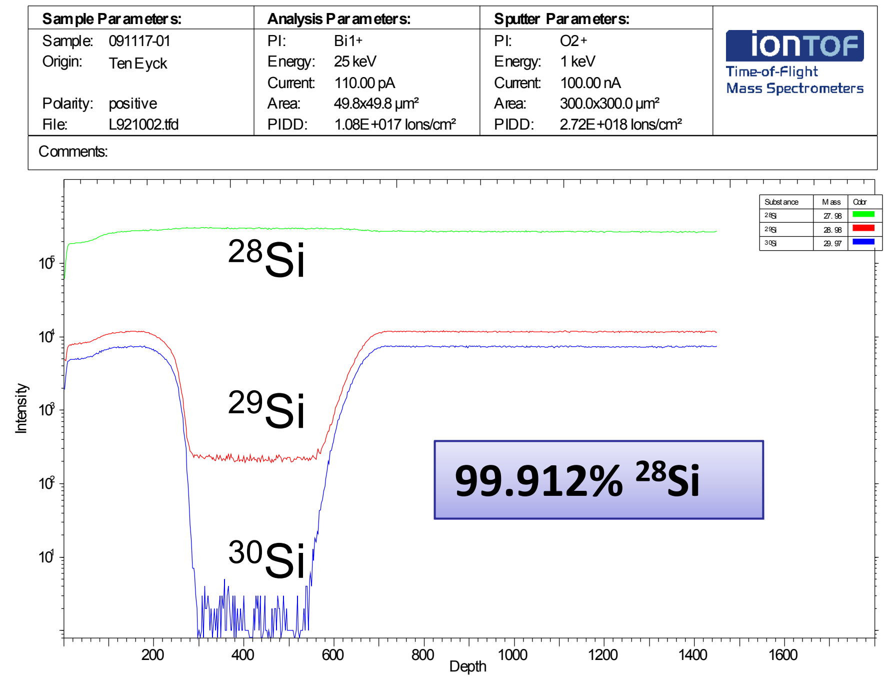
Motivations for **silicon** quantum computing

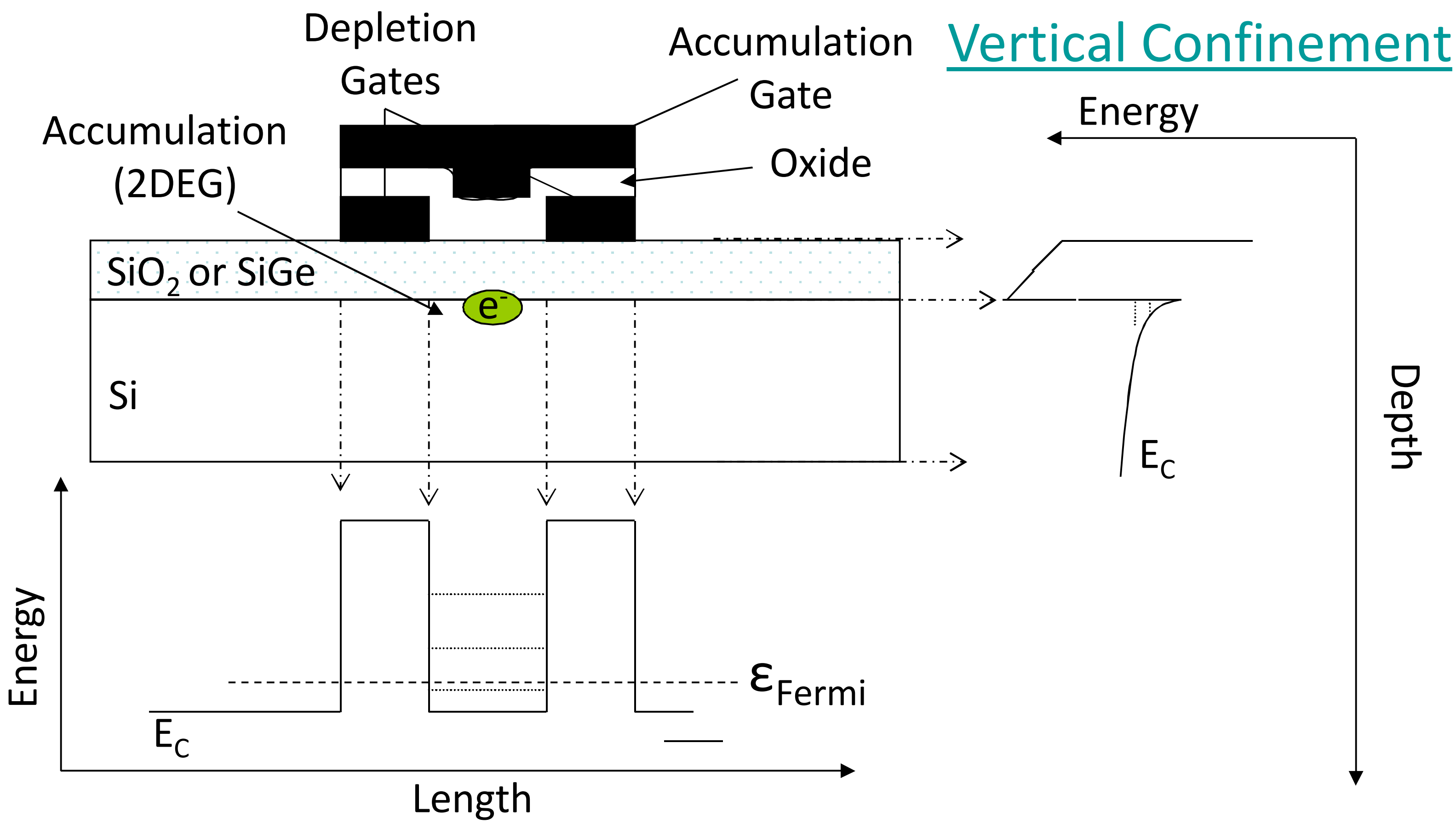




Witzel et al., PRL 105, 187602 (2010)
& PRB 86 035452 (2012)

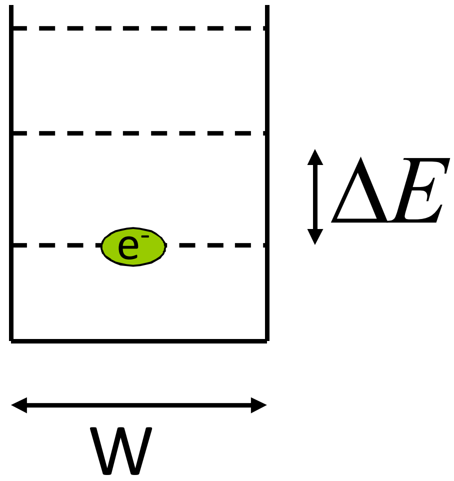
- Silicon appealing because it can be enriched to be a “magnetic vacuum” & purified of other spins
- Very long decoherence times can be achieved – no enrichment is still not bad
- Qubits error probability still much greater than transistor errors
- Error correction circuitry is expected to compensate (e.g. majority vote). Lots of extra circuitry.
- Silicon offers promise of **realizing** very high fidelity, less error correction and Si foundry compatible

Enhancement mode quantum dots to confine spin qubits



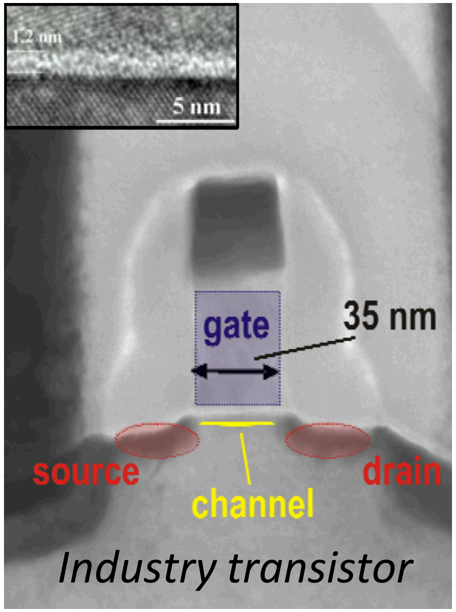
- Modified MISFET design can be used to form quantum dots
- SiGe/sSi and MOS have both successfully been used for single QD qubits

Quantum dot potentials for single electrons



$$\Delta E = \frac{\hbar^2}{2m^*} k^2$$

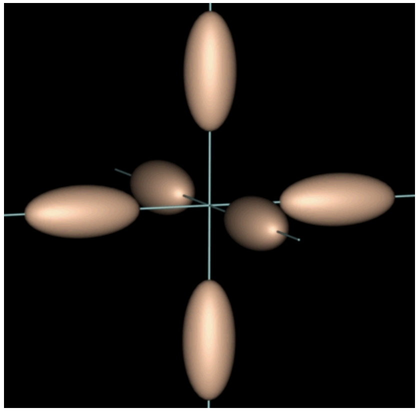
$$k = \pm \frac{2\pi}{W_{Well}} n$$

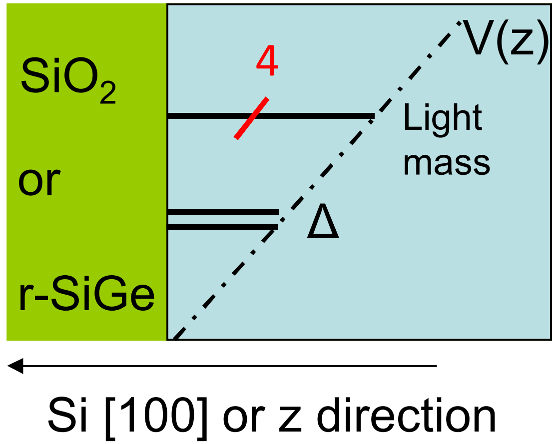


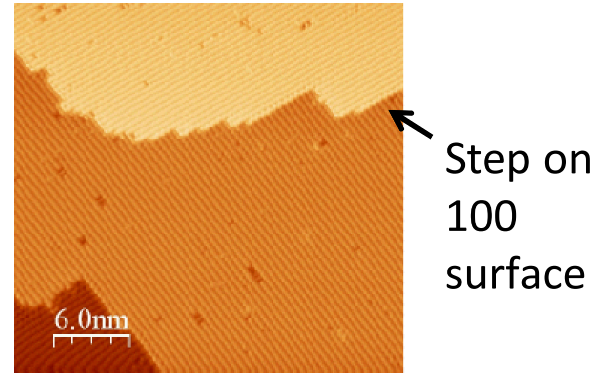
- Qubit requires isolation of two states of the electron
  - Examples: ground and excited state OR spin up/down
- Energy level separation is dependent on size of confining potential & effective mass in quantum dots
- Aim for spacings ~ 5-10*kT (rule of thumb)
- Energy spacings for 40-50 nm well are order 5 meV [Si]

  => Cryogenic temperatures

Conduction band valleys and valley splitting

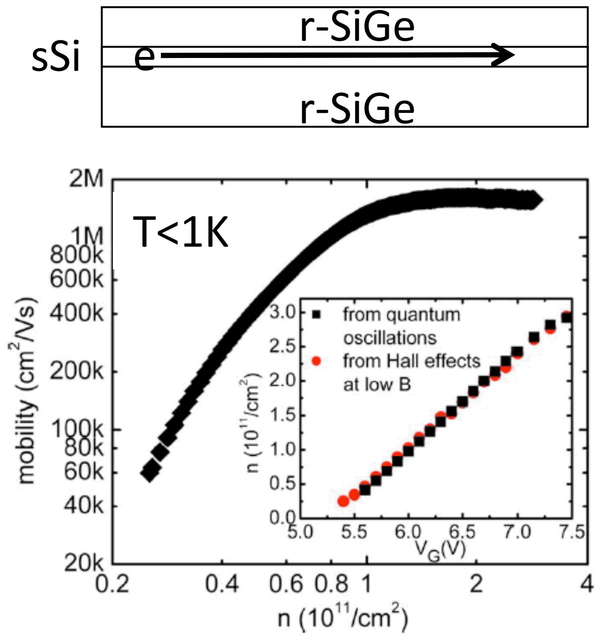




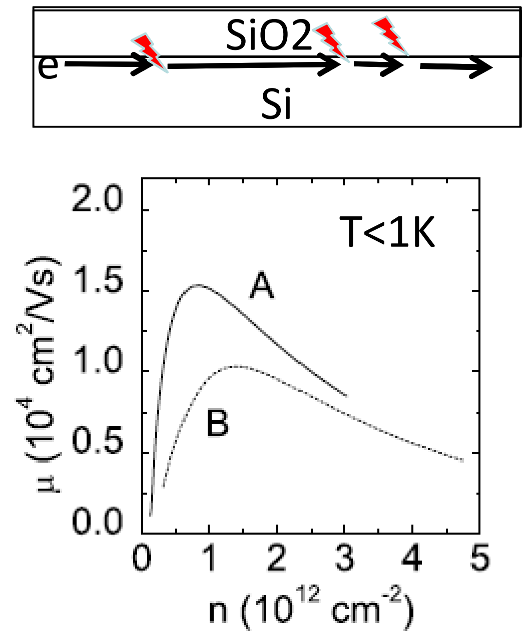


- Conduction band degeneracy is split by several mechanisms
- Splitting of last two levels is often relatively small, ~0-0.5 meV [really cold T<1K]
- A lot of recent work to understand valley splitting because 0 – 0.1 meV is marginal
- A single atomic step edge sufficient to significantly suppress valley splitting in QD [Friesen et al., PRB 81 115324 (2010)]
- Some key observations:
  - Interface sharpness, alloy disorder, miscut and step bunching in epitaxy important (atomic steps)
  - Sharpness of interface, roughness and correlation length important in MOS (dissimilar interface)
  - Vertical field increases valley splitting

Starting material



Lu et al., APL 94 182102 (2009)

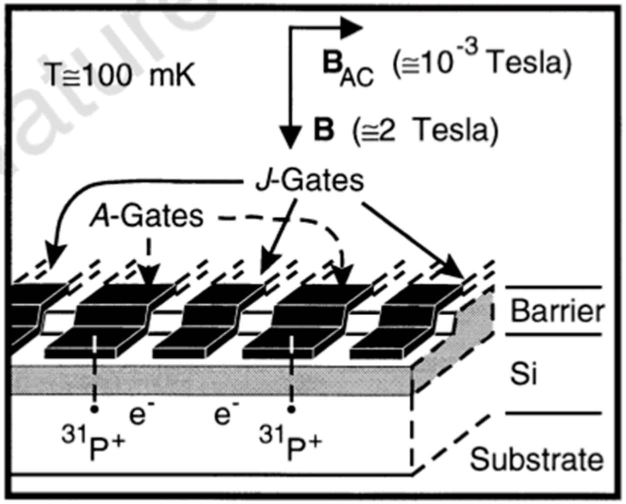


Tracy et al., PRB 79 235307 (2009)

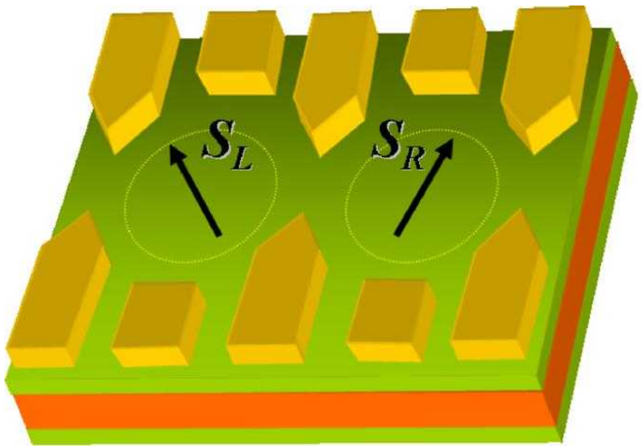
- Mobility is a direct measure of electron scattering along an interface.
- It is often used as a qualitative measure of the "disorder" potential at the interface
- GaAs has been a model system with > 1M mobilities possible, but background nuclear isotopes shorten T2
- Ballistic lengths are order of 10s nm in MOS vs. 100s nm in SiGe/sSi
- Much of the Si quantum dot community favors SiGe/sSi epitaxial heterostructures and have had a great deal of success with making QDs
- Nevertheless, this talk will center on MOS QDs and donor qubits… why?

- Donors have exceptional fidelities
- Good single MOS QDs demonstrated despite doubts
- Donor implant and MOS QDs compatible w/ foundry
- Rest of talk will be about D, QD qubit fab & coupling
  - A 1.5 nm object coupled to a ~50 nm object
- Our work at SNL has found advantages to this combo

Single atom architecture (e.g., silicon, diamond)



[1] B. E. Kane, "A silicon-based nuclear spin quantum computer," Nature, vol. 393, no. 6681, pp. 133–137, 1998.



Quantum dot architecture (e.g., GaAs, SiGe/sSi, MOS)

Nuclear spin ½ (CQC2T, Nat. Nano. 2014):

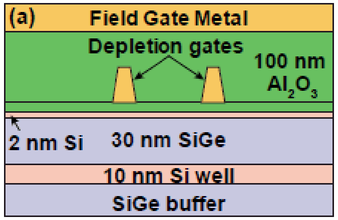
$T_2^* = 600$ ms

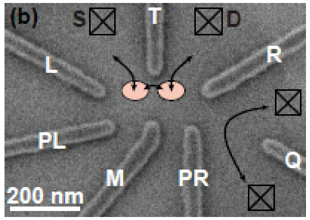
$T_{2,\,CPMG} = 36.5$ s

$F_{prep/readout} = 99.995\%$

$F_{control} = 99.99\%$

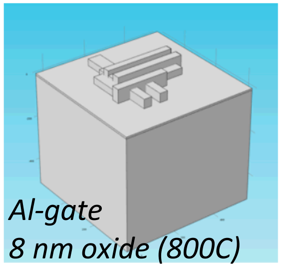
Observations about valley splitting in Si QDs

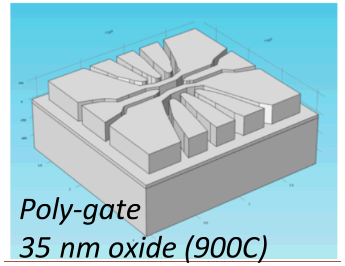




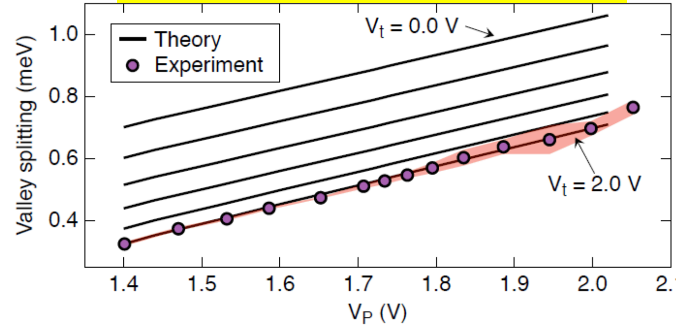
	$\Delta\mu_1$ (meV)		α (eV/V)		$\Delta E_{S\text{-}T}$ (meV)	
Device	left	right	L(PL)	R(PR)	(2,0)	(0,2)
A	7.9	7.4	0.052	0.058	~0.05	~0.05
B	8.0	6.2	0.052	0.066	>0.23	<0.05
C	7.4	7.0	0.045	0.059	—	0.13
Simulation	6.4	5.4	0.049	0.063	≤0.50	

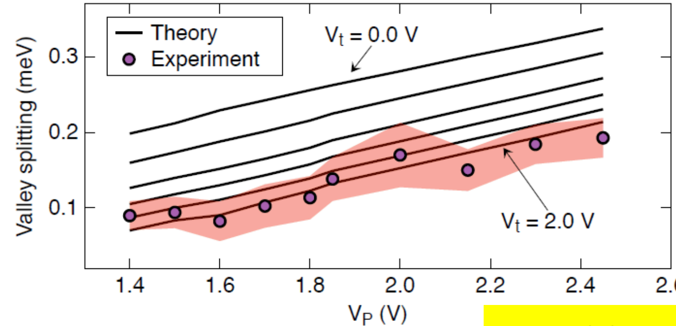
Borselli et al., APL 99 063109 (2011)





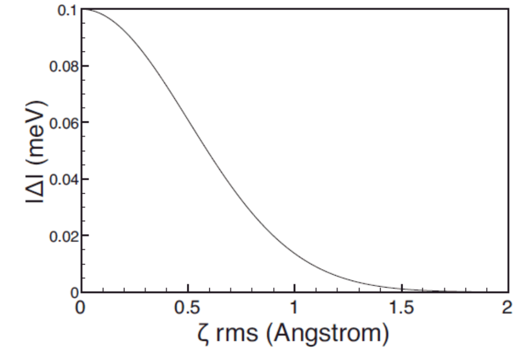
Dzurak group et al., Nature comm.





Gamble

- Valley splitting in SiGe/sSi QDs is frequently low
- Valley splitting in two different MOS fabs appear to produce similar and non-zero results
- MOS has wide range of vertical field available to tune valley splitting
- Theory indicates that interface roughness and correlation length will play a role in MOS

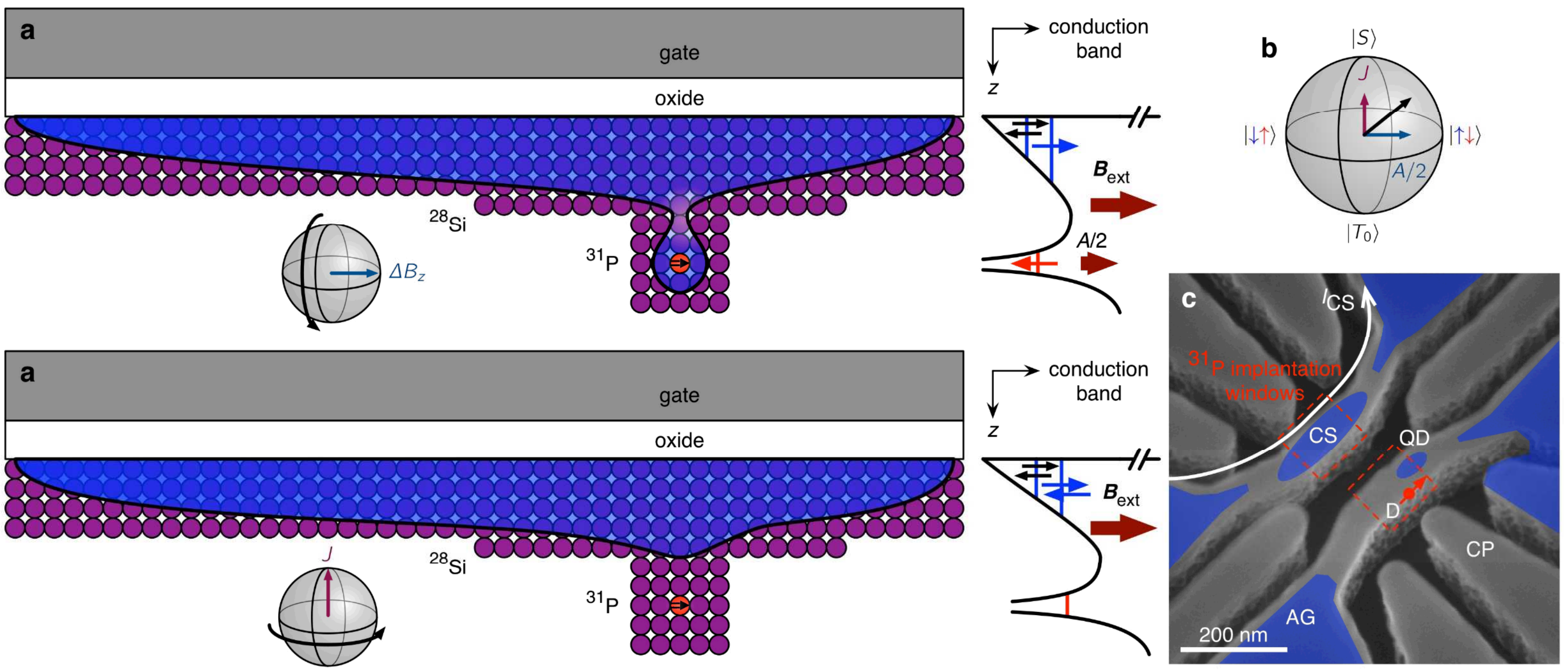


[D. Culcer *et al.* PRB **82**, 205315 (2010)]

Outline

- Introduction to qubits & sources of infidelity
- Fabrication steps
- MOS nanostructures and qubits
- Special donor fabrication techniques
- Summary

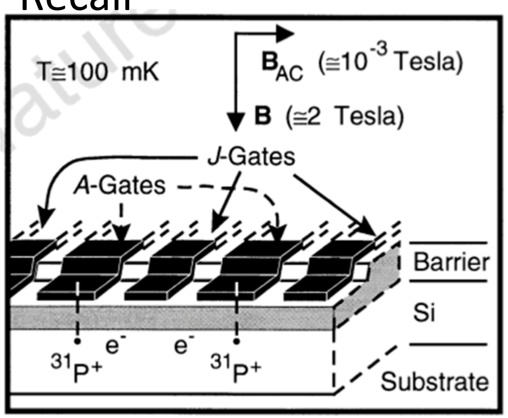
Where we are going



Harvey-Collard et al. arXiv:1512.01606

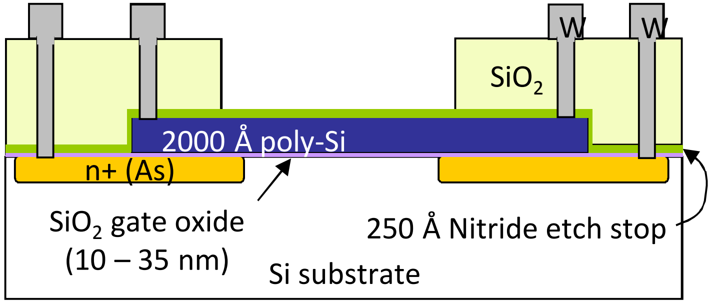
- Donor qubits
- Couple qubits to electron qubits at interface
- Interface is where the qubit coupling occurs

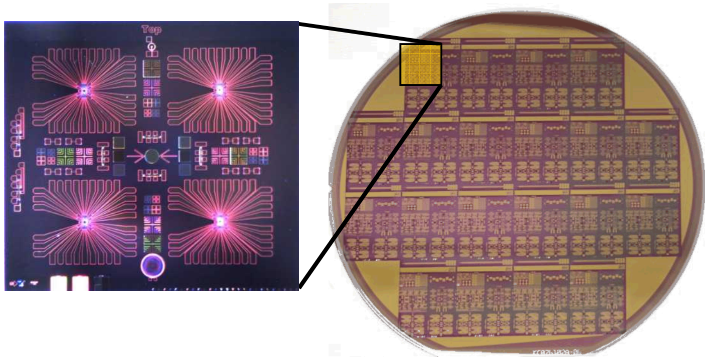
Recall



Nanostructure fabrication at Sandia National Labs

Front-end in silicon fab



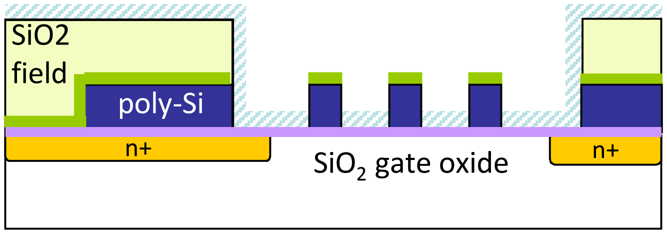


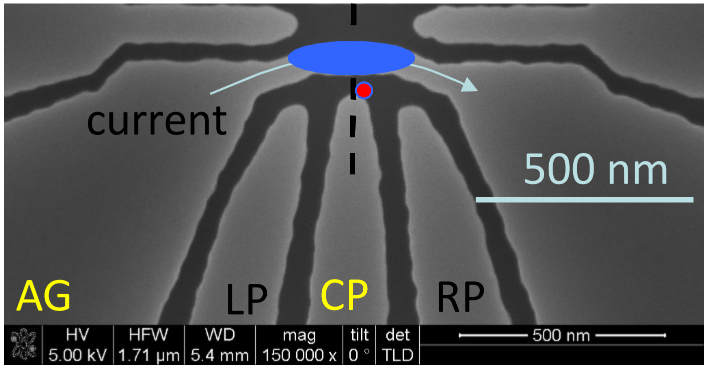
Goal: Use Poly-Si etched structures to produce donor-based qubits

Rationale:

- Self aligned implant
- Foundry like processing
- Potential long term benefits for charge stability

Back-end nanolithography





Nordberg et al., PRB 80 115331 (2009)
Harvey-Collard et al. arXiv:1512.01606
Tracy et al. APL, 108 063101 (2016)

Process Flow

- Silicon Wafer
- Gate Oxide Grown
- Source-Drain Lines Implanted
- Poly-silicon Deposited, Doped, and Patterned
- Contacts and Vias Formed

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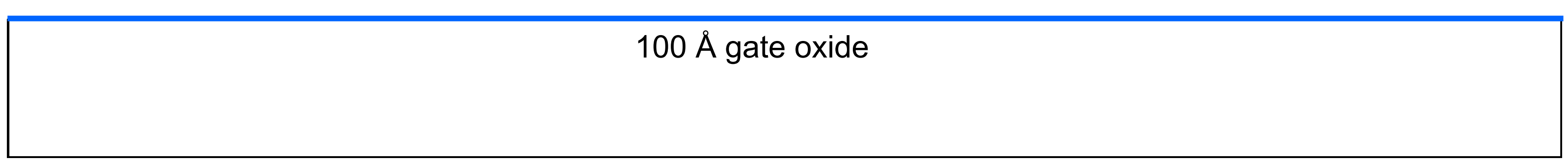
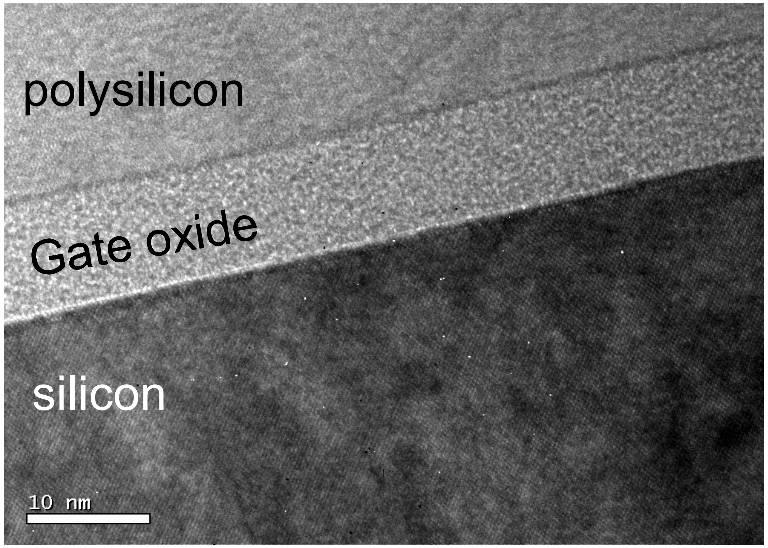
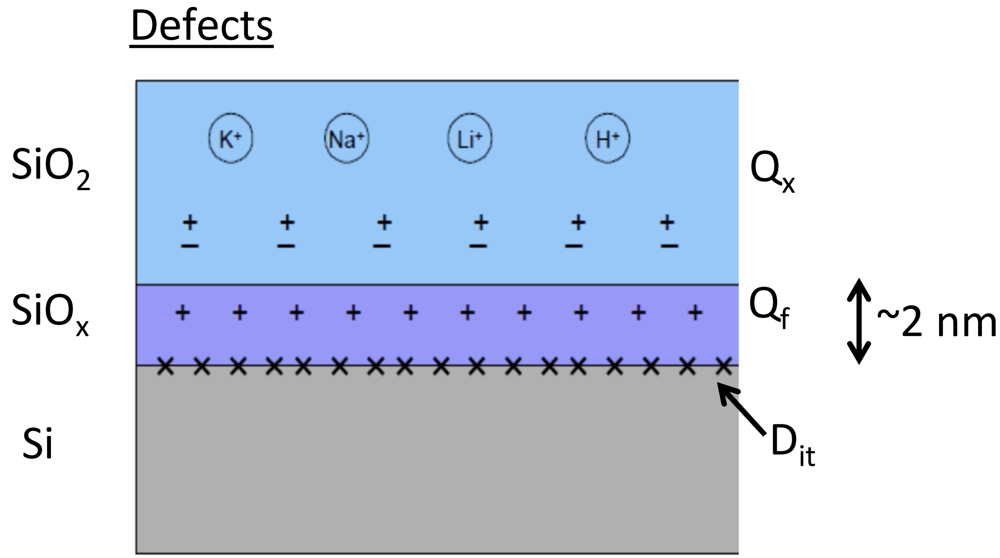
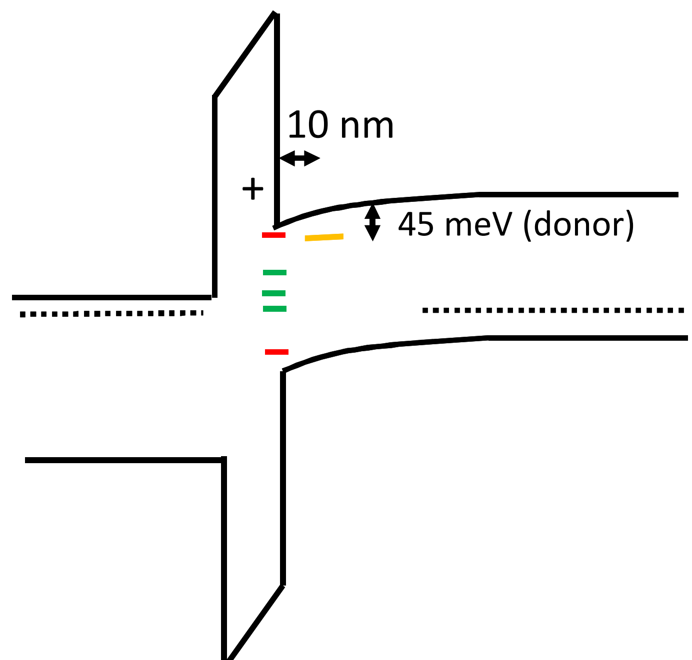


The MOS interface







Room temperature picture

- D_{it} Interface traps and border traps within a “tunneling” distance of interface (Pb)
  - electron traps for n-channel – negative charge
  - paramagnetic
- Q_f Fixed charge deeper in oxide (perhaps E’)
  - hole traps – positive charge
- Qx shouldn’t be a dominant factor for clean process

Low temperature picture

- Unclear picture for interface traps close to band edge
  - These will be the dynamic ones at low T
- Defects can be paramagnetic but probably weak effect on decoherence- supported by qubit experiments

Annealing oxide defects

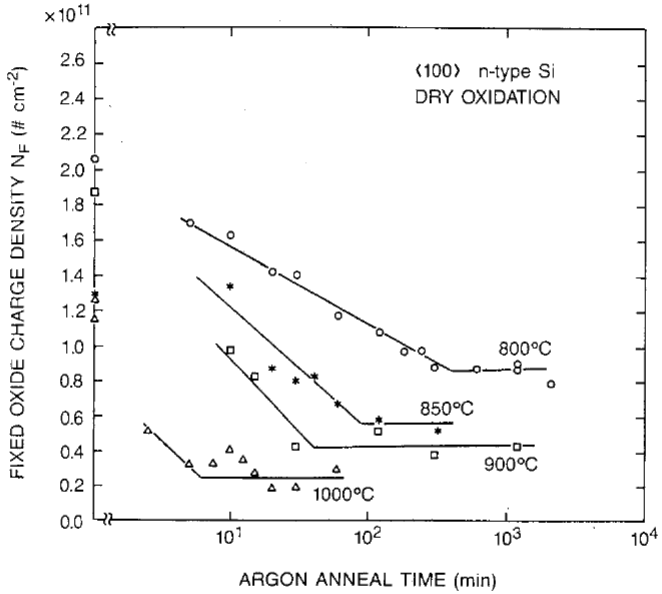
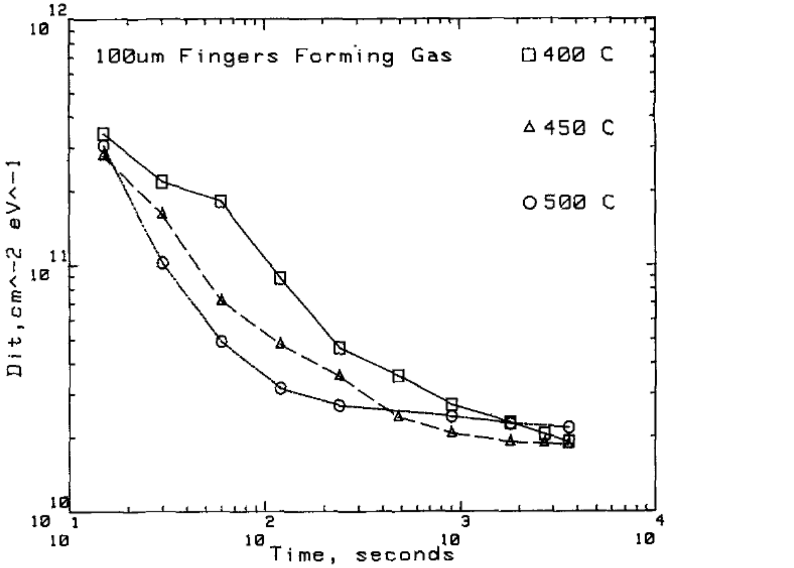


Fig. 2. Temperature-time behavior of argon annealed N_f

Akiwande et al., JECS 134 10 680 (1987)

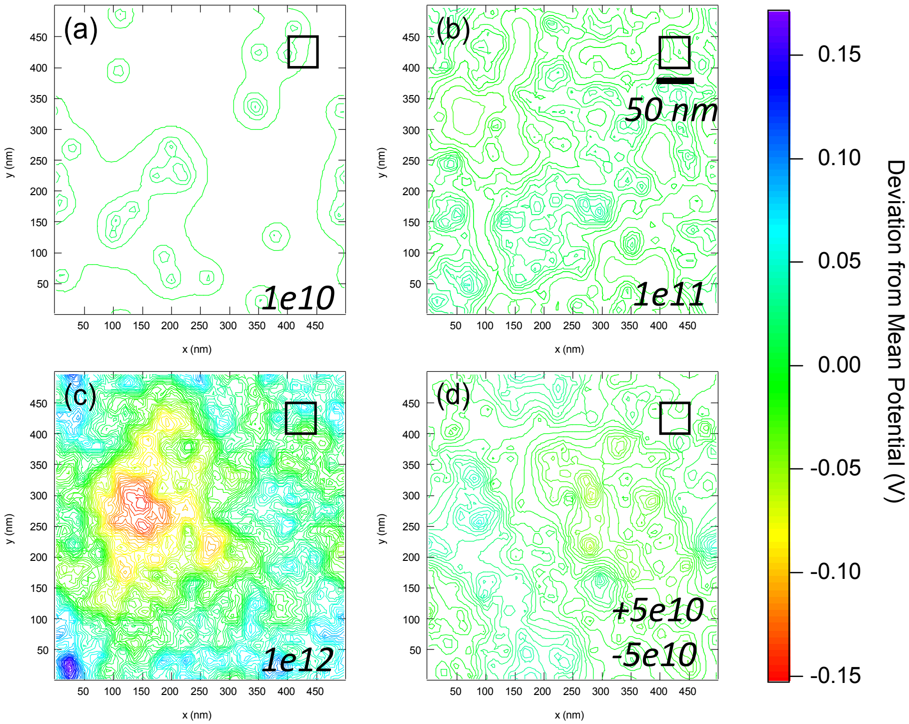


Fishbein et al., JECS 134 3 674 (1987)

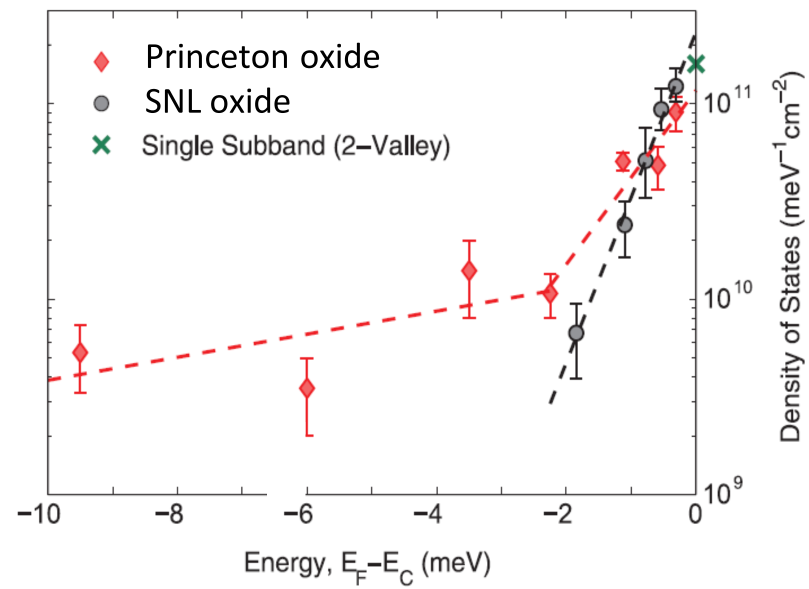
- High temperature anneal reduces the fixed charge
- Forming gas anneal reduces midgap states
  - Forming gas done after all processing
- Defects concentrations low enough to form single electron occupancy QDs
- N_{trap} ~ $4x10^{10}$ cm^{-2} corresponds to <s_{defect}> ~ 50 nm

Trap states due to defects & intrinsic band edge states

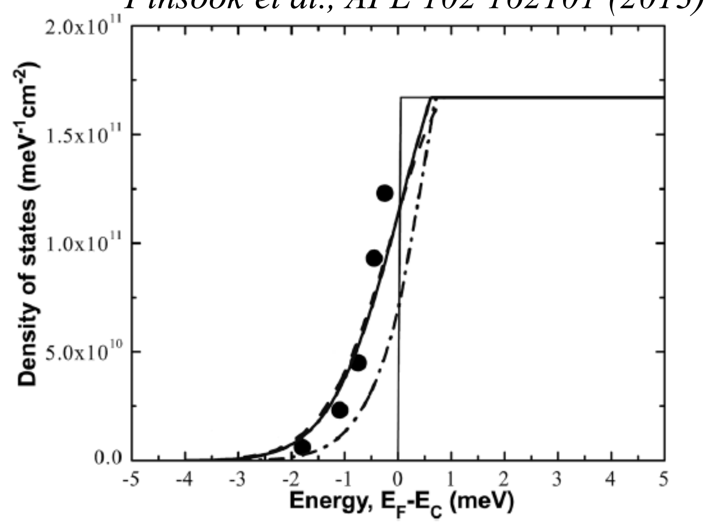
Nordberg et al., PRB 80 115331 (2009)



Jock et al., APL 100 023503 (2012)



Pinsook et al., APL 102 162101 (2013)



- Calculations predict "rough" potential with shallow traps
- Low densities: 0-10 meV or ~0-200 mV on electrode (35 nm t_{ox})
- Gate layouts of length scale of same order of defect potential might be able to compensate
  - State-of-the-art single QDs in MOS have been demonstrated
- Depth of trap states in good oxides are consistent with intrinsic band edge [Pinsook]
- Note: mobility measurements don't always correlate with best shallow trap densities

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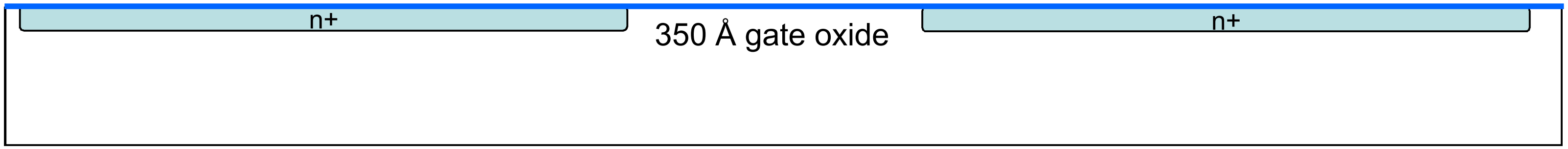

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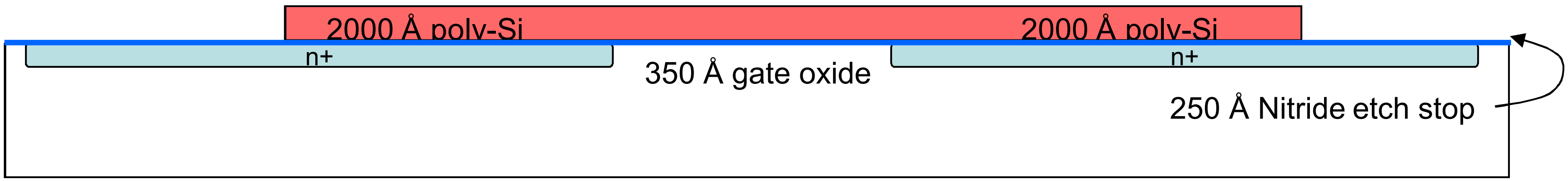

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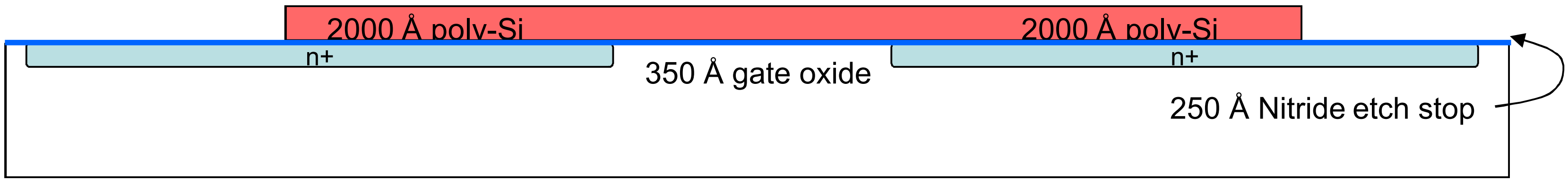
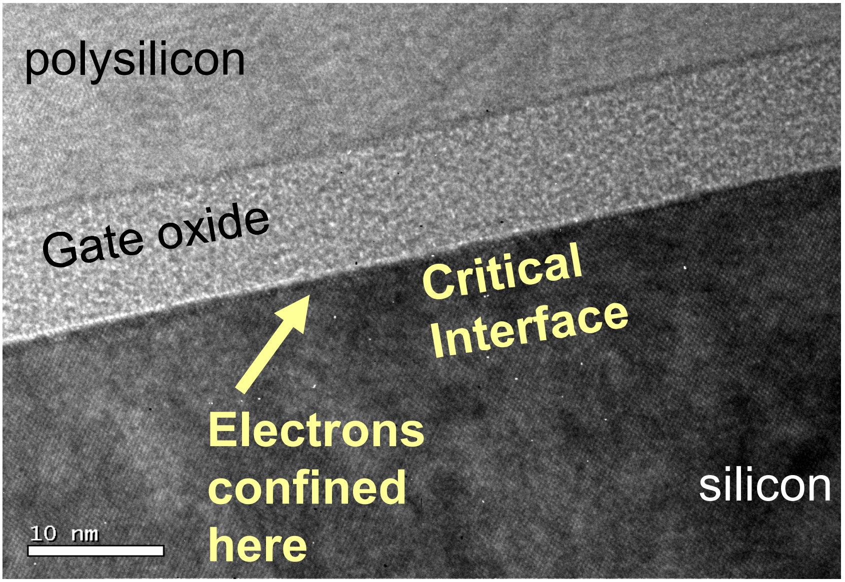
Motivations for polysilicon:

1. *Subtractive processing higher yield than additive "lift-off"*
2. *Self-aligned implant of single donors and QD location*
3. *Poly is good getter of impurities*



Representative interfaces



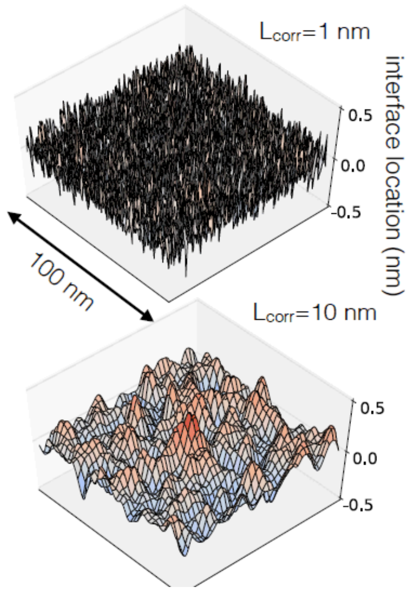
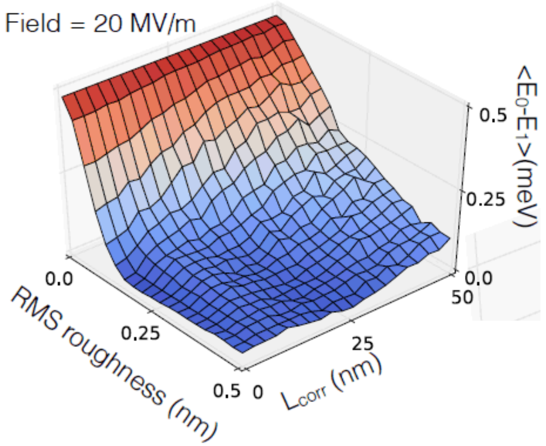


TABLE I
RMS AND CORRELATION LENGTH VALUES
OBTAINED FROM AFM MEASUREMENTS AND MOBILITY DATA

	AFM		Mobility	
Sample	Δ (Å)	Λ (Å)	Δ (Å)	Λ (Å)
S1	1.8	180	2.70	15.5
S2	1.8	180	2.70	15.5
S3	14.2	250	3.05	15.5

Pirovano EDL 21 1 (2000)

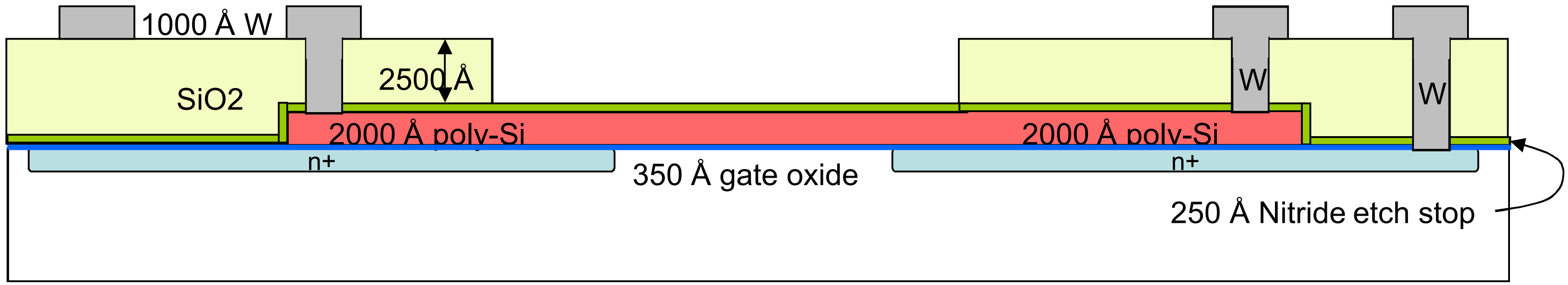
- MOS interface is usually very sharp
- Representative case: ~2 A RMS and 15A correlation length
- Reasonably large valley splittings predicted and observed



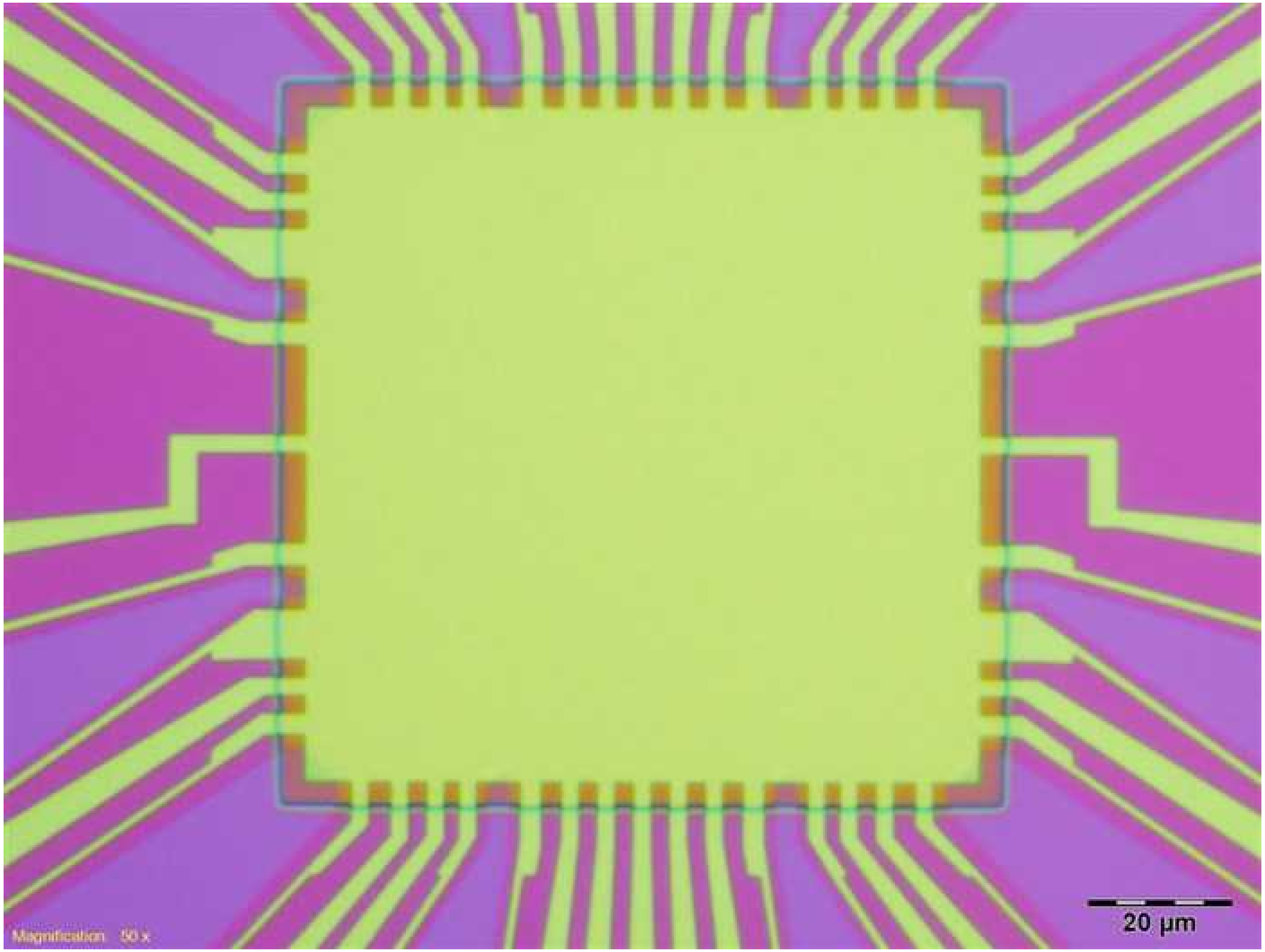
Gamble (SNL)

Process Flow

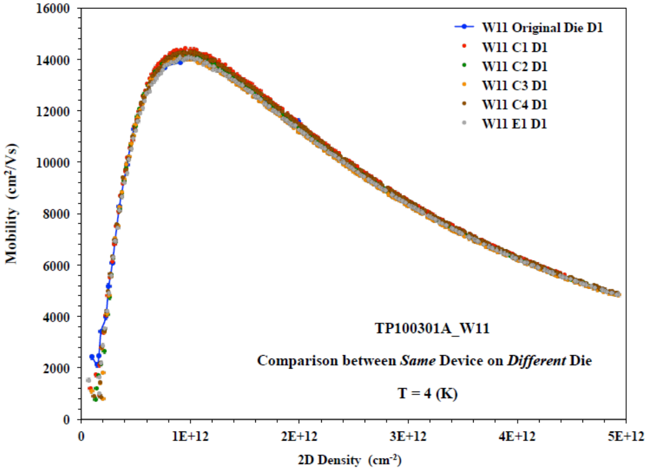
- Resistivity Silicon Wafer
- Gate Oxide Grown
- Source-Drain Lines Implanted
- Poly-silicon Deposited, Doped, and Patterned
- Contacts and Vias Formed

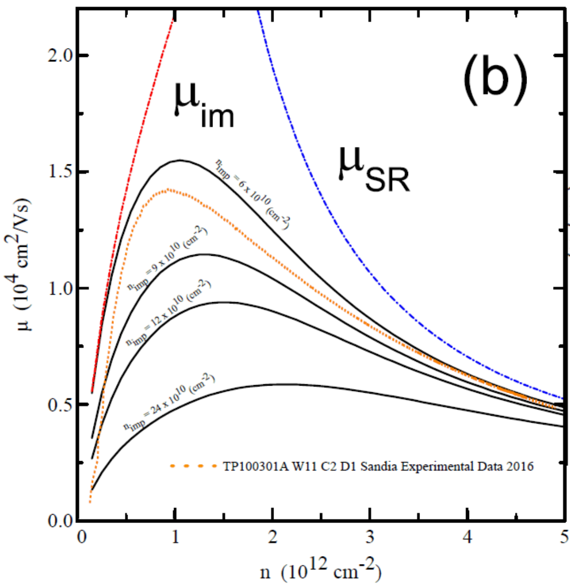


Incoming



Hall bar characterization of “starting material”

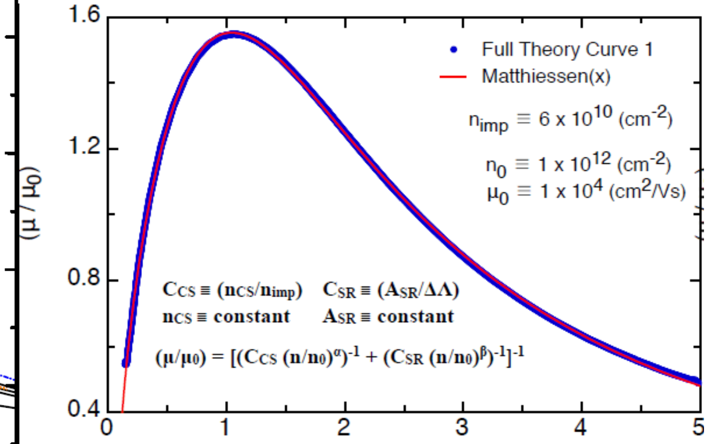




$\Delta \equiv$ average interface displacement = 1.9 Å

and

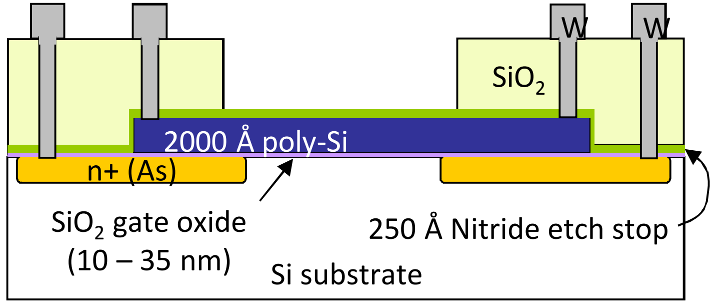
$\Lambda \equiv$ correlation length = 26 Å

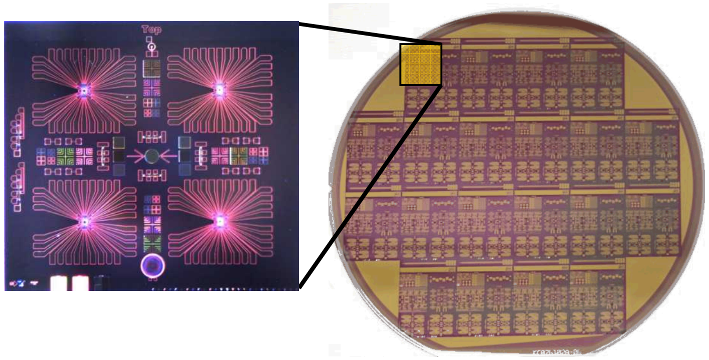


- Before nanostructure fabrication material is removed from Si foundry
- Low temperature thresholds and mobility are measured
- Impurity scattering density, fixed charge and interface roughness can be extracted
  - Two regimes – Mathiessen rule works relatively well
- Representative example shown above
- Mobilities might be suppressed because of nitride layer (H blocking layer)

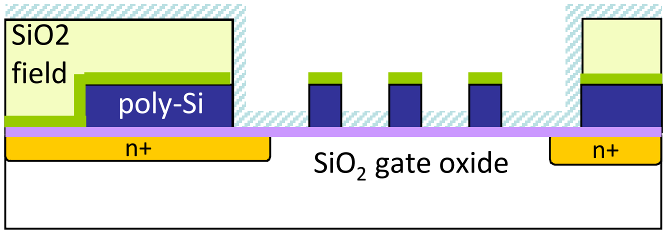
Nanostructure fabrication at Sandia National Labs

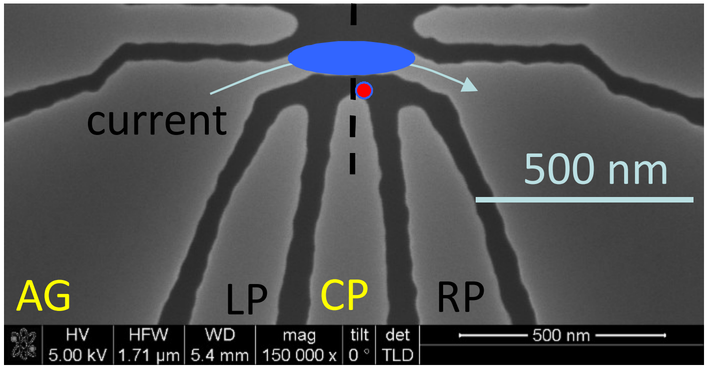
Front-end in silicon fab





Back-end nanolithography





Goal: Use Poly-Si etched structures to produce donor-based qubits

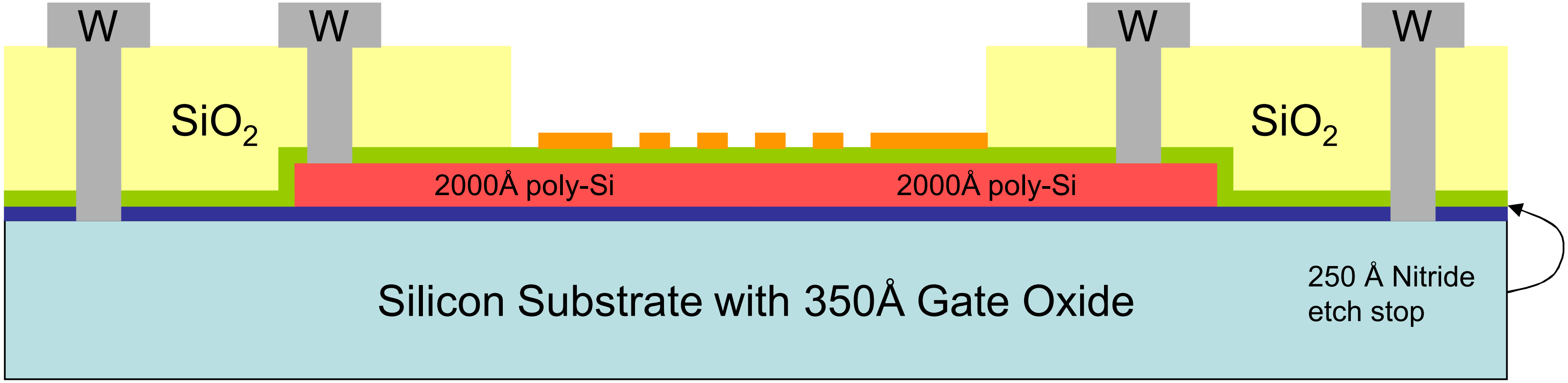
Rationale:

- Self aligned implant
- Foundry like processing
- Potential long term benefits for charge stability

Nordberg et al., PRB 80 115331 (2009)

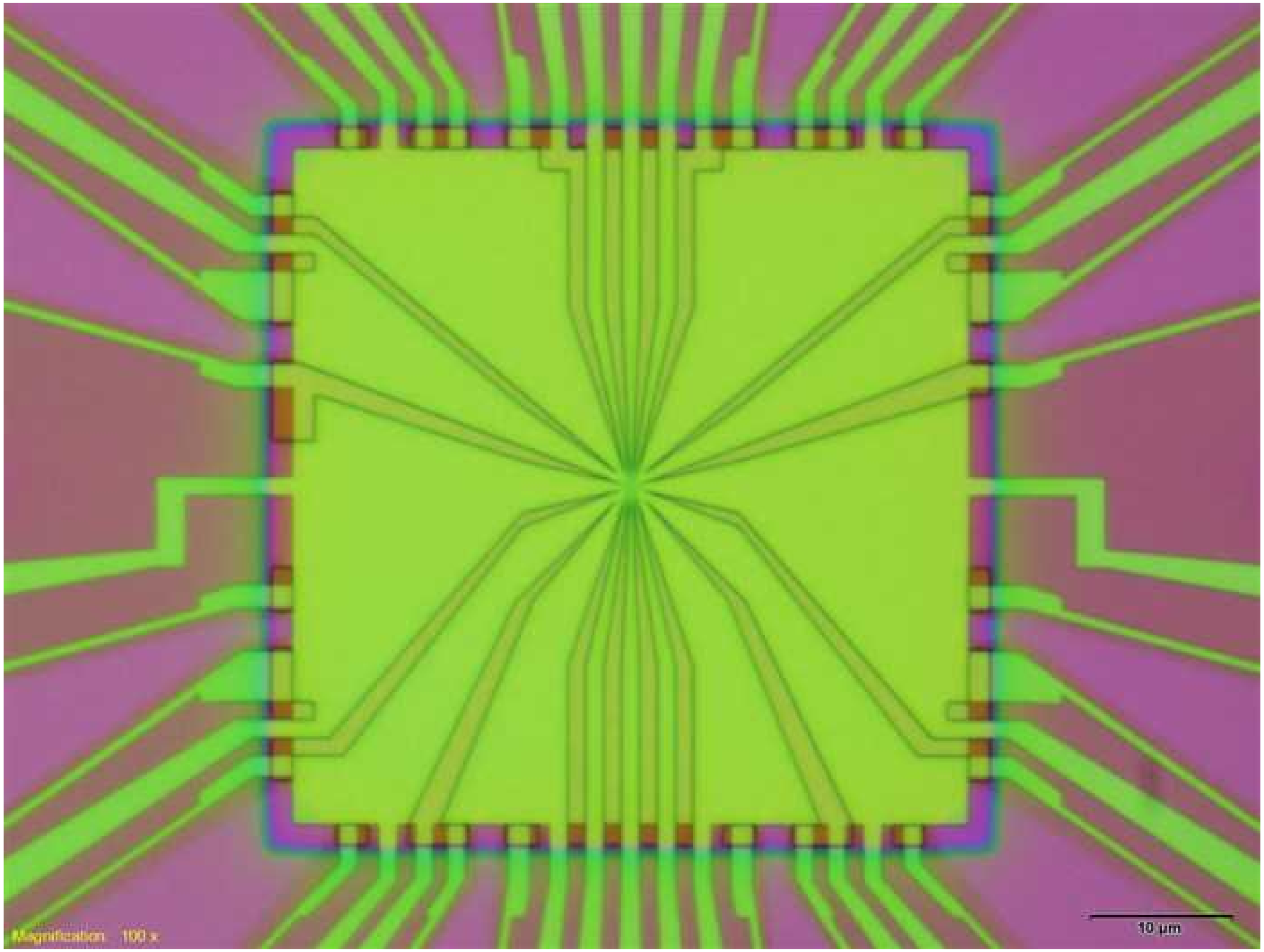
Tracy et al., APL 103 143115 (2013)

EBL Patterning

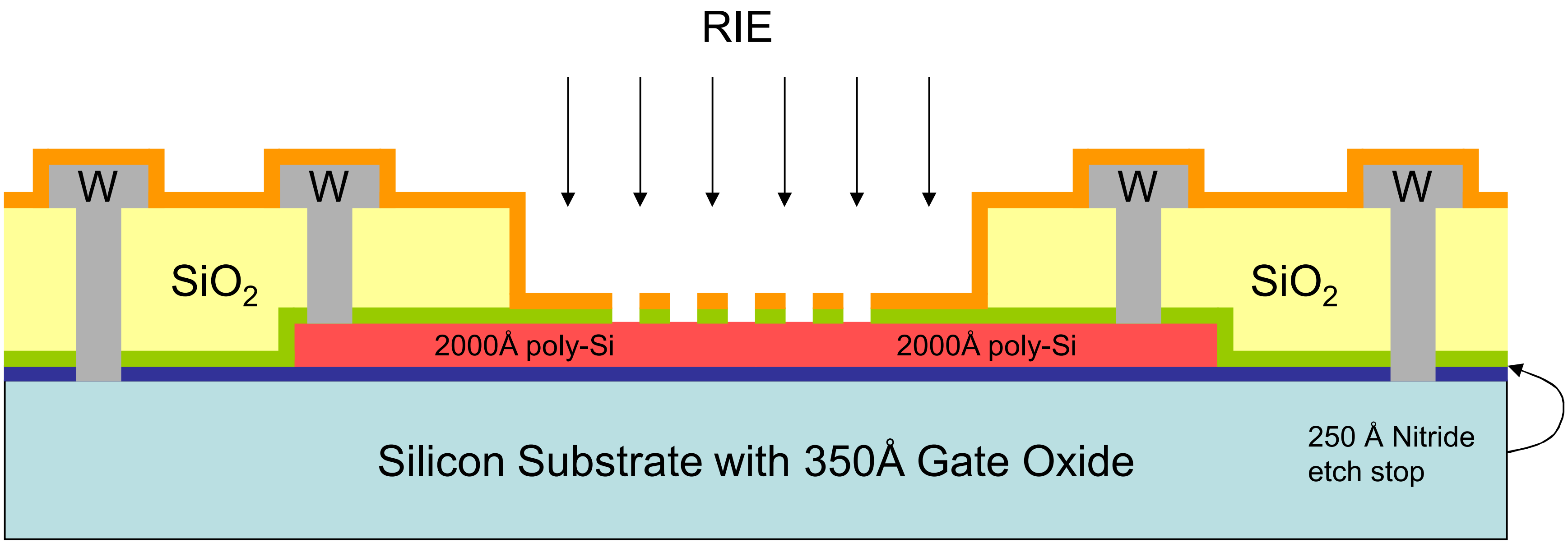


- EBL resist patterned to form one of the qubit structures
- This process flow is a little unusual because we remove wafers from foundry to do EBL
- Tungsten provides good contrast for EBL alignment to Si foundry stepper based litho

Pre HM & Poly-Si etch

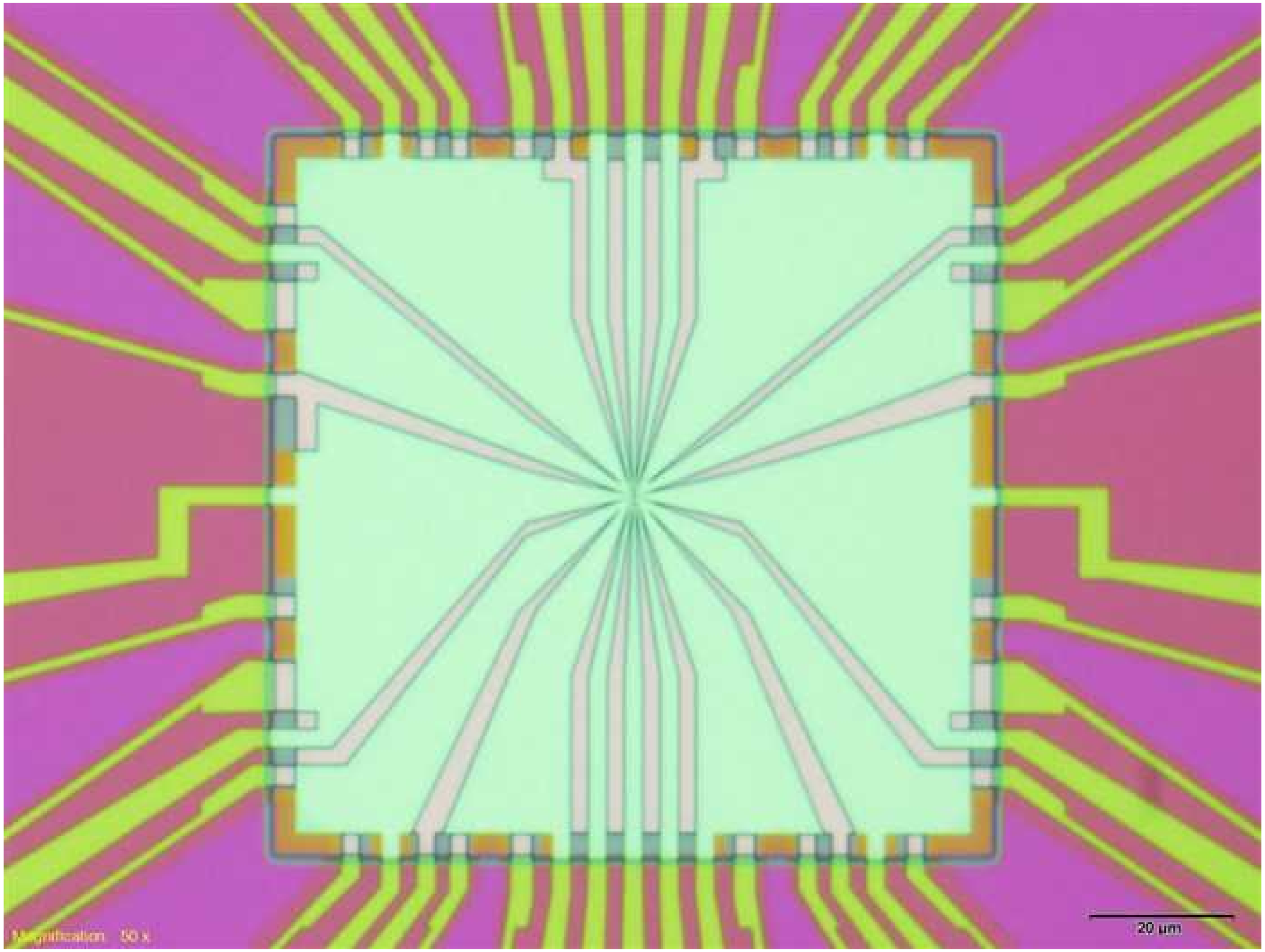


Hard Mask

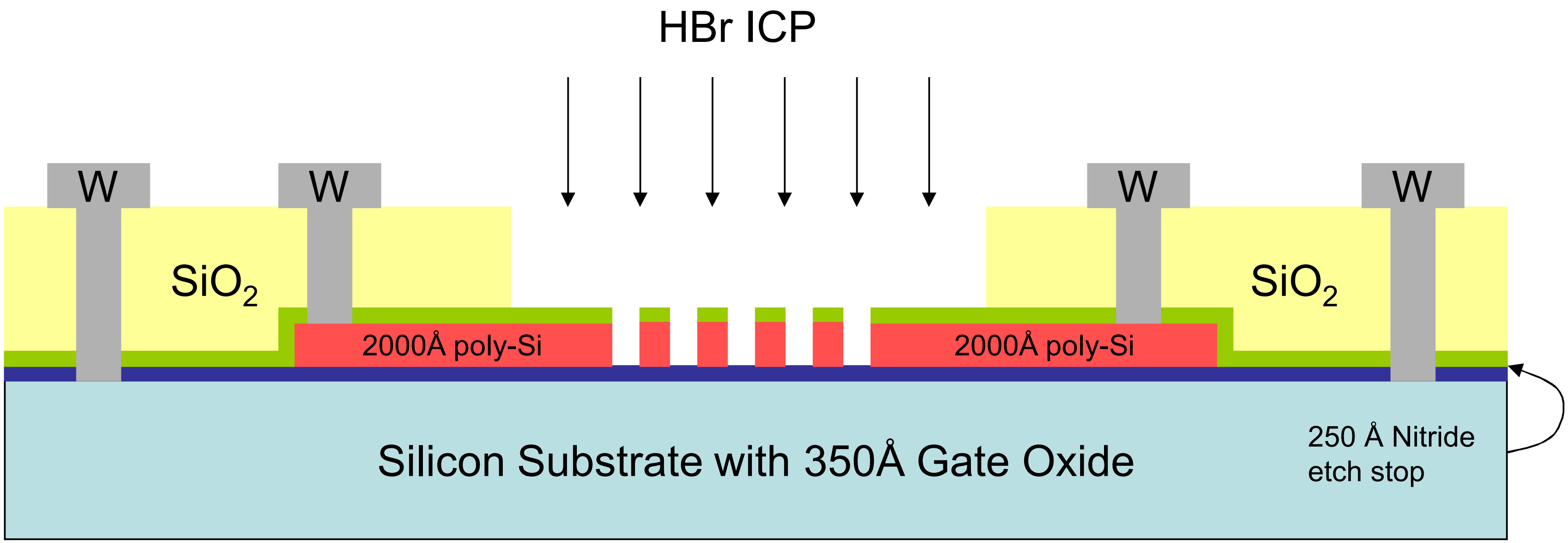


- CF_4/O_2 or Cl2/Ar used to etch dielectric hard mask down to poly-Si

Post HM & Poly-Si etch

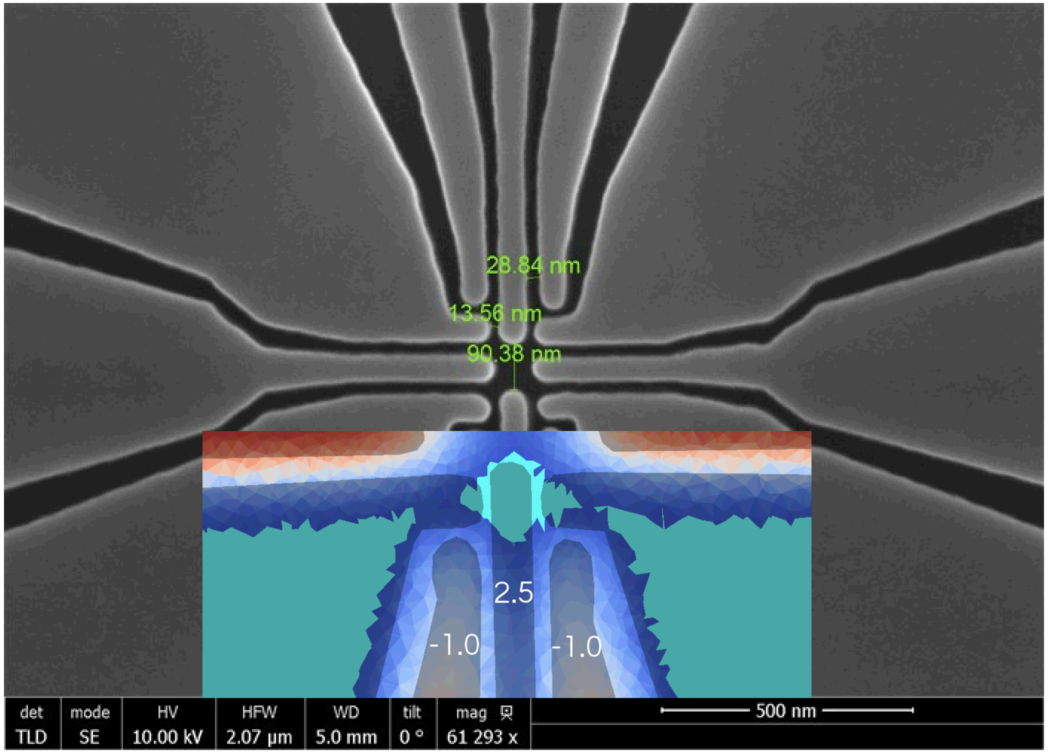


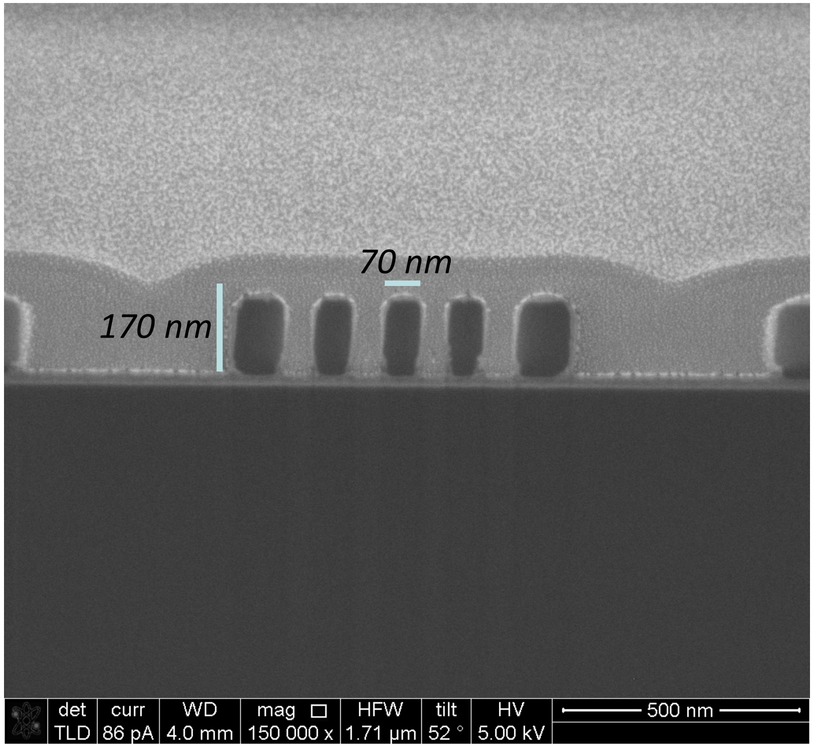
Poly Etch



- 15 mtorr of HBr/Ar (15/40), ICP ~ 300W w/ bias used to etch poly-Si down to gate oxide
- Selectivity is ~100:1 with etch rate of ~150 nm / min

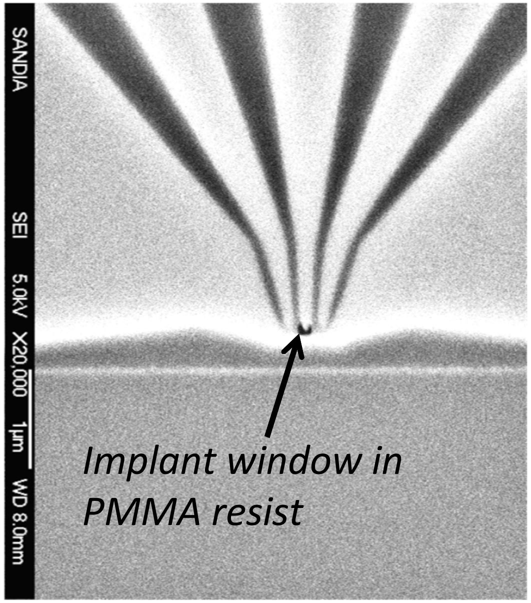
Post poly-Si etch



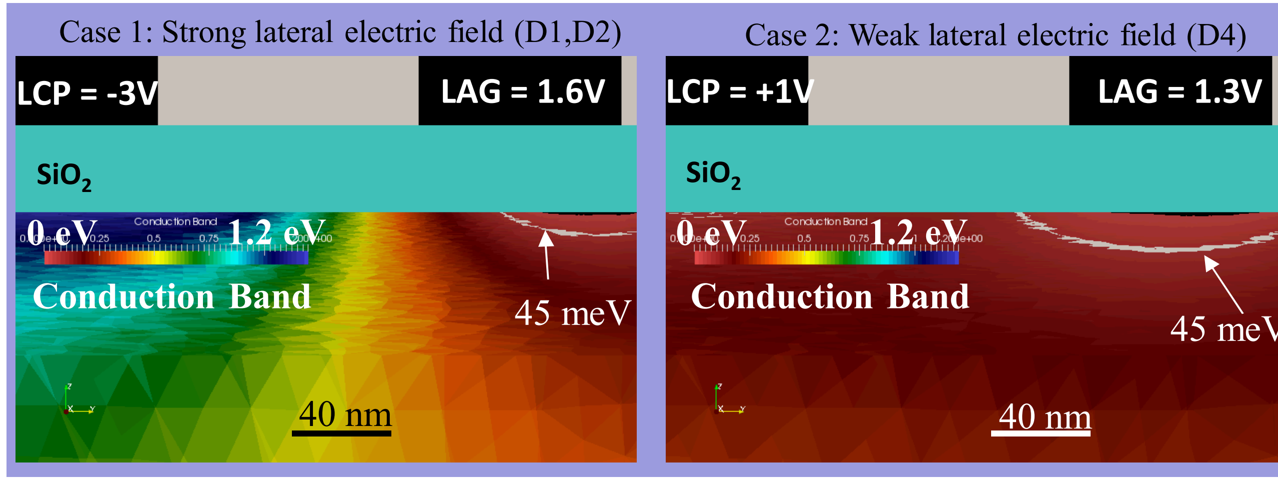


- Gaps range from ~15-30 nm in active region of left design
- These dimensions are of order or smaller than average spacing of charge defects
- Narrow trenches etched in to thick poly
  - Representative example: 170 nm tall and 70 nm wide
- Simulation predicts dot to form below tip of positive biased electrode

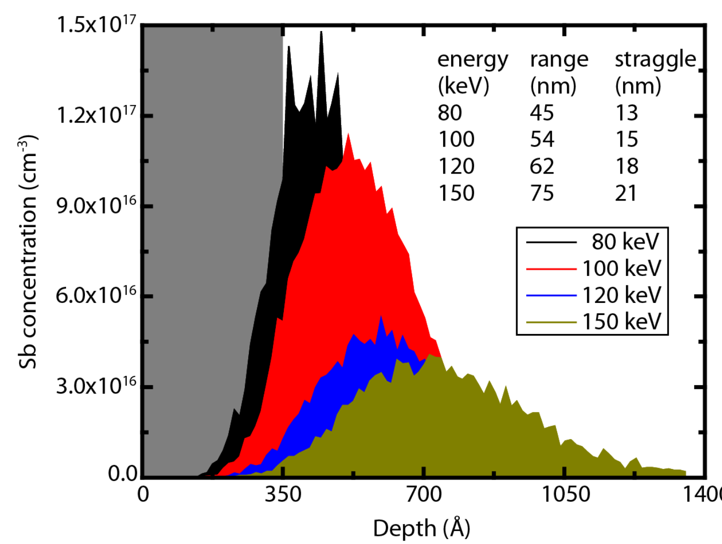
Self-aligned implant



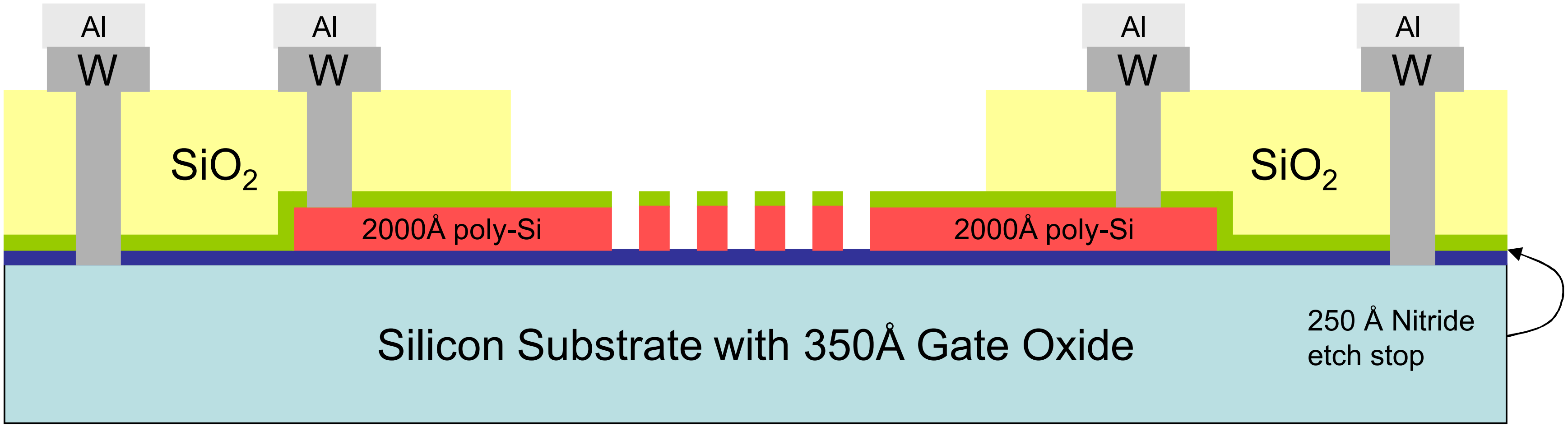
Donor ionization contours for different lateral fields



- Implant window formed with EBL
- Timed implant
- Contour of donor ionization is shallow
- Low energy and approximately 2-8x10^{11} cm^{-2} dose
- Short activation anneal T = 900-1000C to fully activate at these low concentrations
  - Diffusion length can be smaller than implant straggle

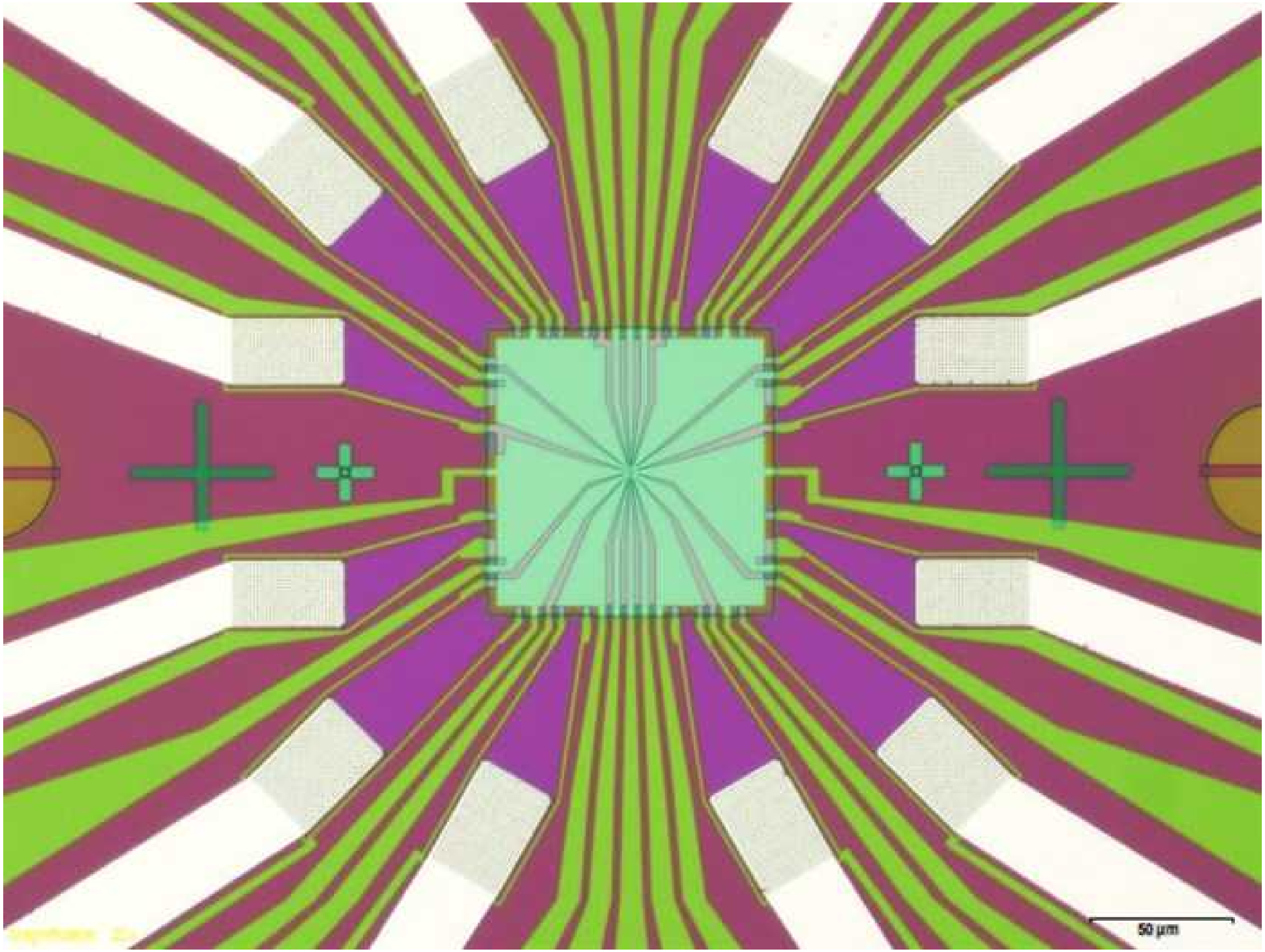


Al lift-off & forming gas anneal



- ~1000Å Al deposited to form global gate and bond pads for W vias
- Thermal preferred to minimize damage
- Forming gas anneal

Final Metal



Damage & Annealing

Damage mechanisms

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 50, NO. 3, JUNE 2003

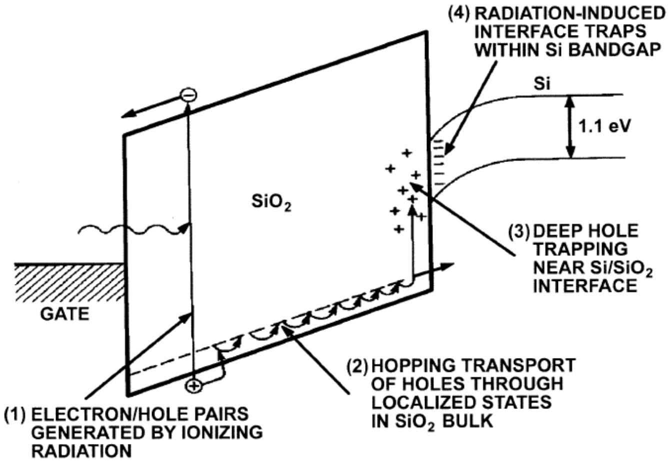
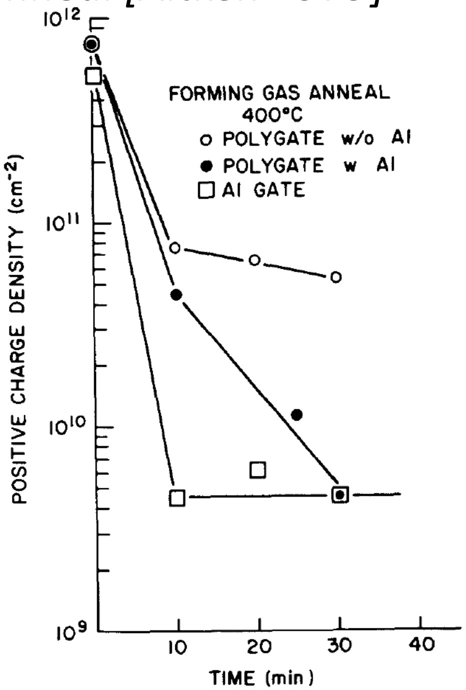
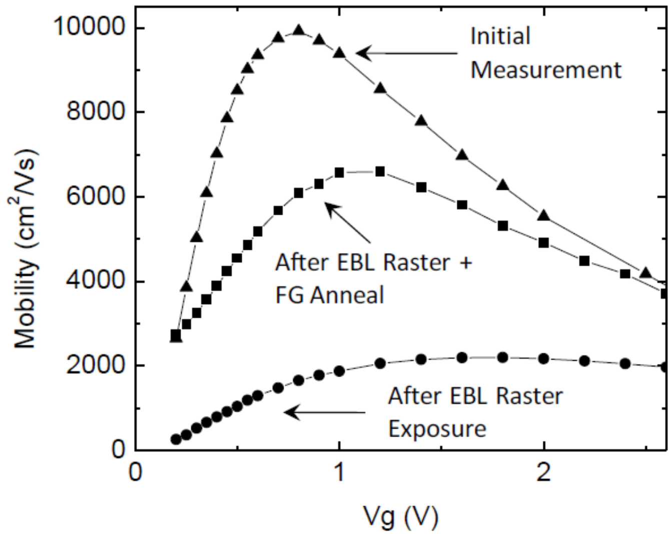


Fig. 2. Schematic energy band diagram for MOS structure, indicating major physical processes underlying radiation response.

IBM, ebeam damage & anneal [Aitken 1979]



SNL 4K Hall [Tracy et al.]

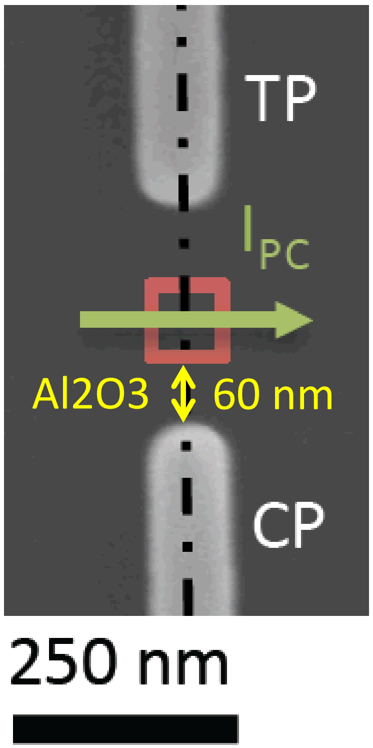


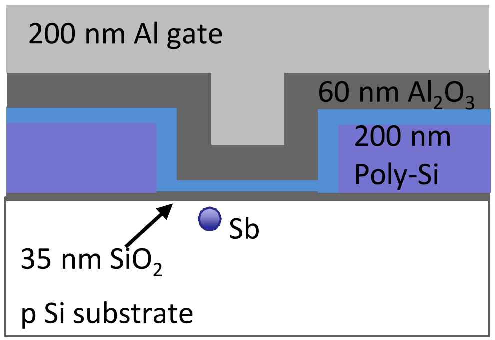
- Radiation damage of MOS is well studied
- EBL and other steps induce damage
- Models point to resulting E’ or Pb center formation as concluding defect state
- Low temperature anneals reported sufficient to remove damage
- Not clear if all damage can be removed
  - For example: full mobility at low T not recovered
  - but not clear that anneal benefits have saturated

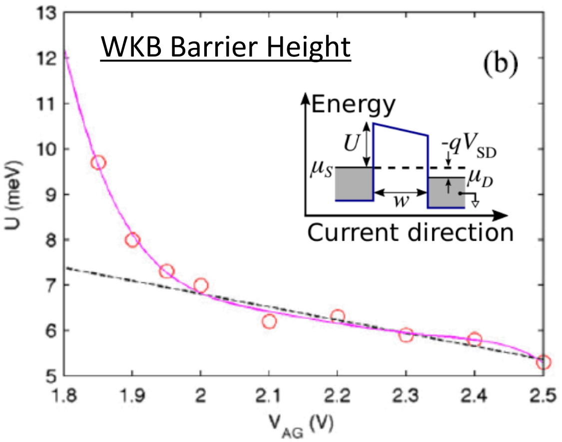
Outline

- Introduction to qubits & sources of infidelity
- Fabrication steps
- MOS nanostructures and qubits
- Special donor fabrication techniques
- Summary

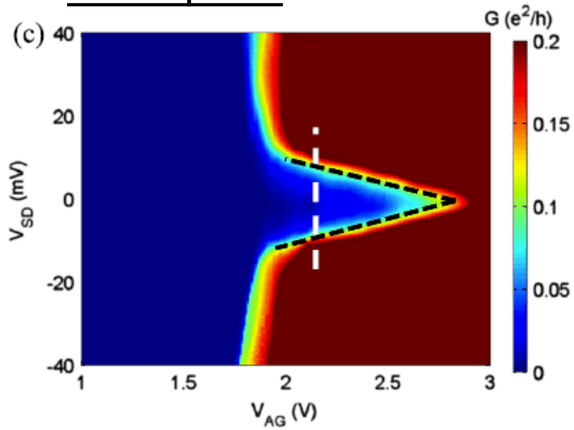
Barriers without "shallow traps" (i.e., donors)





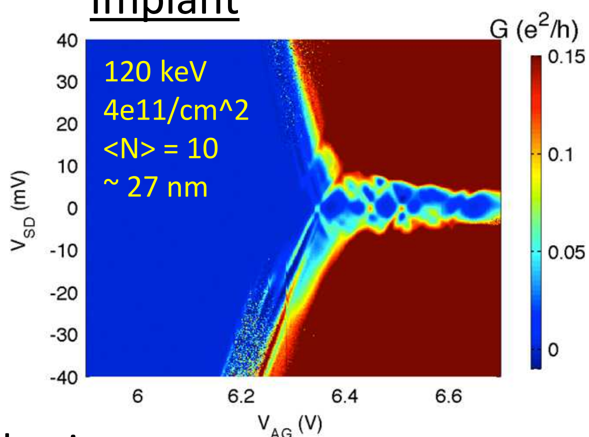


No implant



T ~ 4K

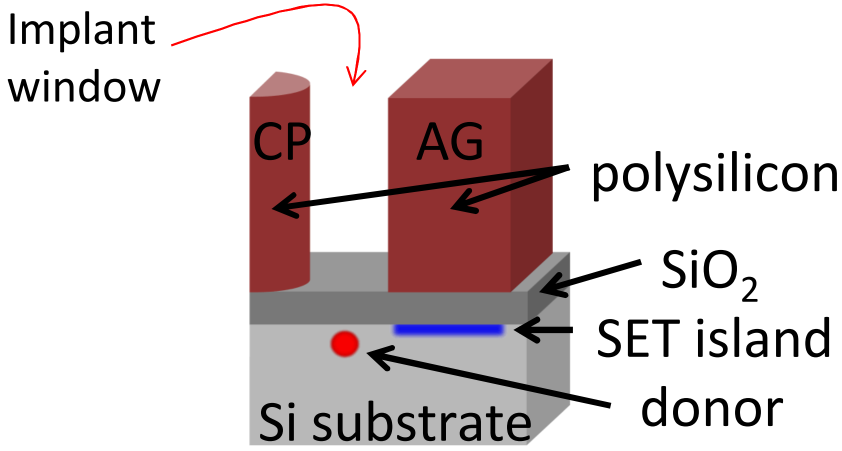
Implant

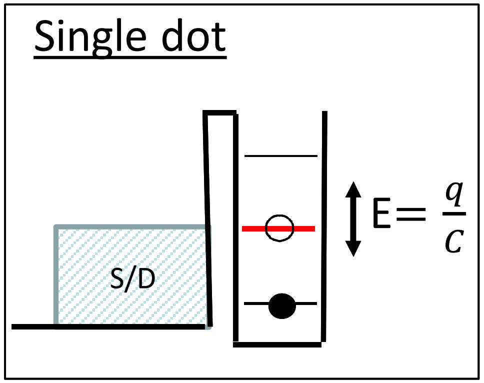


T ~ 4K

- Simple point contact (no implant) shows no resonant behavior
- Existence proof that MOS interface can produce 'clean' tunnel barrier in large area
- Sb implanted point contact shows many resonances & threshold shift
- Resonances represent states in the barrier – approach to measure shallow DOS

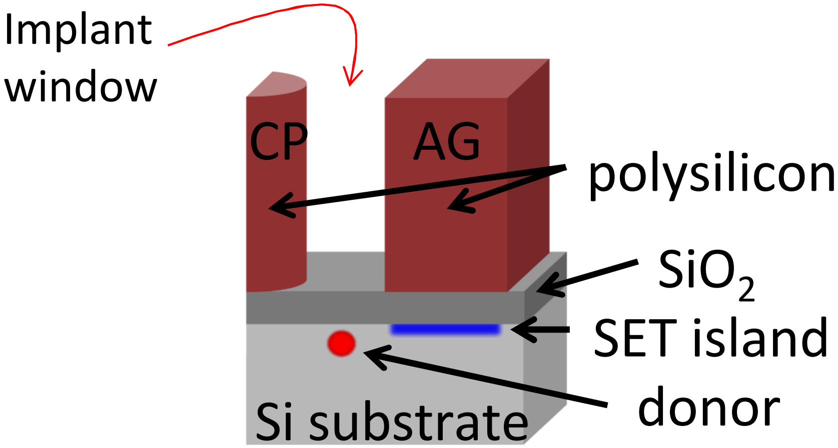
Gate wire with implant – QD coupling to donor

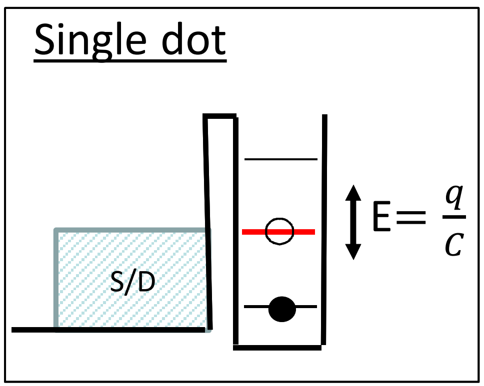




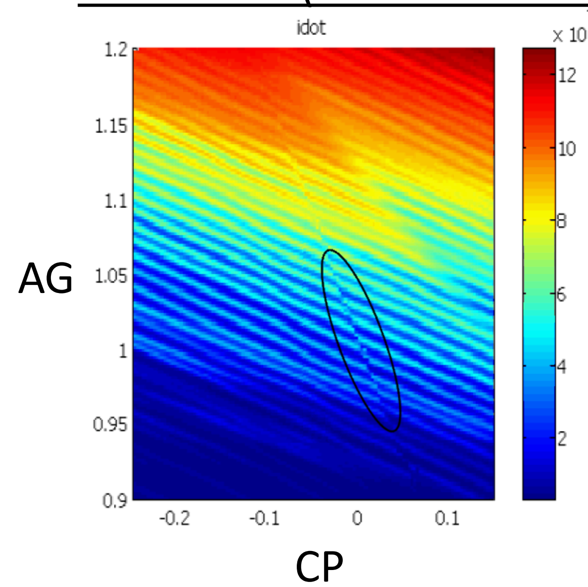
- Poly-Si gated nanostructures
- Use Poly-Si for self-alignment of donors
- Donor qubit readout through quantum dot
- Quantum dot senses the spin dependent ionization of the donor

Gate wire with implant – QD coupling to donor

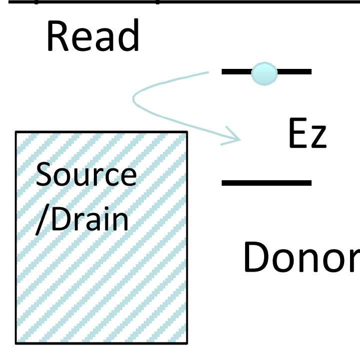




SET offsets (detection of ionization)



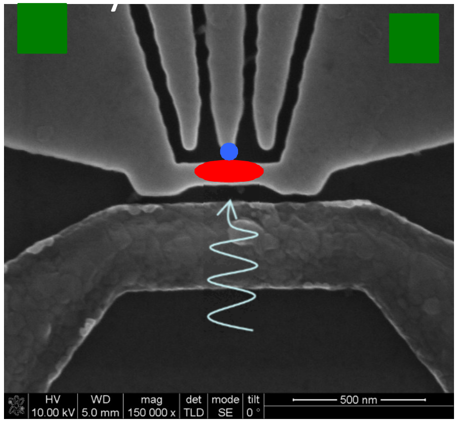
Spin dependent ionization



- Poly-Si gated nanostructures
- Use Poly-Si for self-alignment of donors
- Donor qubit readout through quantum dot
- Quantum dot senses the spin dependent ionization of the donor

Morello et al., Nature 2010
Tracy et al., APL 2013

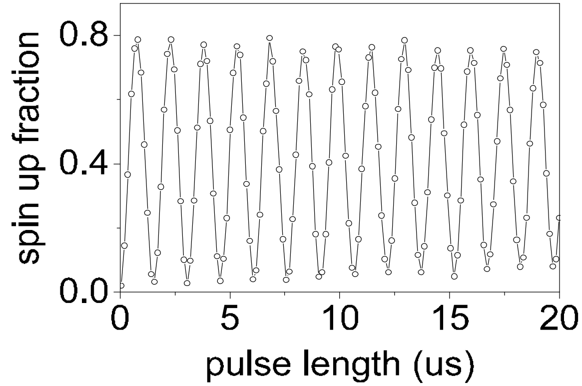
Single donor qubits & dephasing metrics

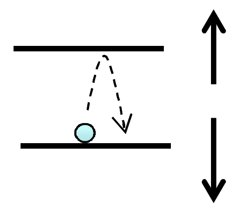


Ohmics

Donor

Quantum Dot





^{28}Si epilayer

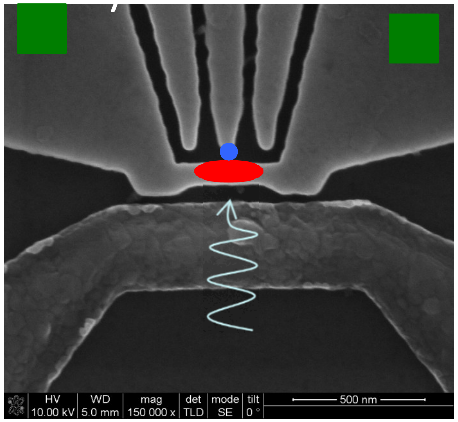
- 2.5 μm thick
- 500 ppm ^{29}Si (ToF SIMS)

Nominally identical processing

- Coarse metrics of material quality with respect to spin “vacuum” are T2 & T2*
- Roughly, this is a measure of inhomogeneous local B-field from dipoles (T2*) & how rapidly that field is changing (T2)
- This case: ESR: T2 = 0.31 ms, T2* = 10-20 μs

Tracy et al. APL, 108 063101 (2016)

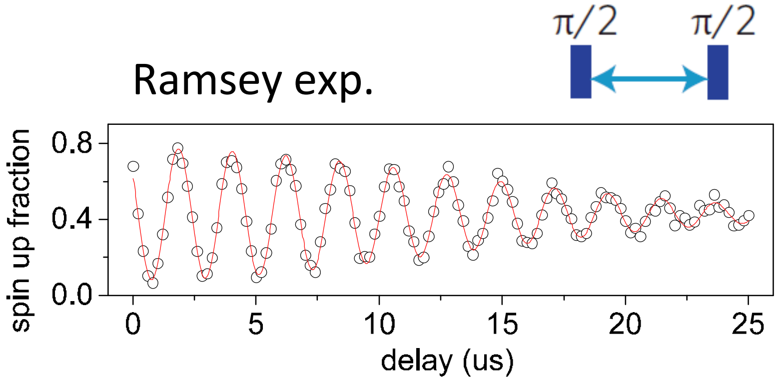
Single donor qubits & dephasing metrics



Ohmics

Donor

Quantum Dot



^{28}Si epilayer

- 2.5 μm thick
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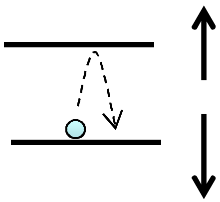
Nominally identical processing



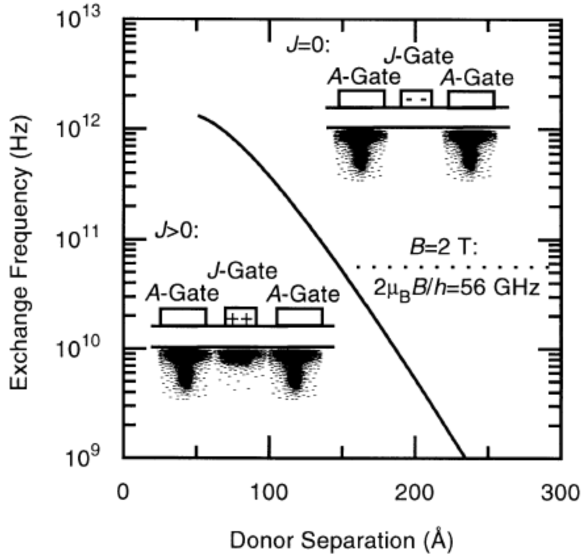
- Ramsey and Hahn-echo: T2 = 0.31 ms, T2* = 10-20 μs
- Line width is approximately 30 kHz
- Max B1 corresponds to order of MHz

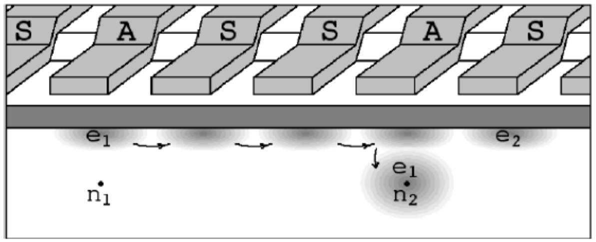
- In natural silicon: line width is order of 5 MHz
- T2* ~ 50 ns

Tracy et al. APL, 108 063101 (2016)

Donor-donor coupling concept

Kane (1998)

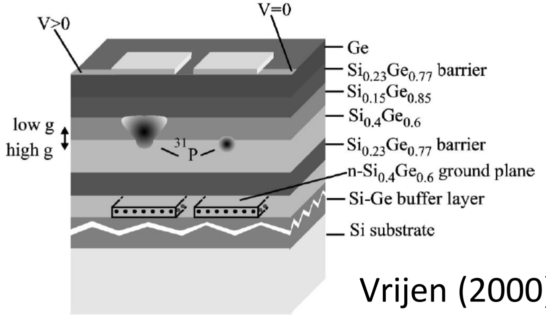




Transport: Skinner & Kane (2003)
Also transport: Hollenberg (2007), Morton (2009); Witzel (2015)

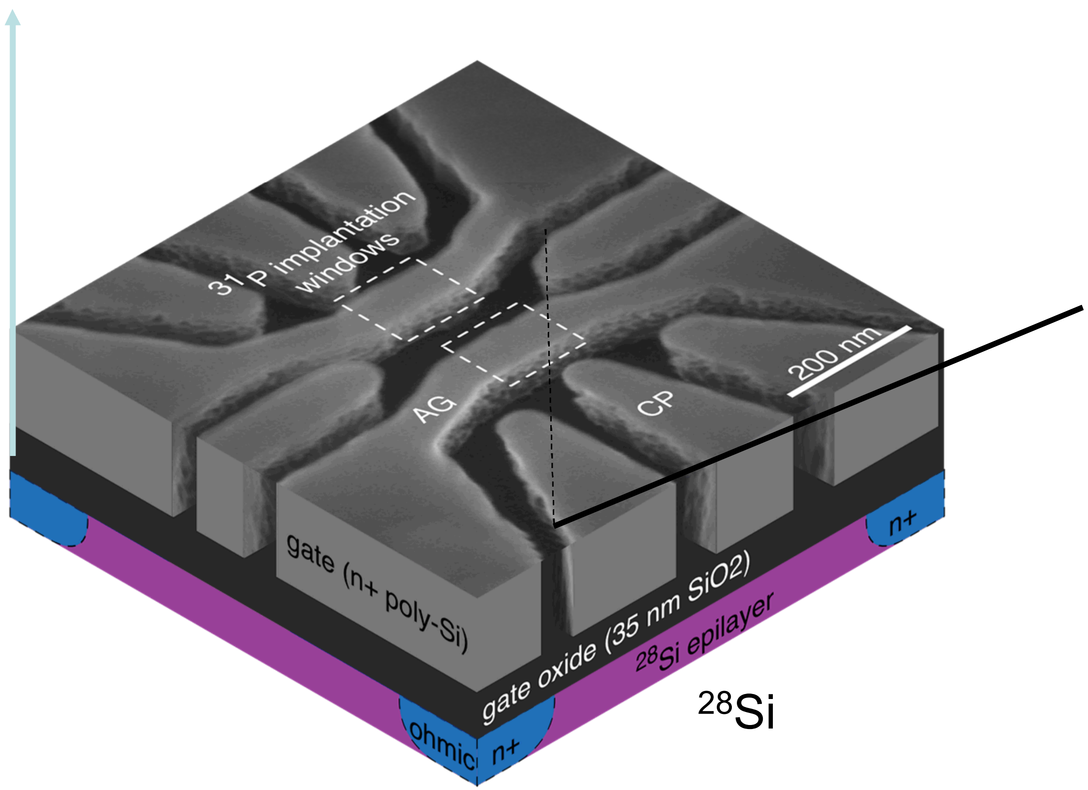
- Donors are a great qubit
- Many ideas about coupling donors that use interface
- Very general question that we needed to address: can a donor practically be coherently-coupled to something at an interface and can that capability be extended
- SNL: donor coherently coupled to MOS QD recently

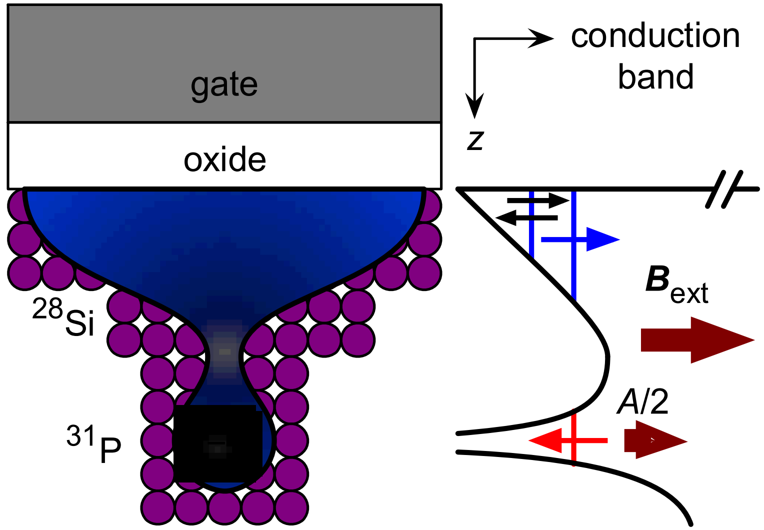
G-factor control for EDSR



Vrijen (2000)

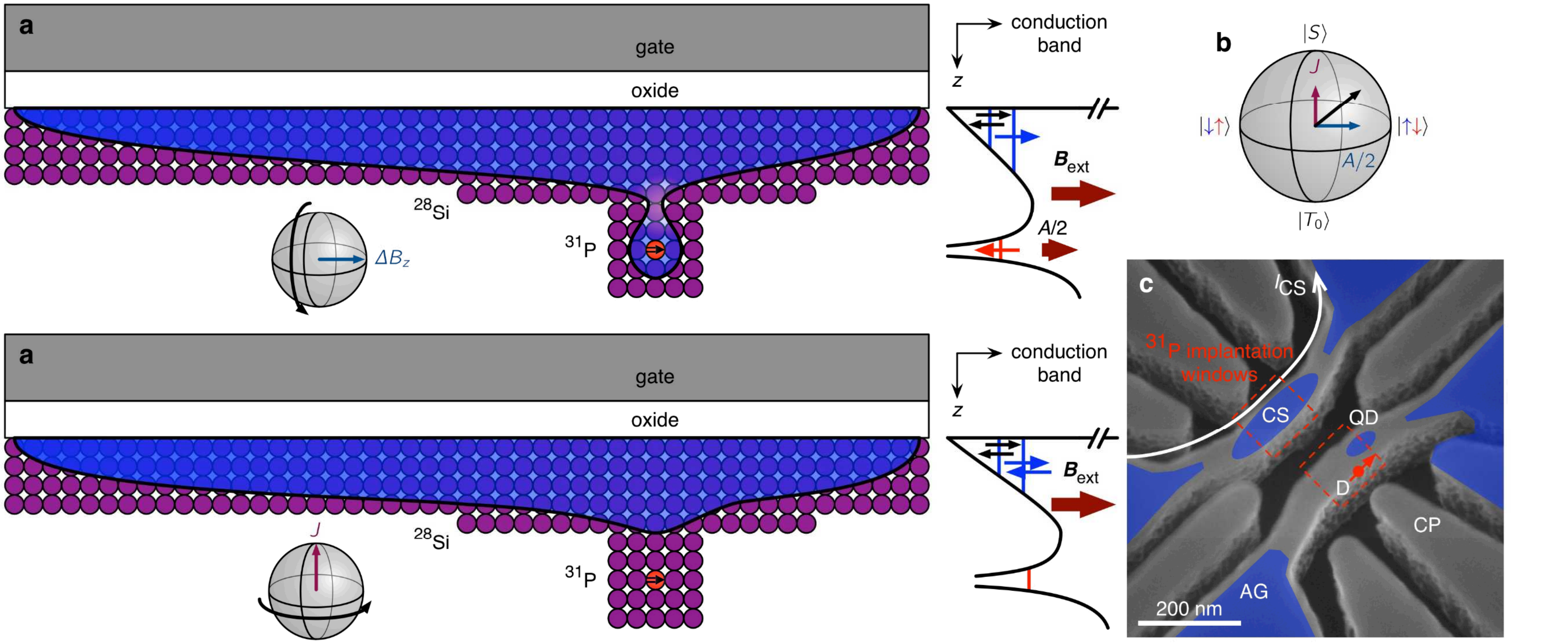
Approach: Couple a N=1 MOS-QD to a Buried Donor



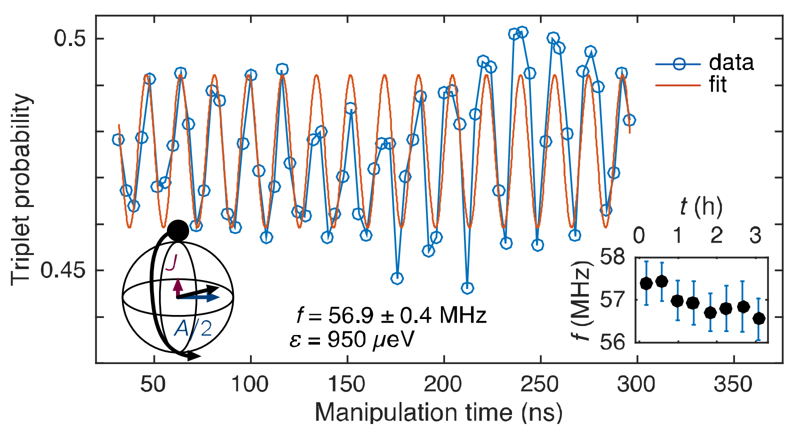


- Extend the single donor qubit lay-out to include a charge sensor
- Charge sensed donor-QD system is now an experimental double quantum dot platform to test the D to surface coupling idea

Coherent coupling of donor qubit to electron interface qubit

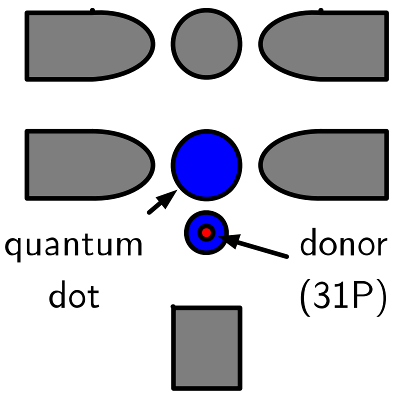


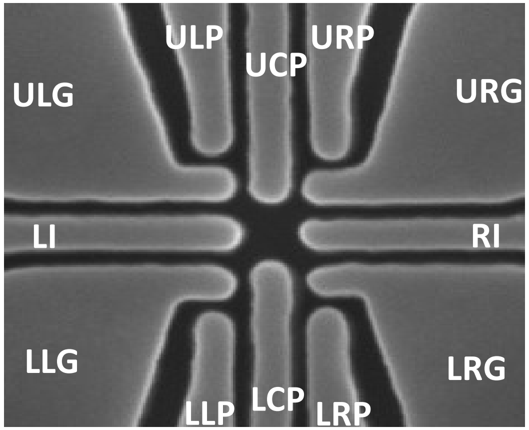
- Two different solid-state qubit systems successfully coupled together coherently

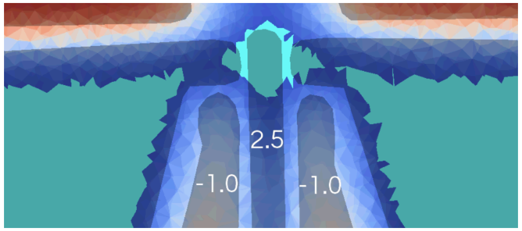


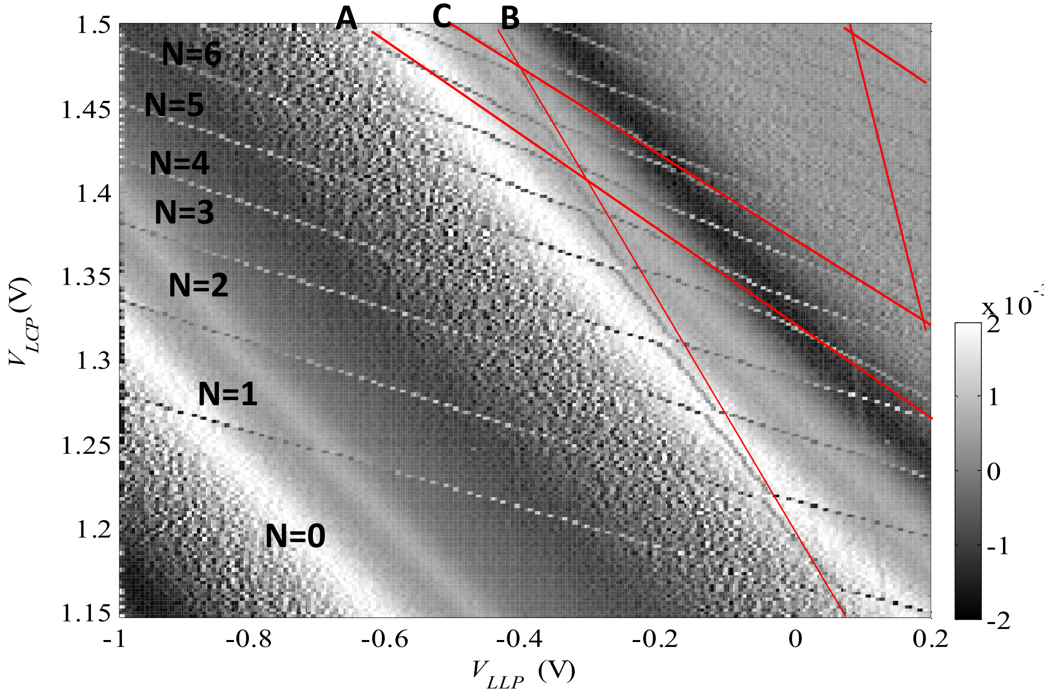
New design: very tunable quantum dots in MOS

- Can tune MOS QD to N=1 while keeping both barriers open
- Good charge sense signal from neighboring QD
- Coherent spin coupling between QD and donor in related layout
  - Harvey-Collard et al., arxiv 1512.01606





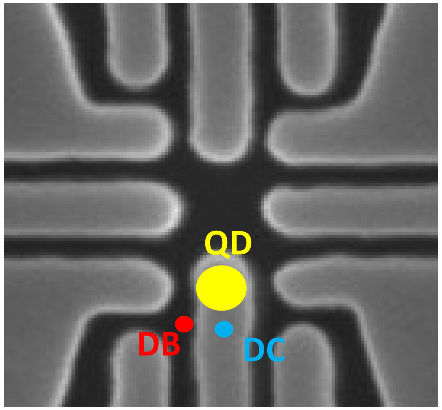




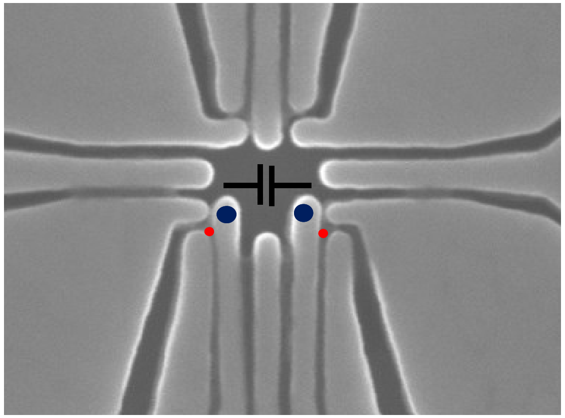
Rudolph

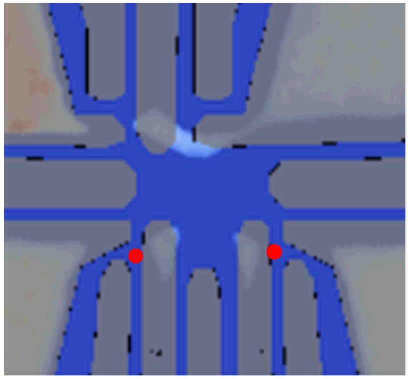
Multi-QD exchange coupling or capacitance coupling

- Single poly can be extended in a 1D multi-QD path

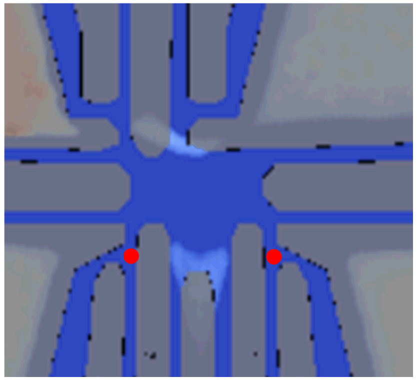


Capacitance coupling of qubits

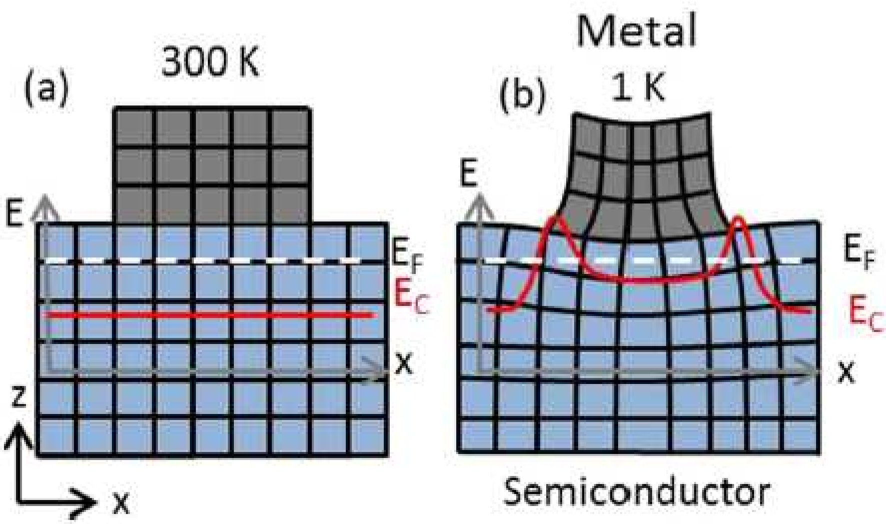


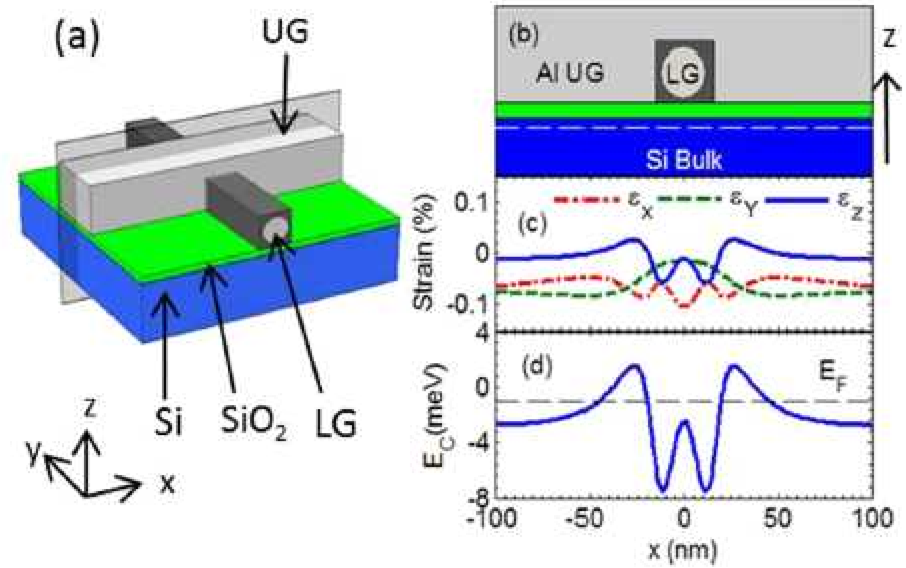


Exchange coupling of qubits

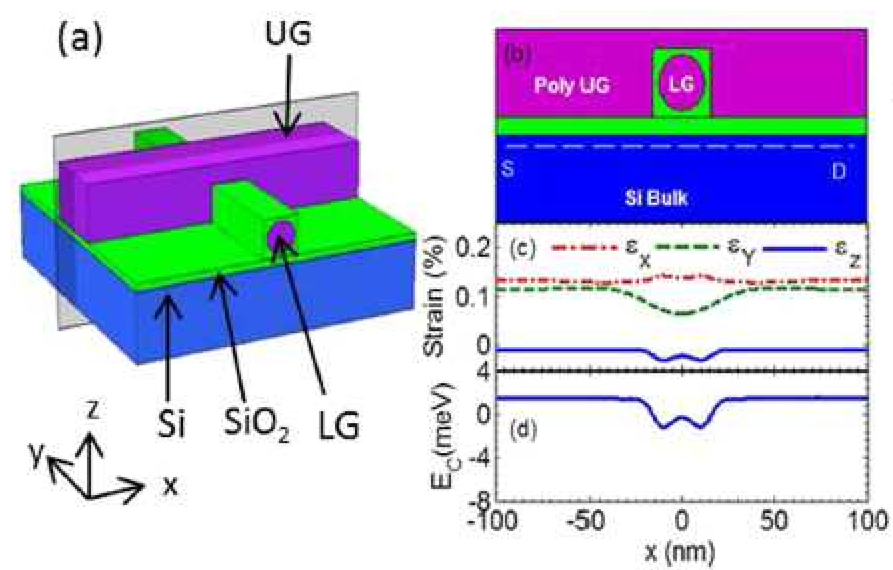


Future: strain variations in more complex structures?





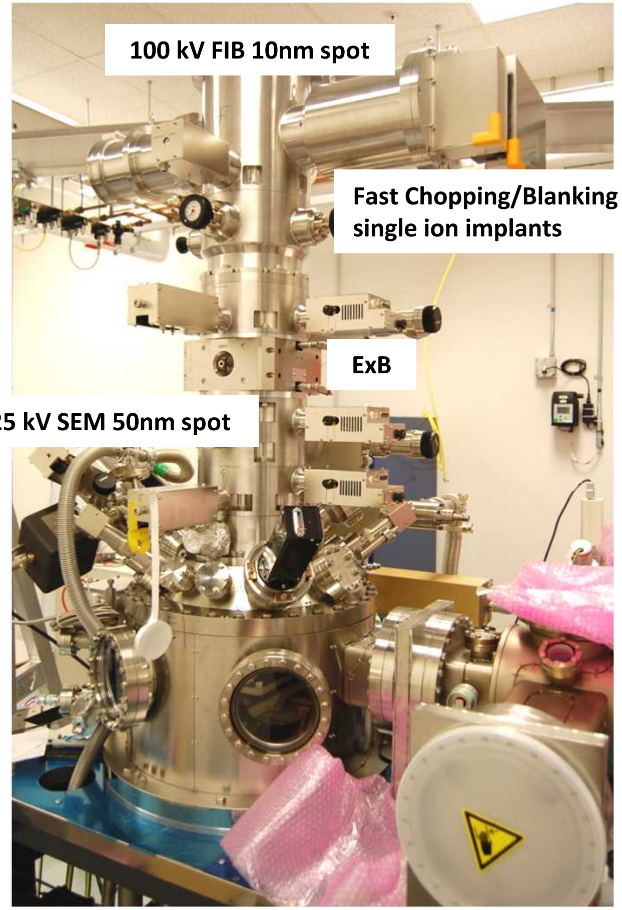
- Zimmerman group has highlighted possible non-uniform, systematic potential due to thermal mismatch stressors
- Process induced stressors also exist and might need examination
  - Poly gates will minimize stresses compared to metal gates
  - However, nitride on top of gates are high stress
- Other strain fluctuations?
  - Is cross hatch or threading dislocations in SiGe important?



Outline

- Introduction to qubits & sources of infidelity
- Fabrication steps
- MOS nanostructures and qubits
- Special donor fabrication techniques
- Summary

Implant system at Sandia National Labs

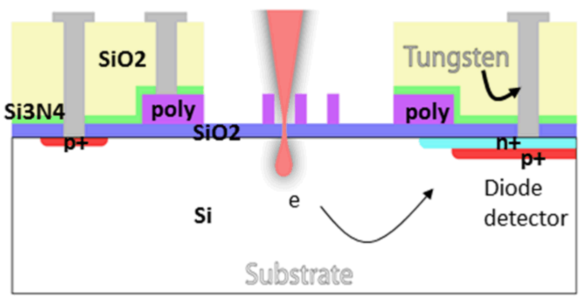


- NanoImplanter (nI)
  - Variable Energy 10-100 kV
  - Liquid Metal Alloy Ion Source (LMAIS)
    - Sb, P, Si, Ga
  - Mass Velocity Filter to pick out ion of interest
  - Fast Blanking and Chopping for single ion implants
  - Demonstrated
    - 10 nm 100 keV Ga^+
    - ~20-30 nm 200 keV Si^{++}

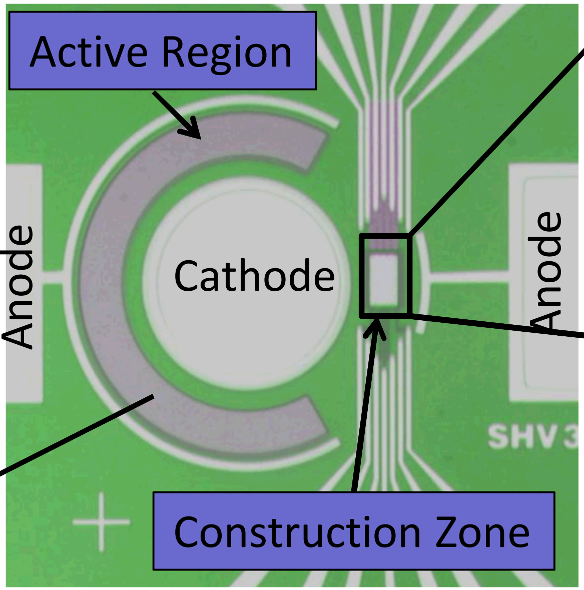
- Beam Spot Size depends on
  - $\Delta E/E$ spread
    - Ion Mass ($\propto m^{1/3}$)
    - Accelerating Voltage ($\propto E^{1/3}$)
  - ***Expect 20-30 nm spot at 30 keV Sb^+***

Detector and nanostructure Integration

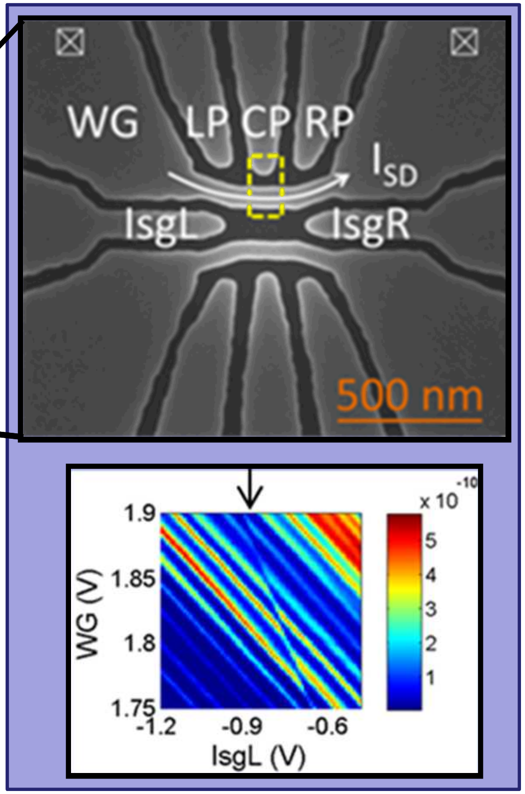
Single Ion Implant Approach



Single Ion Detectors

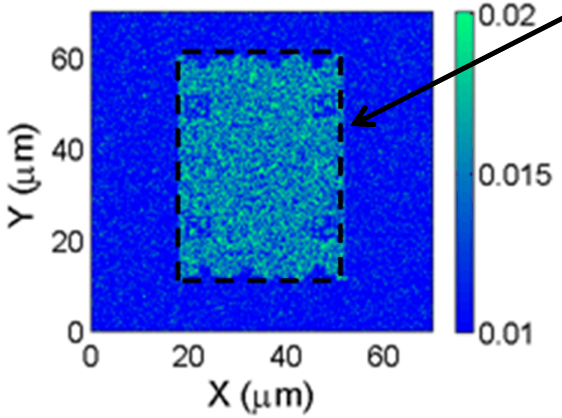


Nanostructures



Meenakshi Singh

1 ion @ 120 keV Sb / pulse



Singh et al. APL 108 062101 (2016)
Bielejec et al., Nanotechnology 21 085201 (2010)

Ultimate lateral and vertical control of donors

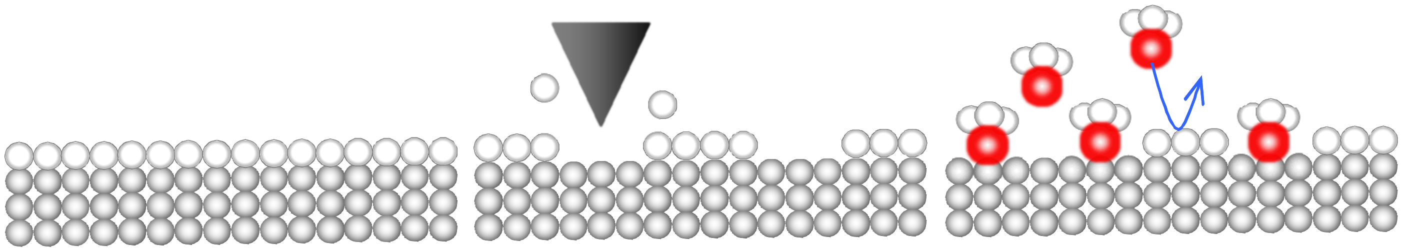
1. Start w clean Si(001)

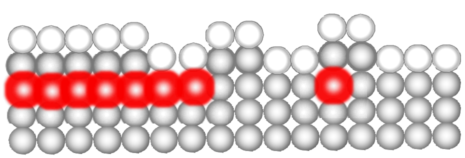
2. Adsorb H resist
Self-limiting 1 monolayer

3. Pattern w STM
Atomic-precision

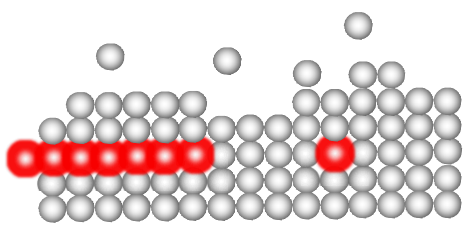
4. Adsorb PH_3

Etched alignment marks



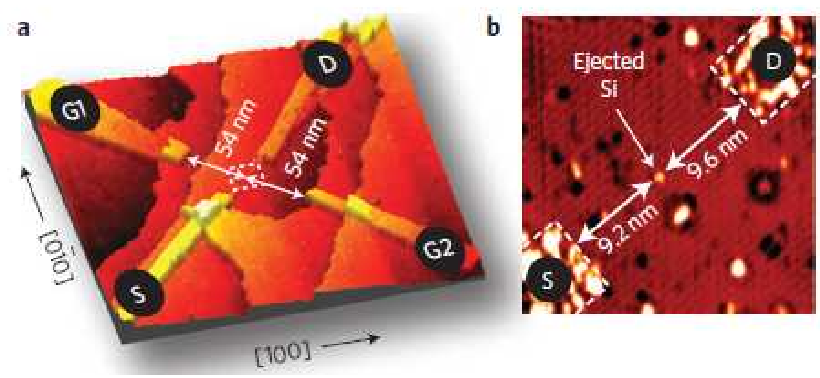


5. Incorporate P
-Anneal➔ Si-P swap
-H resist constrains P



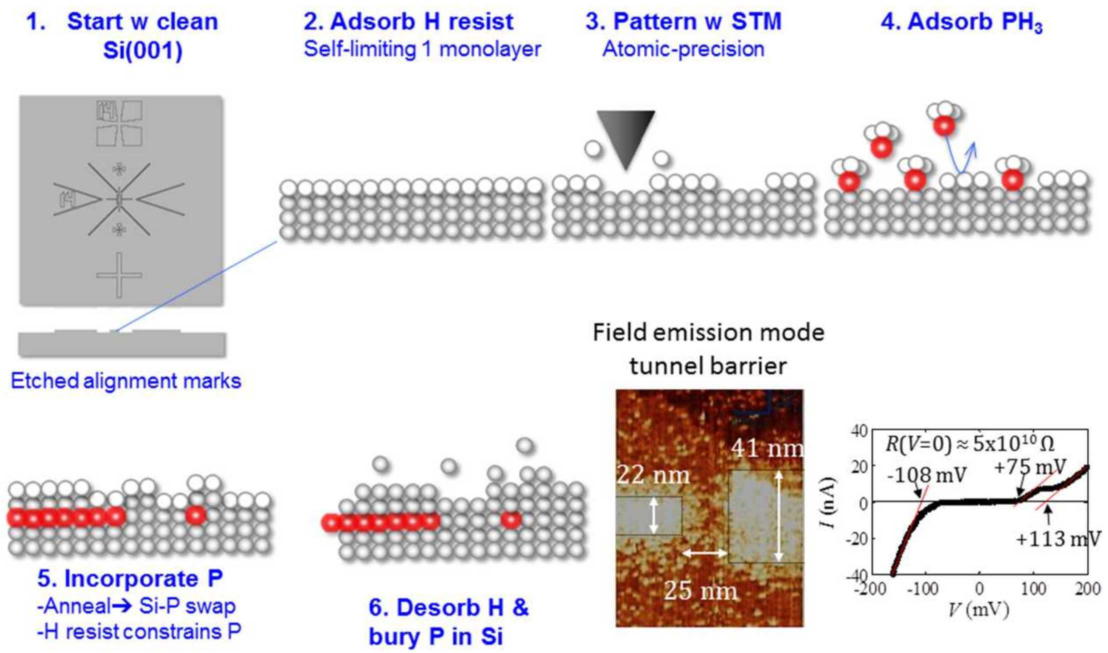
6. Desorb H & bury P in Si

NATURE NANOTECHNOLOGY | VOL 7 | APRIL 2012 |

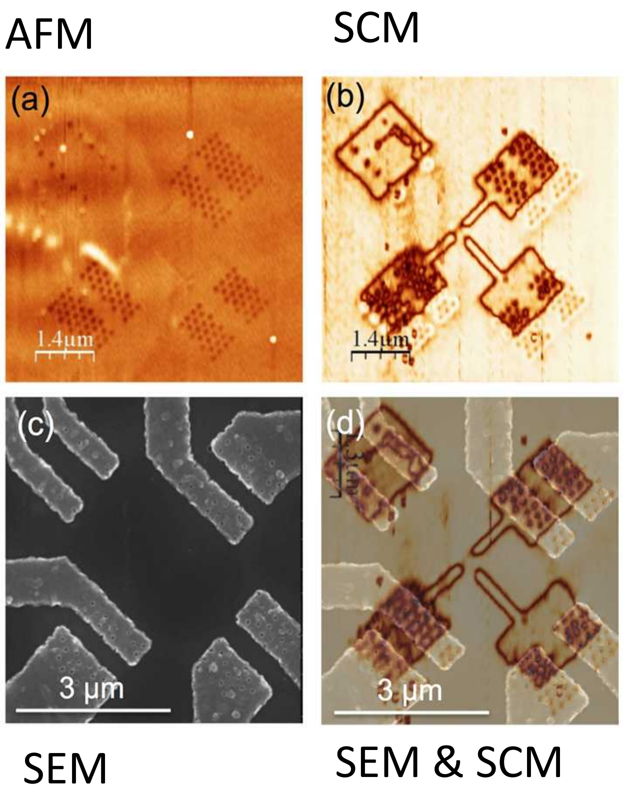


Finding the donors after they are placed

STM fabrication path pioneered by Simmons group:



Rudolph et al., APL 105 163110 (2014)



Result:

~300 nm resolution now

10-20 nm possible at RT

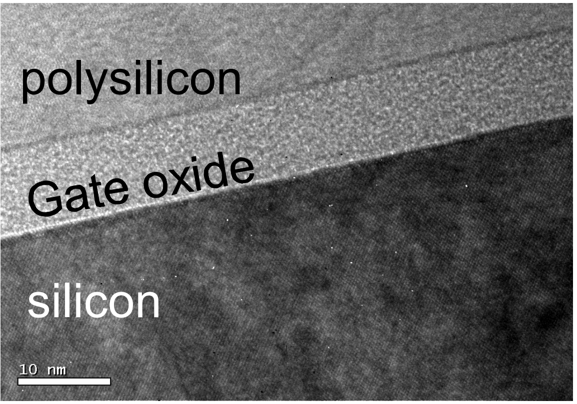
Bussman et al., Nanotechnology 26 (2015) 085701

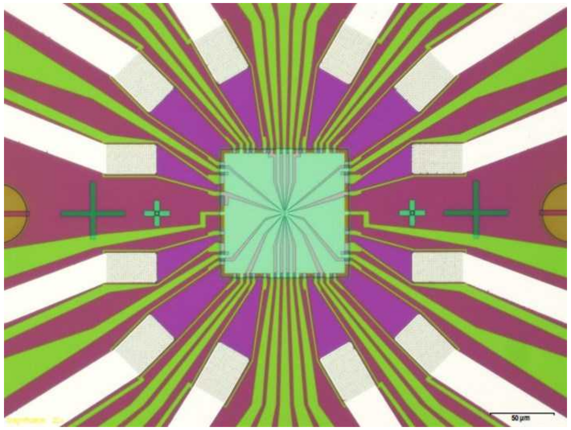
- Hydrogen lithography path also being pursued at SNL
- We're using scanning capacitance measurements for example for alignment and metrology. We'd like to improve it – or having something better

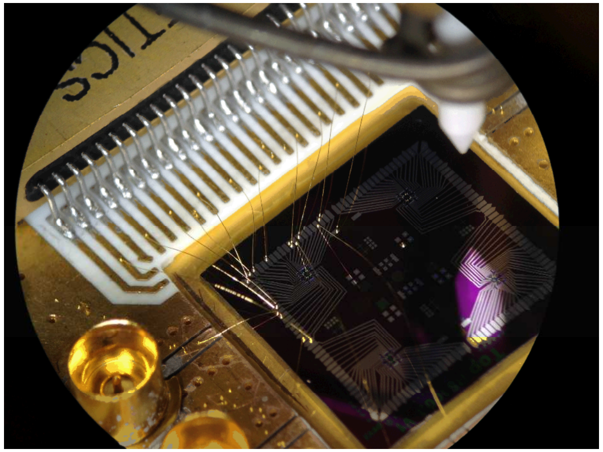
QIST team & external connections

- QIST contributors at SNL
  - **QD & Timed Implant Qubit Fab:** J. Dominguez, R. Manginell, T. Pluym, B. Silva, J. Wendt, S. Wolfley
  - **Qubit control & measurement:** S. Carr, M. Curry, T. England, A. Grine, K. Fortier, R. Lewis, M. Lilly, T.-M. Lu, D. Luhman, J. Rivera, M. Rudolph, P. Sharma, A. Shirkhorshidian, M. Singh, L. Tracy, M. Wanke
  - **Advanced fabrication (two qubit):** E. Bielejec, E. Bussmann, E. Garratt, J. Koepke, A. MacDonald, E. Langlois, M. Marshal, B. McWatters, S. Miller, S. Misra, D. Perry, S. Samora, D. Scrymgeour, R. Simonson, G. Subramanian, D. Ward, E. Yitamben
  - **Device modeling:** J. Gamble, S. Gao, M. Grace, T. Jacobson, R. Muller, E. Nielsen, I. Montano, W. Witzel, K. Young
- Joint research efforts with external community:
  - Australian Centre for Quantum Computing and Communication Technology (D. Jamieson, A. Dzurak, A. Morello, M. Simmons, L. Hollenberg)
  - Princeton University (S. Lyon, J. Petta)
  - NIST (N. Zimmerman, M. Stewart, J. Pomeroy)
  - U. Maryland (S. Das Sarma)
  - National Research Council (A. Sachrajda)
  - U. Sherbrooke (M. Pioro-Ladriere, C. Bureau-Oxton, P. Harvey-Collard)
  - Purdue University (G. Klimeck & R. Rahman)
  - U. New Mexico (I. Deutsch, P. Zarkesh-Ha)
  - U. Wisconsin (M. Eriksson, S. Coppersmith, D. Savage)
  - University College London (J. Morton)
  - Zyvex (J. Randall)
  - Chee Wee (U. Taiwan)
  - McGill (W. Coish, D'Anjou)

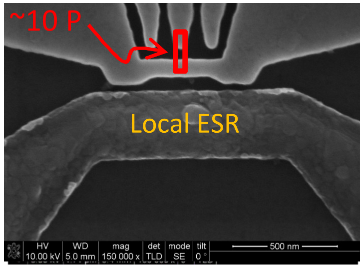
Summary

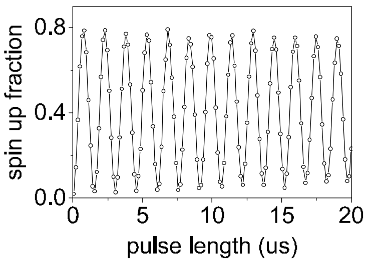


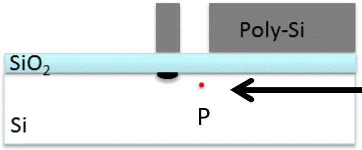




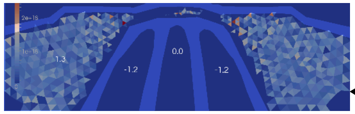
Single spin donor ESR in 28Si





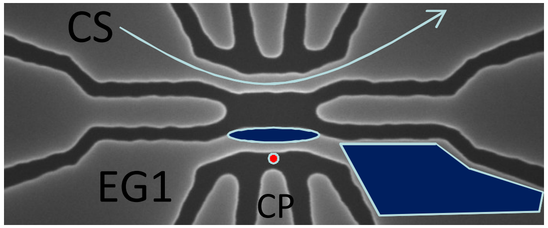


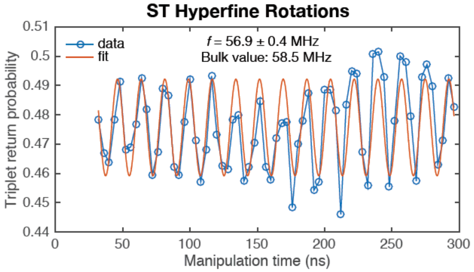
Donor qubit

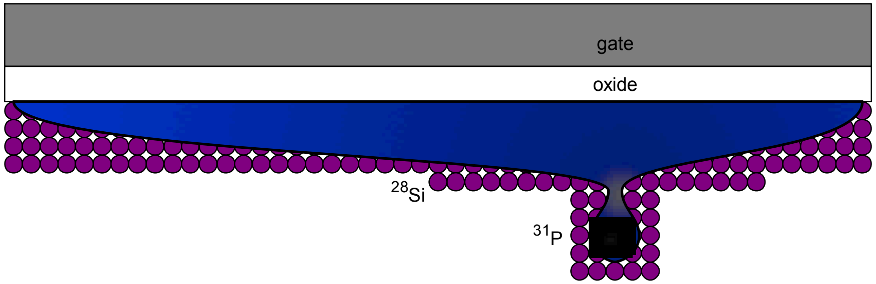


Si QD simulation

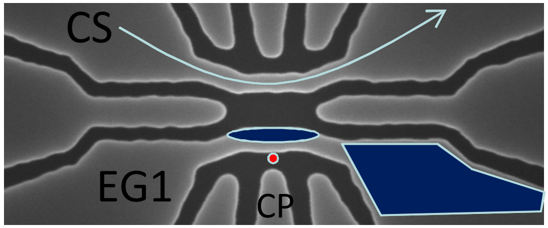
MOS S/T qubit driven by single donor

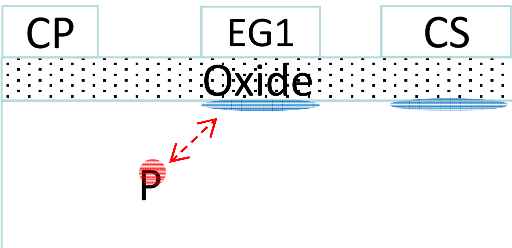




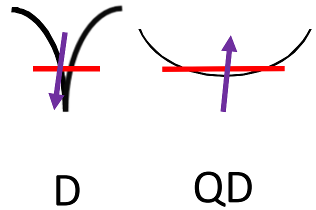


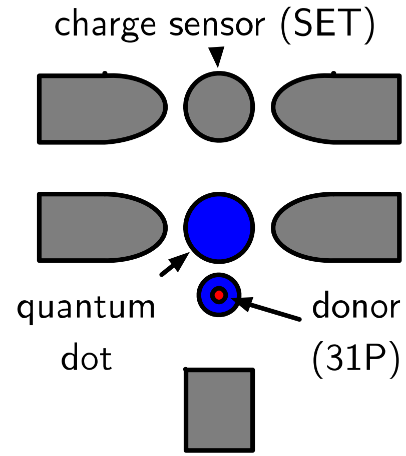
Approach: Couple a N=1 MOS-QD to a Buried Donor



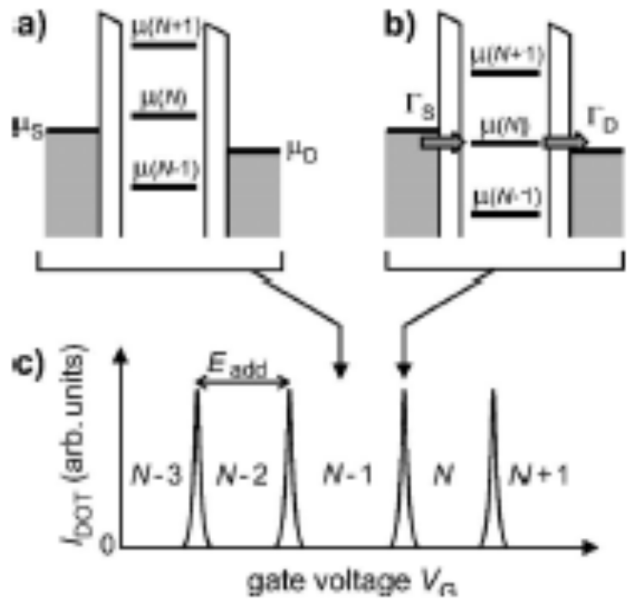


2-spin singlet-triplet qubit





- Extend the single donor qubit lay-out to include a charge sensor
- Charge sensed donor-QD system is now an experimental double quantum dot platform to test the D to surface coupling idea



Hanson, Rev. Mod. Phys. (2007)

Two qubit operations for quantum "parallelism"

Multiple Qubits: The Space Grows Exponentially

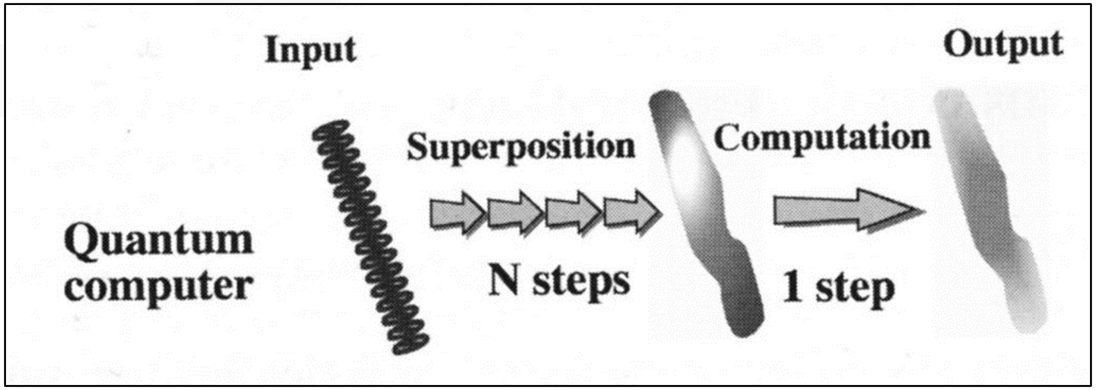
E.g. 3-qubits, dim=8

$$|0\rangle = |0\rangle|0\rangle|0\rangle \quad |1\rangle = |0\rangle|0\rangle|1\rangle \quad |2\rangle = |0\rangle|1\rangle|0\rangle \quad |3\rangle = |0\rangle|1\rangle|1\rangle$$

$$|4\rangle = |1\rangle|0\rangle|0\rangle \quad |5\rangle = |1\rangle|0\rangle|1\rangle \quad |6\rangle = |1\rangle|1\rangle|0\rangle \quad |7\rangle = |1\rangle|1\rangle|1\rangle$$

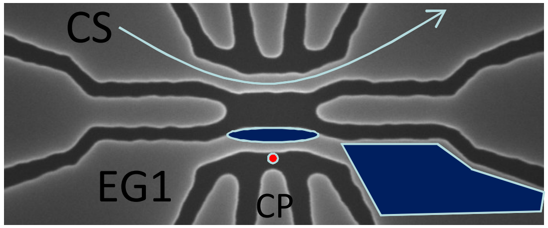
General state: $|\psi\rangle = \sum_{x=0}^{2^n-1} c_x |x\rangle$

n-qubits: 2^n alternatives



- Two qubit operations can be used to form non-trivial superpositions (entangled states)
- An entangled qubit register (n qubits) can have non-zero probability amplitude in as many as 2^n basis states *simultaneously!*
- The register acts as an inseparable single object as opposed to many individual bits
- Quantum algorithms designed to exploit the correlations from entanglement for speed-ups

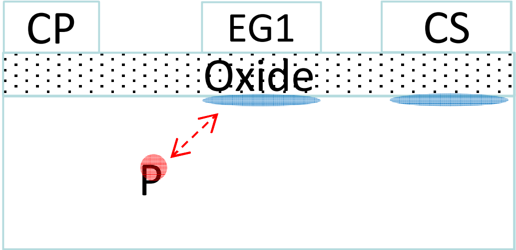
Approach: couple buried donor to surface QD

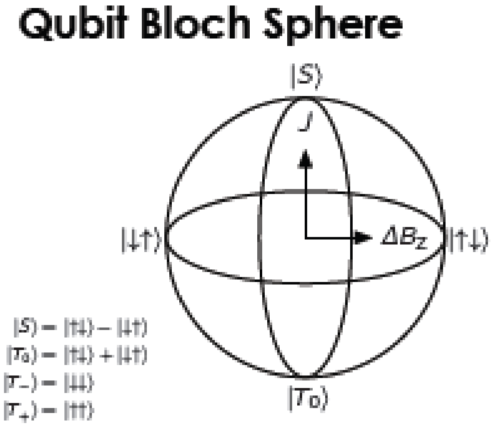


Canonical S/T qubit

$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z(\epsilon)\hat{\sigma}_x$$

Donor-QD S/T qubit → $AI \cdot S$





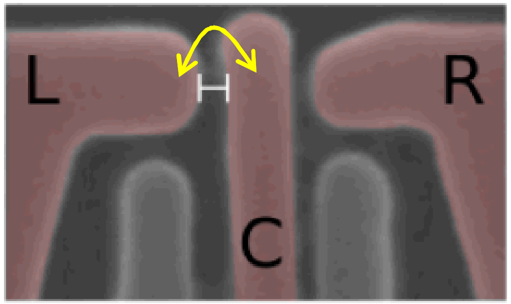
$|S\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$
$|T_0\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$
$|T_-\rangle = |\downarrow\downarrow\rangle$
$|T_+\rangle = |\uparrow\uparrow\rangle$

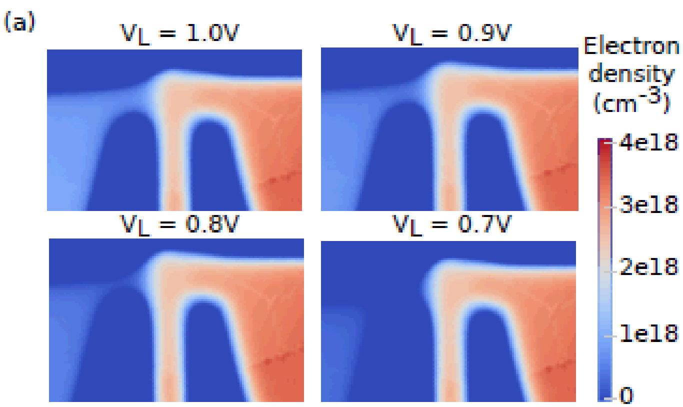
$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z\hat{\sigma}_x$$

- Encode as singlet-triplet qubit
- Rationale for using this choice as test platform:
  - Platform to examine tuning of the charge & dynamics (e.g., tunnel coupling)
  - Produces an appealing two-axis controlled S/T qubit
  - Rotation frequency is chemically distinct
  - Opens up a potential electrical read-out of nuclear spin
  - Directly probes coherence times of surface-bulk-donor coupling

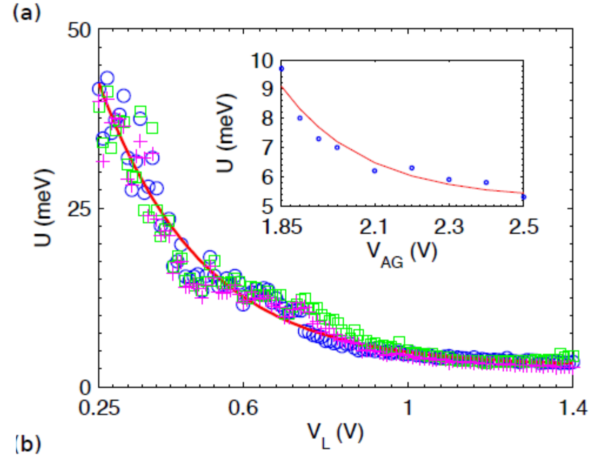
Barrier dependence on local potentials (reservoir-reservoir)

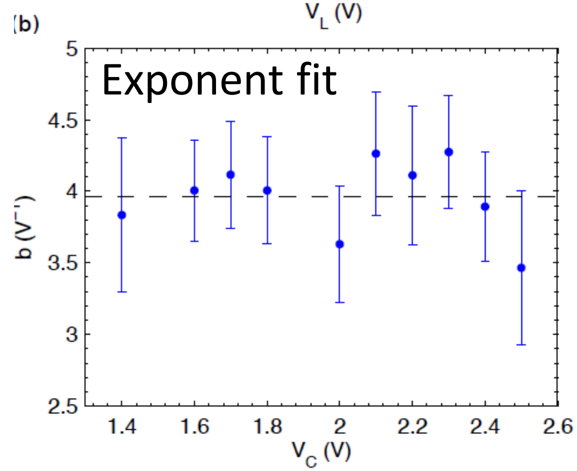
Lay-out & Simulation



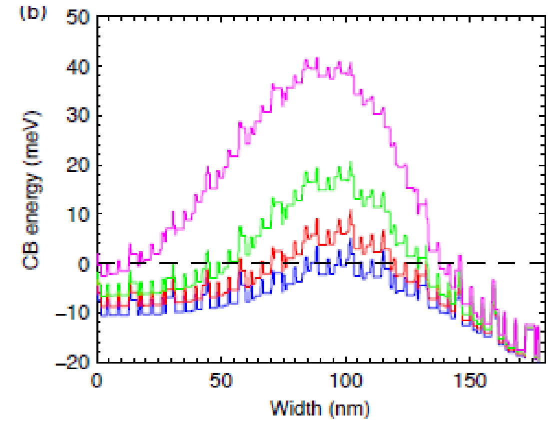


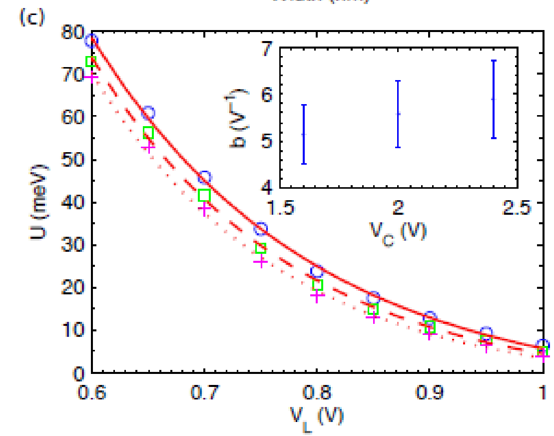
Experiment





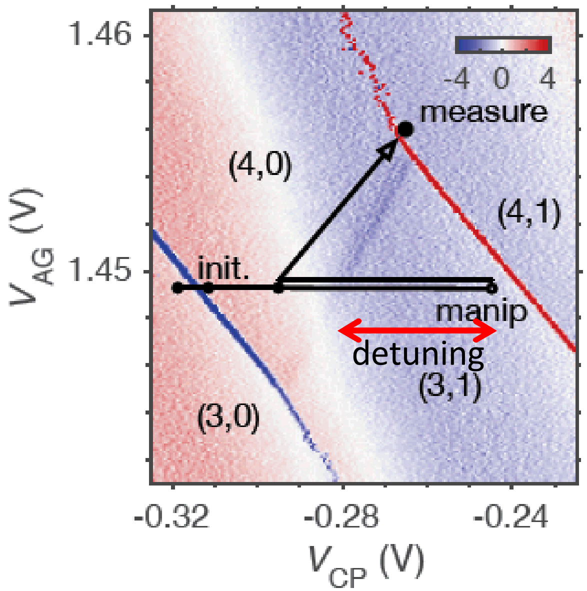
Sim. Line Cut

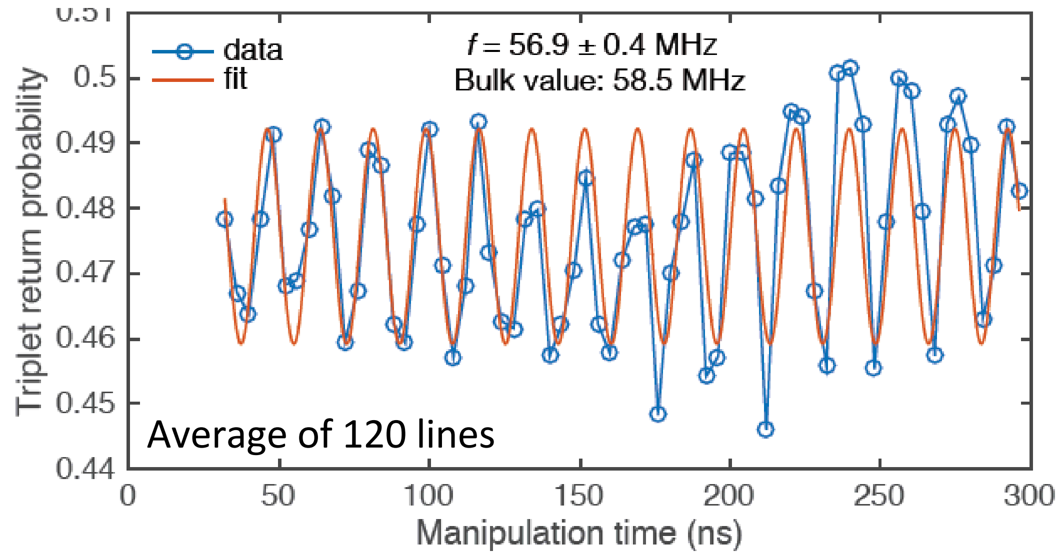




- Multiple electrodes often used to form tunnel barriers
- Reservoir-reservoir barrier fits exponential dependences on reservoir gate (xpt. & simulation)
  - WKB log-linear?
- Opposing gate introduces voltage shift with modest or no affect on quantitative exponential dependence
- Relatively small influence on width

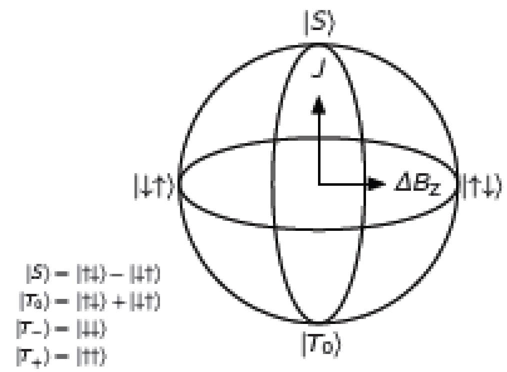
Pulse sequence & singlet-triplet rotations





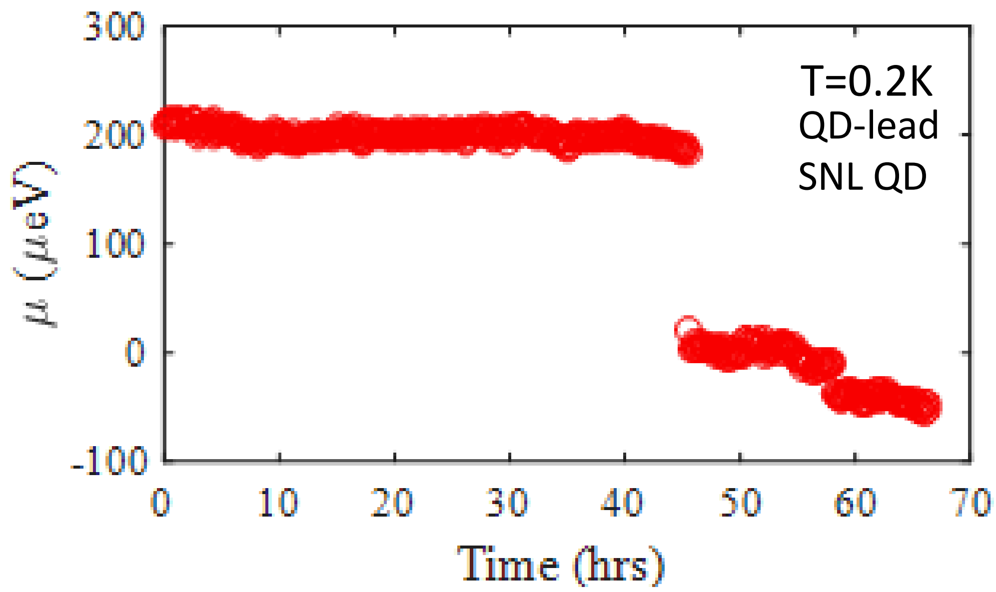
- Coherent oscillations observed for variable time & fixed detuning
  - Note: only the measurement point differs
- Oscillation frequency is close to bulk donor contact hyperfine value of 58.5 MHz
  - Close to measured ESR case – but a little misleading
- Frequency is detuning dependent – J changes
- T2* order of 1 us from coarse measures at longer times and different detunings

Qubit Bloch Sphere



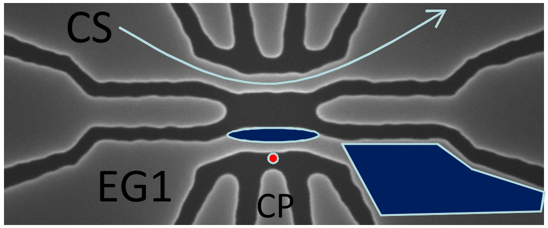
$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z \hat{\sigma}_x$$

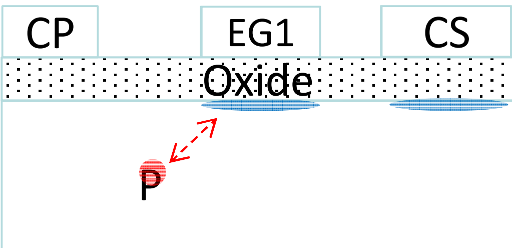
Drift in MOS QDs



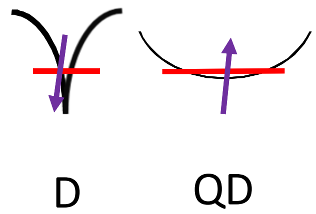
- Drift in QDs is a concern
- Zimmerman et al. developed technique to track QD transport resonance over time
  - JAP 104 033710 (2008)
- Small drift obtainable in MOS QDs

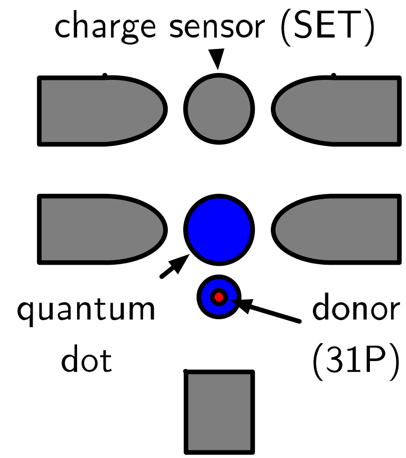
Approach: Couple a N=1 MOS-QD to a Buried Donor





2-spin singlet-triplet qubit





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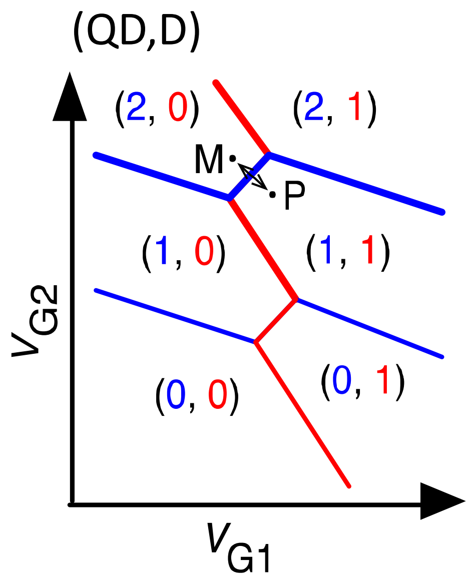
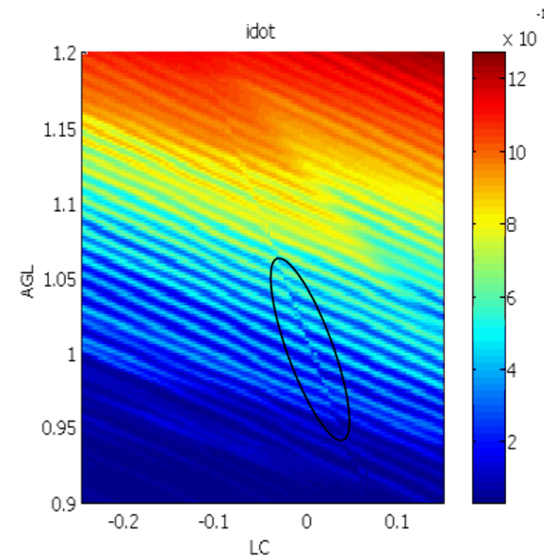
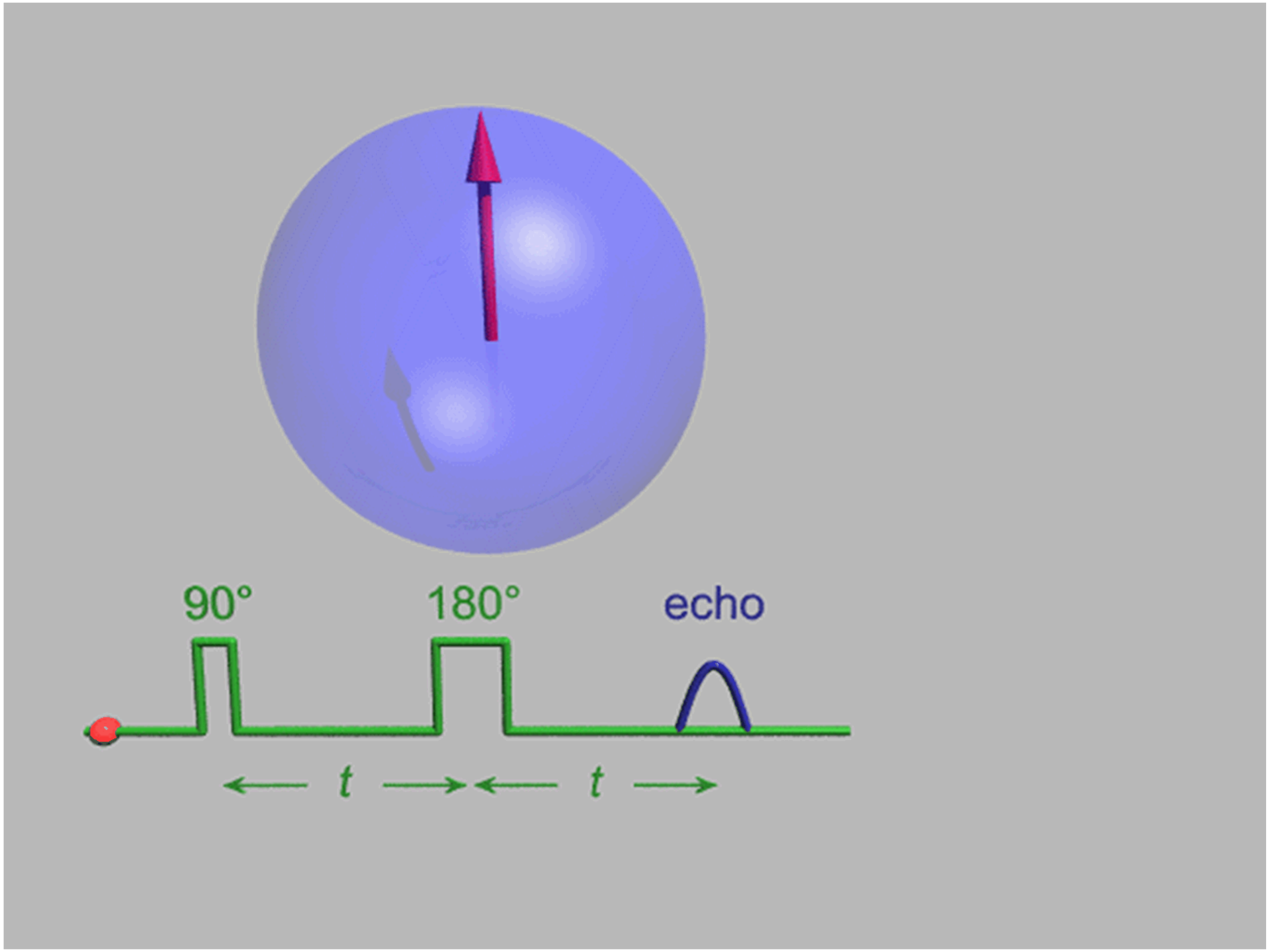




Electron spin qubit, evolution & decoherence



http://en.wikipedia.org/wiki/Spin_echo