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Road to qubits
Outlook

Towards quantum information processing with spins in silicon

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2008-12-02

Outline

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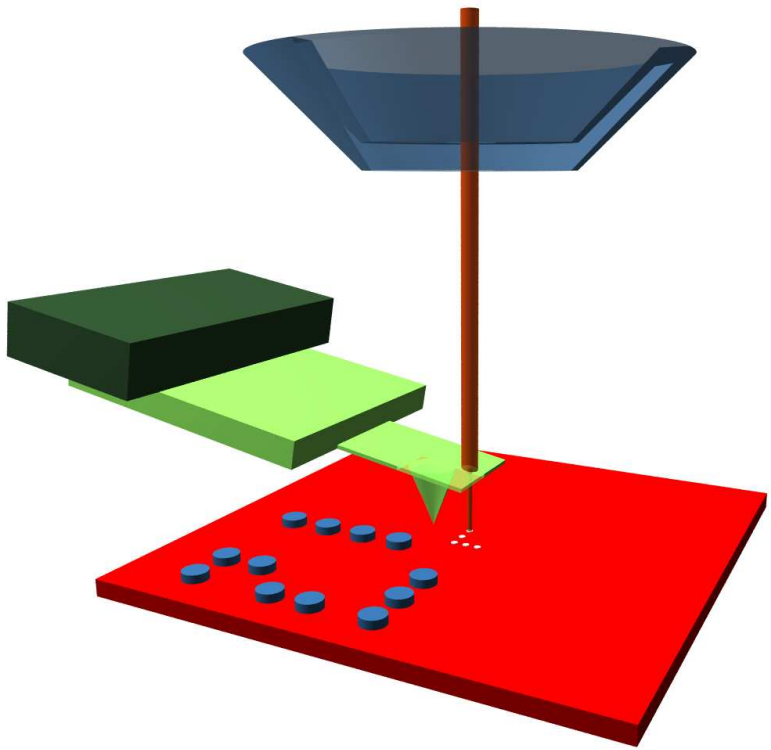
- Which donor to use?
- Single donor placement
- Single ion detection
- How to initialize
- Decoherence times
- Gates
- Readout
  - SET
  - Electrical detection of spin

6 Outlook



Status

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- Other approaches already have working QCs (e.g. ion traps)
- Many ideas using semiconductors: quantum dots, SQUIDS, donors in silicon
- No donor-qubits in silicon yet, therefore:
  - No entanglement
  - No density matrix
  - No fidelity measurements

Why bother?

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Scalability

- Technology to scale solid state devices is remarkable
- Once we have a few qubits scaling should be easy :)

Why quantum computing in silicon?

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Vastly abundant semiconductor that is "easy" to work with:

- SiO_2/Si interface has quite low defect density ($\leq 10^{10}\,/\mathrm{cm}^2$, but that's still $\sim$ 1 defect per $100 \times 100\,\mathrm{nm}^2$ area)
- Very high degree of control over electrical properties
- Allows large scale integration
- Most importantly: long spin coherence times ($\gg 1\,\mathrm{ms}$) because it can be prepared as a nuclear spin-free environment (pure ^{28}Si)

Compare to diamond (e.g. NV defects):

- Larger band gap for high temperature operation
- Low spin orbit coupling
- But difficult to make larger wafers, hard to dope, ...

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Silicon-based QC

Moore's Law

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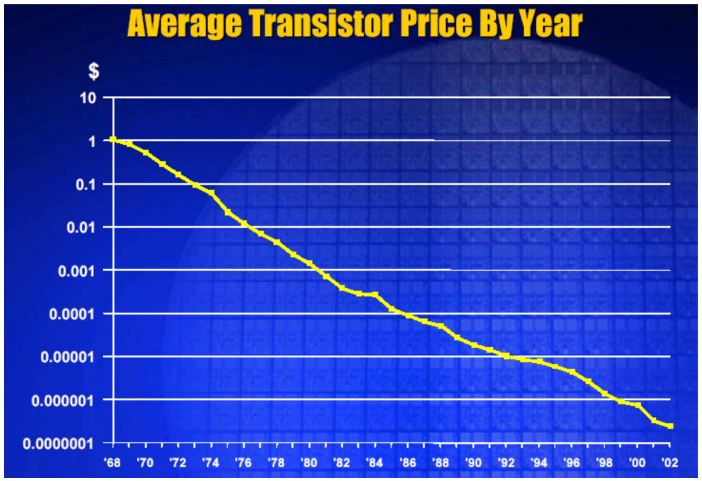
- Exponentially more, cheaper, faster and smaller transistors

more

cheaper



- More transistors made each year than raindrops fall on California

Moore's Law

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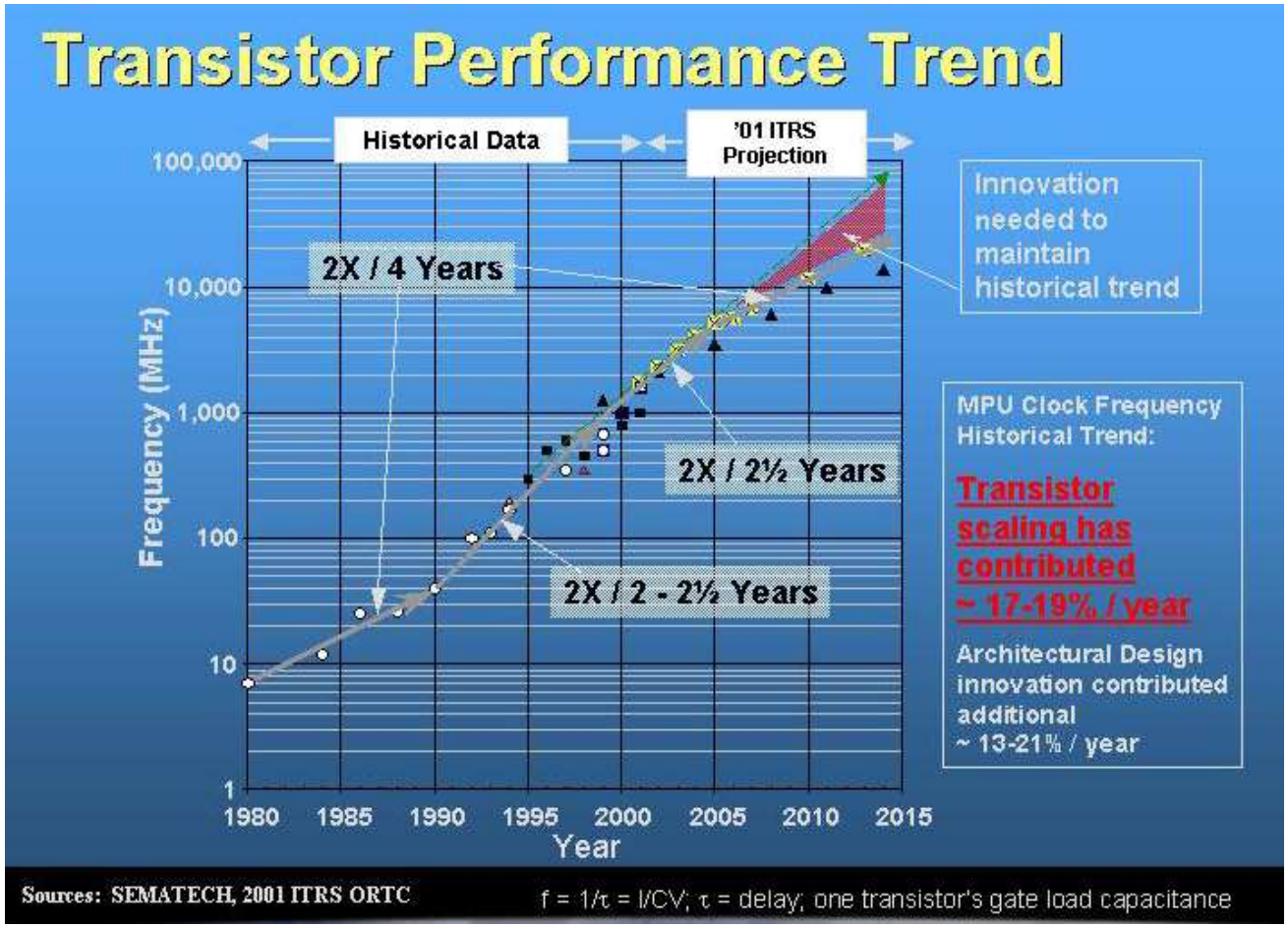
faster



Moore's Law

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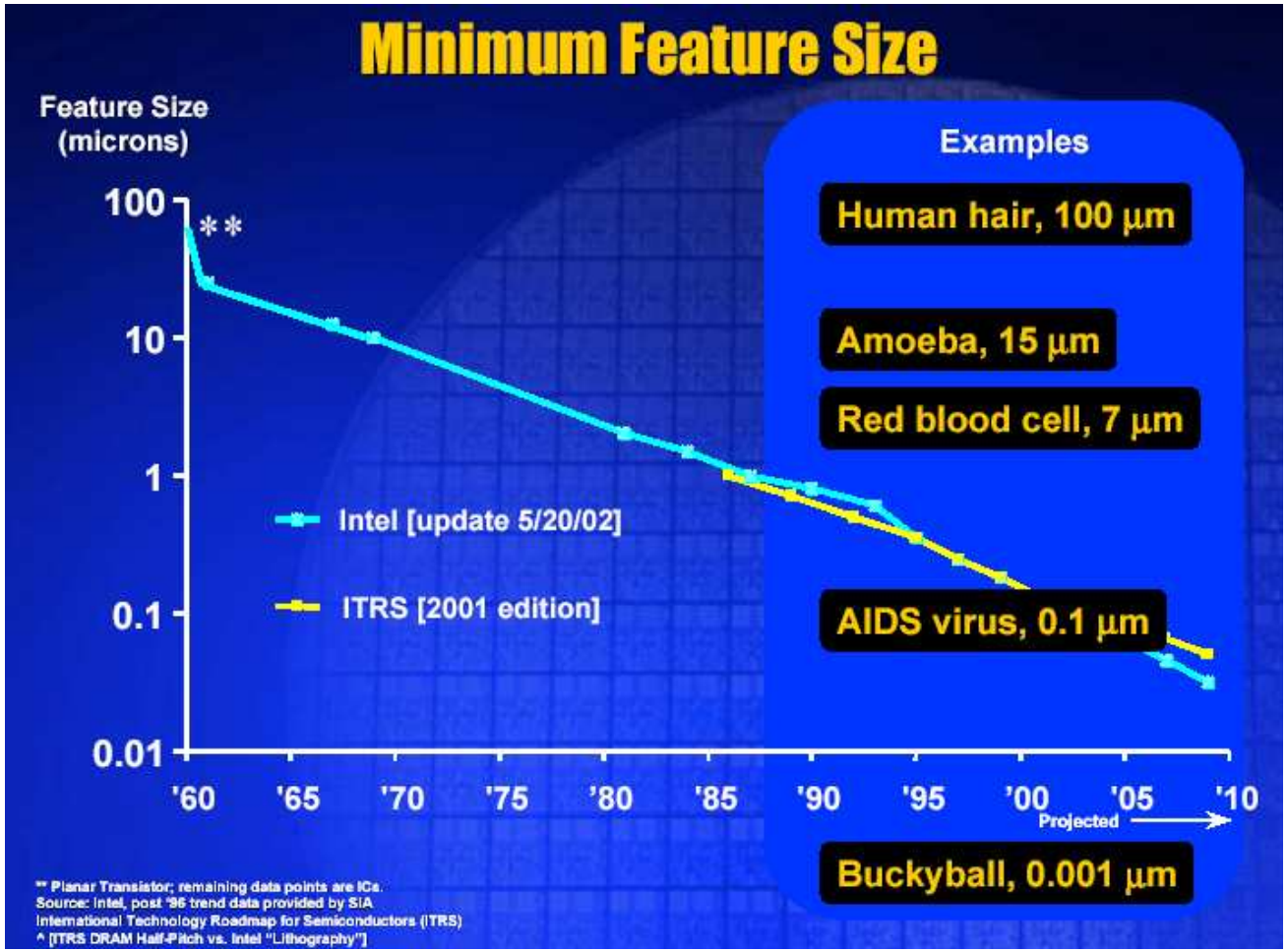
smaller



What's next?

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Scaling of CMOS (complementary metal oxide semiconductor) transistors is projected to reach extremely hard limits in speed and power dissipation by about 2020.

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- Size of CMOS devices will reach the quantum regime
- Natural overlap with what we want to do in QC

DiVincenzo criteria

Criteria for physical implementation of a quantum computer

The DiVincenzo criteria

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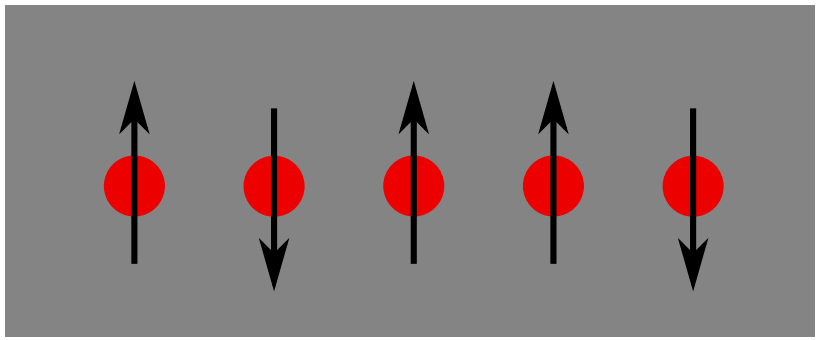
- Well defined expendable qubit array - stable memory
- Initialization in the "000. . ." state
- Universal set of gate operations (e.g. not, cnot)
- Long decoherence time ($\geq 10^4$ operation time, to allow for error correction)
- Read-out: Single-quantum measurements (projective measurement)
- Efficient quantum communication (form, transmit and convert "flying qubits")



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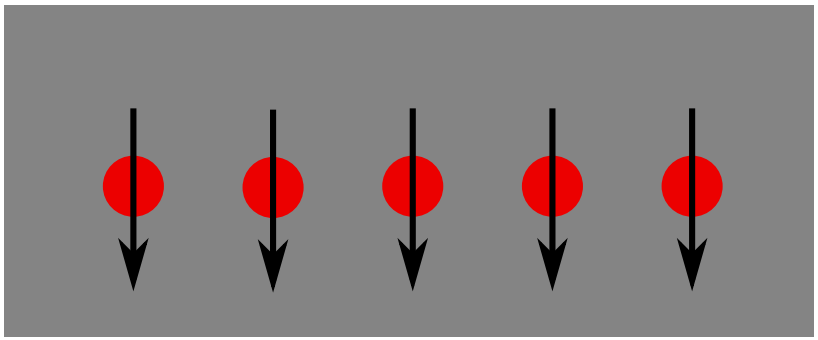

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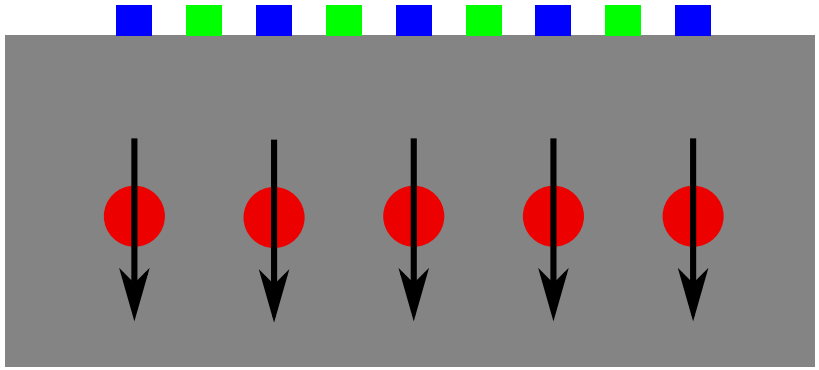

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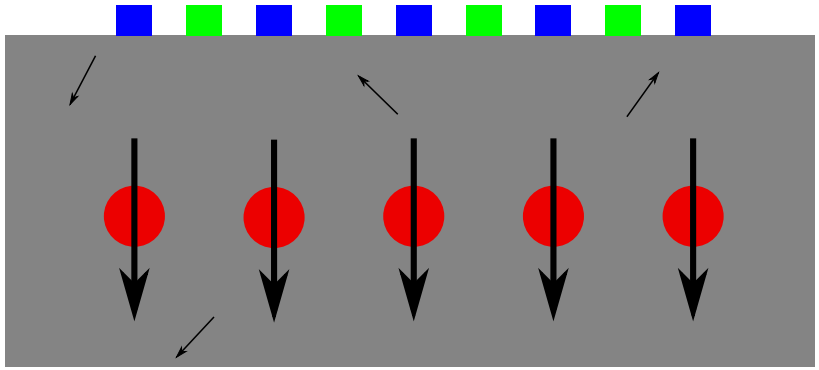

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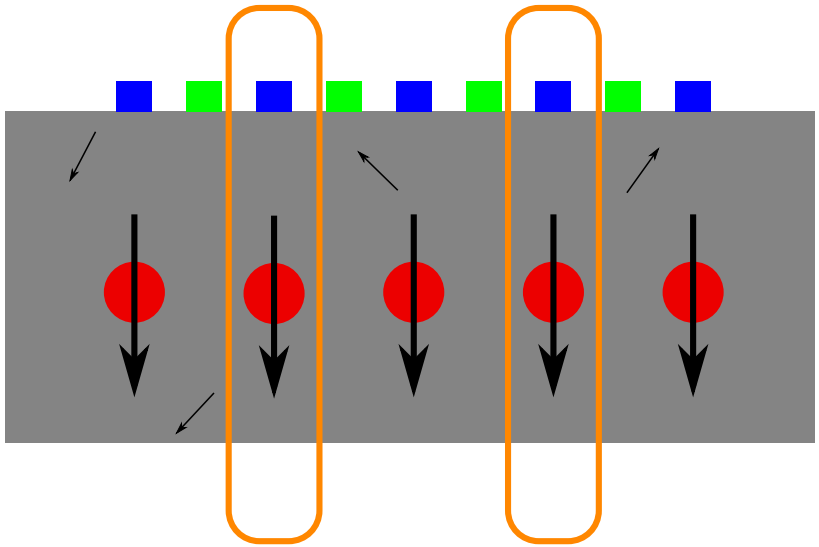

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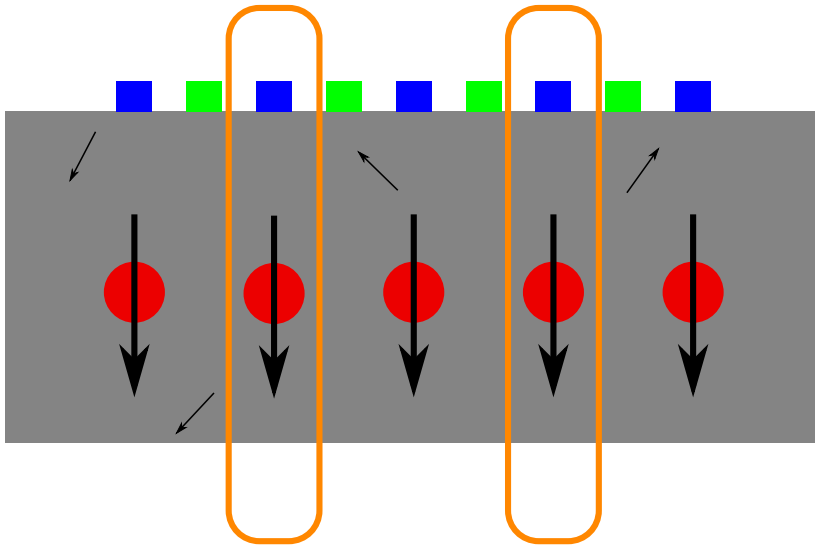

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Kane, Nature **393**,133

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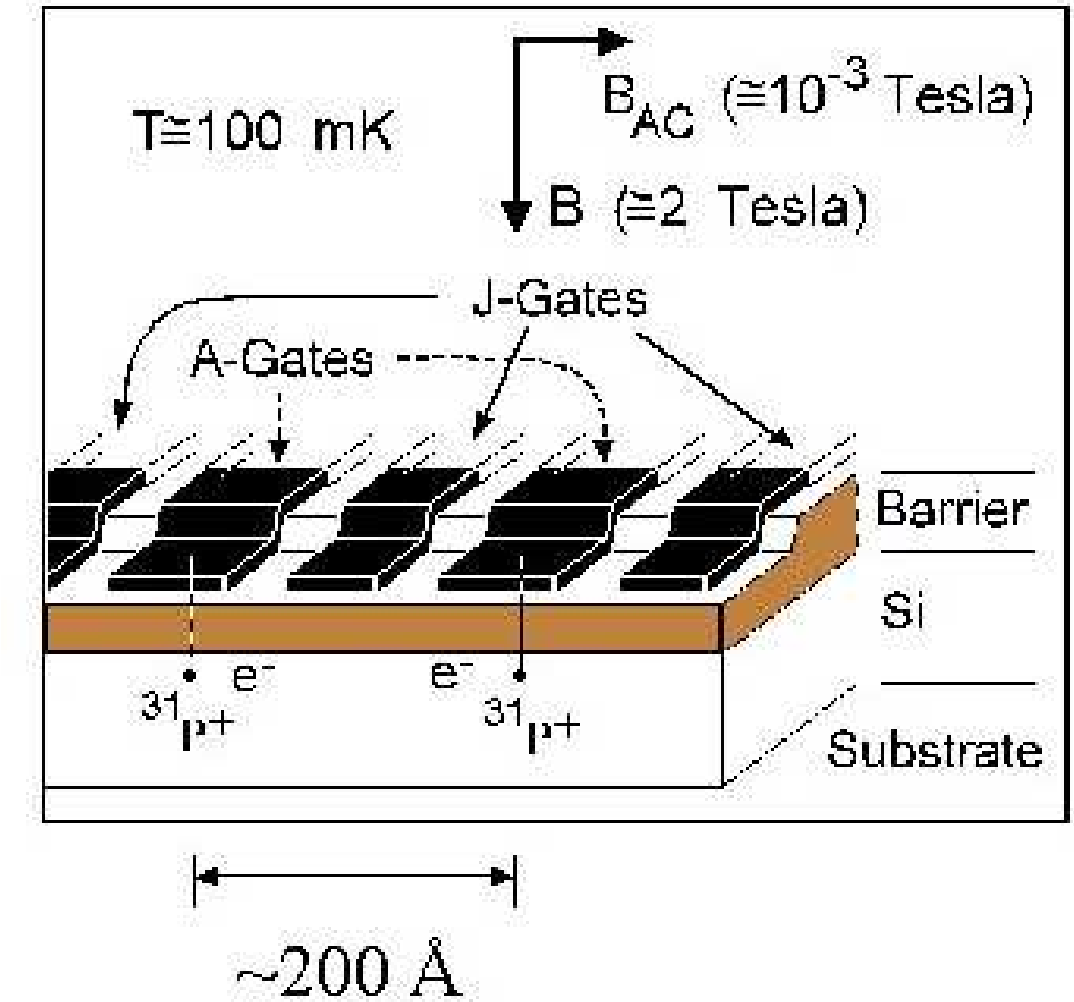

Kane, Nature **393**,133

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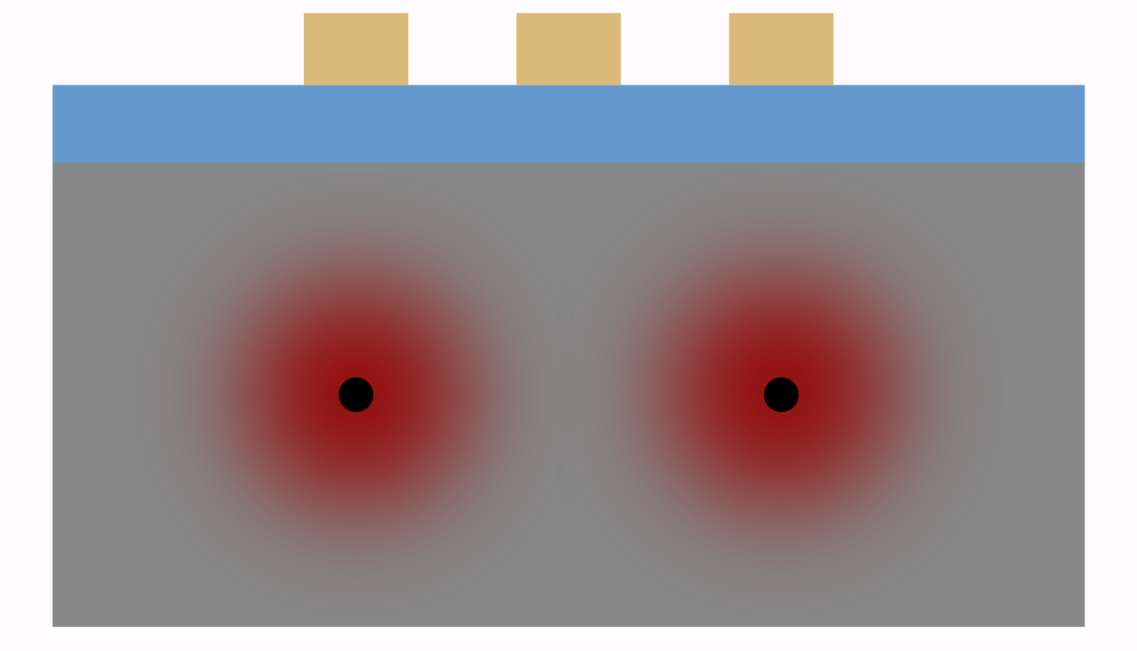

$$\mathcal{H} = \ldots + A\, S_n \cdot S_e + \ldots$$

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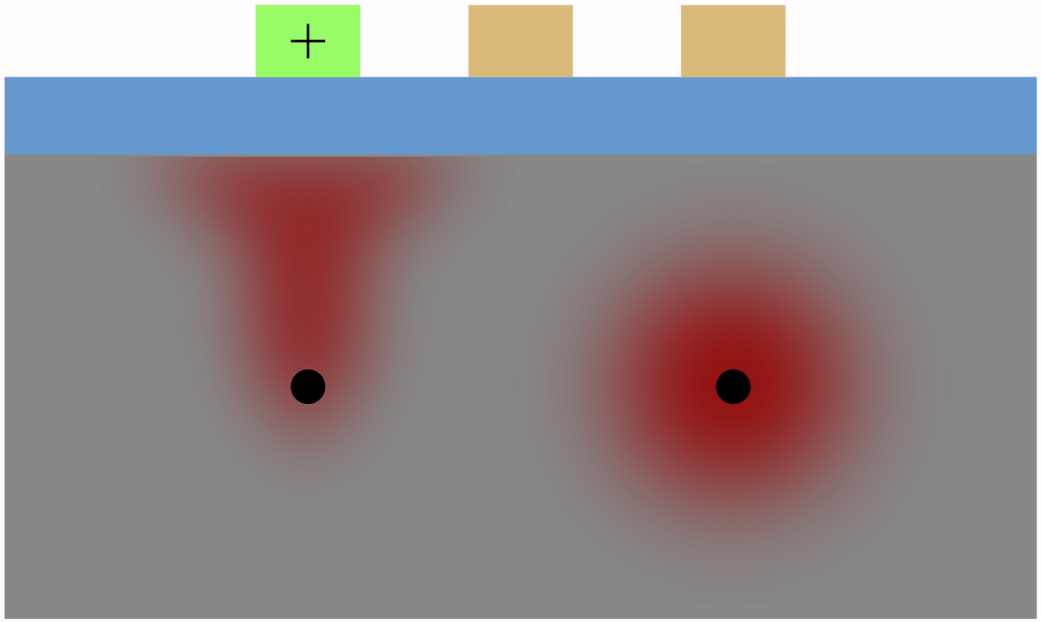

$$A \sim |\Psi_e(x = 0)|^2$$

Kane, Nature **393**,133

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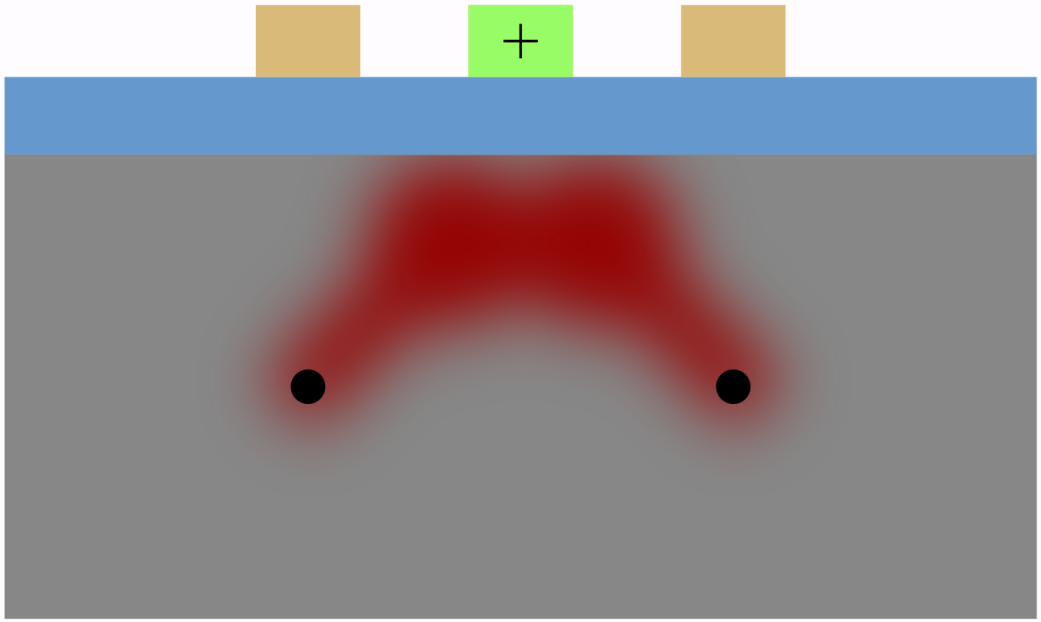

$$\mathcal{H} = \ldots + J\, S_{e1} \cdot S_{e2} + \ldots$$

Accessing donor spin qubits in silicon
from bulk ensemble studies to quantum devices

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1. Randomly bulk-doped natural silicon, ^{28}Si crystals, and ^{28}Si epilayers
   - Spectral and instantaneous diffusion
   - $T_2 \geq 60\,\mathrm{ms}$ at 5 K (Tyryshkin, *et al.*, Phys. Rev. B **68**, 193207 (2003))
2. Randomly ion implanted ^{28}Si epilayers with gate dielectrics (SiO_2, Si_3N_4, Si-H)
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4. Development of single spin readout transistors for projective single spin measurements
5. Integrated multi-qubit arrays, q-logic demonstrations, . . .

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Path to quantum logic demonstrations with donor electron spin qubits in silicon

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1. Develop devices for single spin readout:
   Spin dependent transport in transistors
2. Develop a technique for qubit array formation:
   Single ion implantation with scanning probe alignment
3. Process and materials studies for T_2 optimization:
   Spin dynamics in pre-device structures
4. Demonstration of quantum logic:
   Formulate logic protocol by mapping of physical interactions to qubit gates

The team:

- Theory - fabrication - measurement collaboration between LBNL (T. Schenkel - PI), UC Berkeley (J. Bokor, B. Whaley), and Princeton University (S. Lyon, A. Tyryshkin)

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Possible donor atoms

Error budget in donor qubit placement

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Ion beam spot size
- $\sim 5\,\mathrm{nm}$?

Ion straggling
- $\sim \frac{1}{\text{ion mass}}$
- Energy dependence

Dopant diffusion
- Dopants diffuse during annealing
- Dopant specific
- P: interstitial-mediated diffusion, oxidation-enhanced segregation
- As: mixed vacancy / interstitial diffusion
- Sb: vacancy diffusion, oxidation-retarded segregation
- Bi: transient-enhanced diffusion

Scattering kinematics favors implantation of heavy donors into Si

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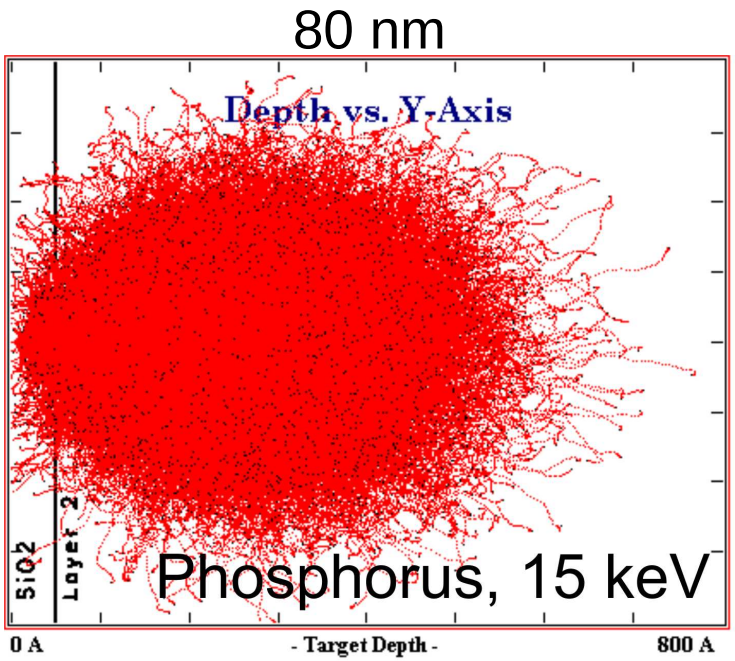

- Implantation to a depth of 25 nm is accompanied by a much narrower dopant distribution (less straggling) for dopants heavier then silicon
- A straggling of 10 nm can be achieved with 120 keV Bi, or 15 keV P (SRIM estimates)
- We want to reserve As for S/D contacts

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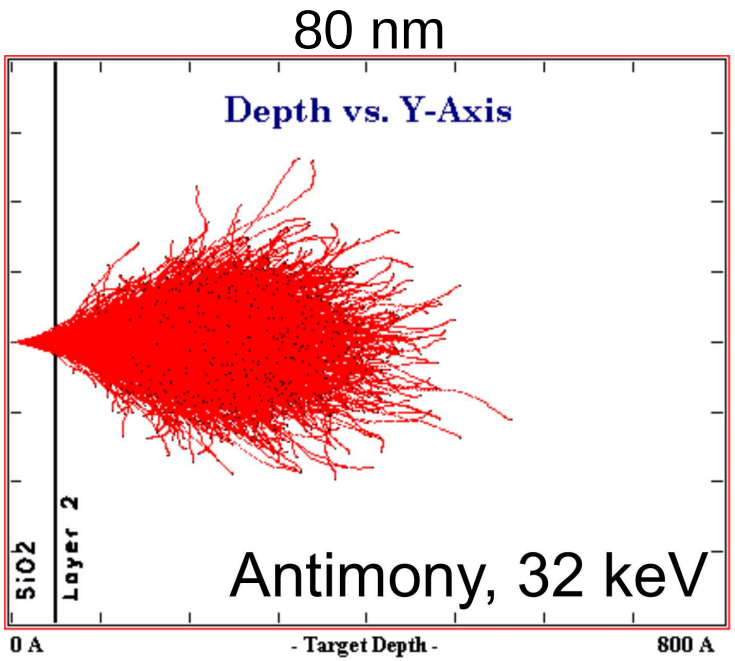

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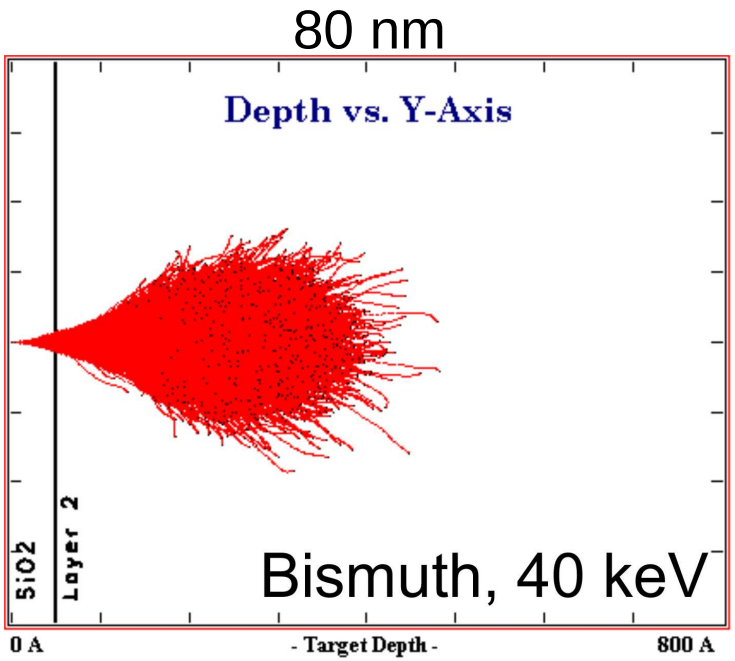

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Annealing – P

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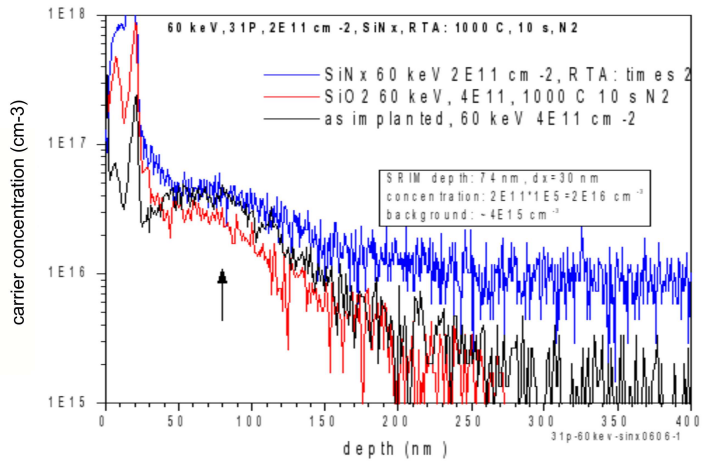
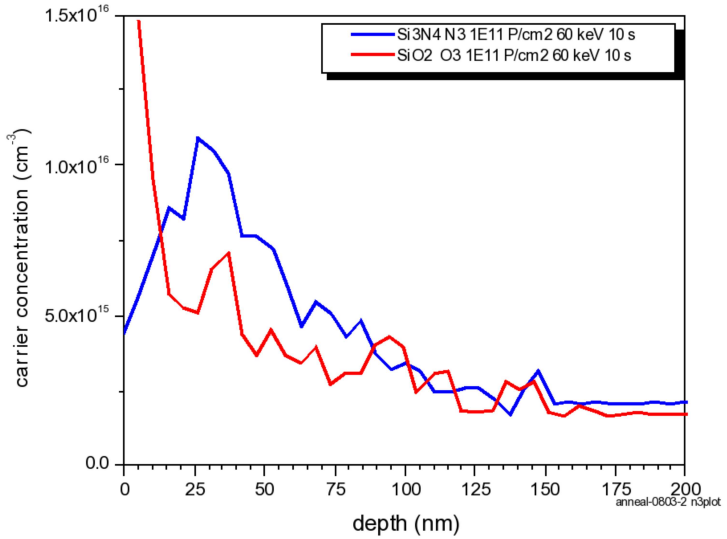
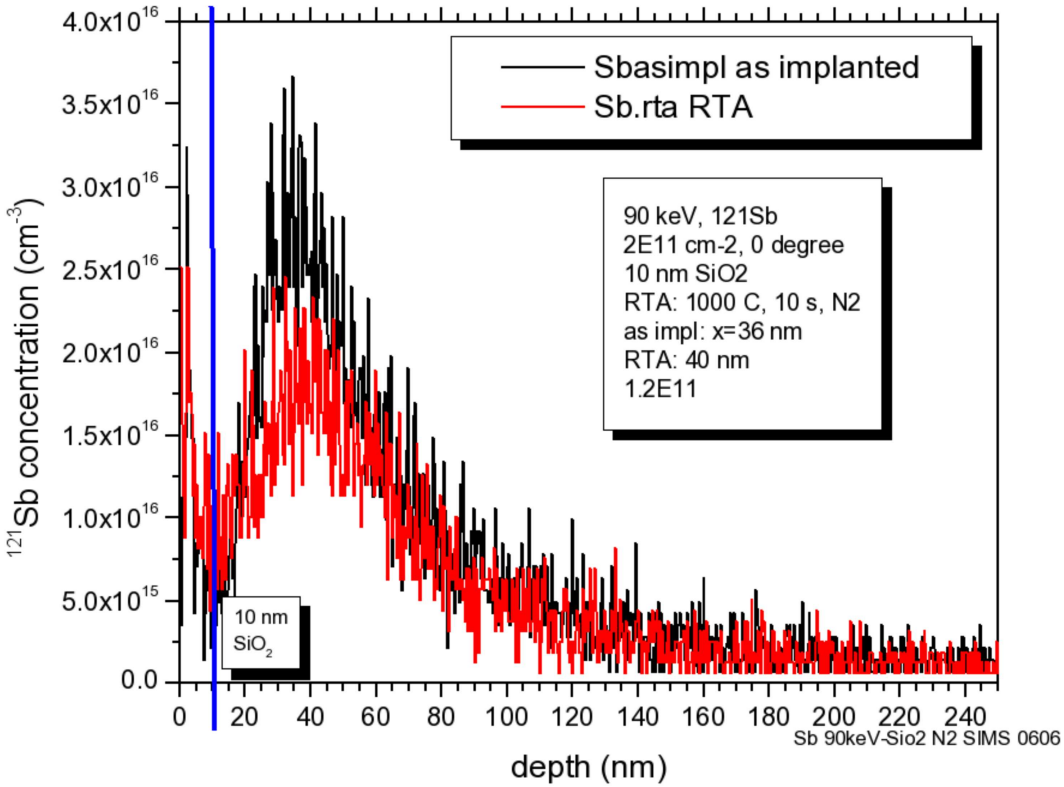




- P in Si: OED and large straggling due to symmetrical scattering

Annealing – Sb



- Sb – Si, 90 keV FWHM $\sim 45\,\mathrm{nm}$ after RTA, average depth $\sim 40\,\mathrm{nm}$, dose: $2 \times 10^{11}\,/\mathrm{cm}^2$

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Single donor placement – bottom up approach

Qubit arrays bottom up: STM hydrogen lithography

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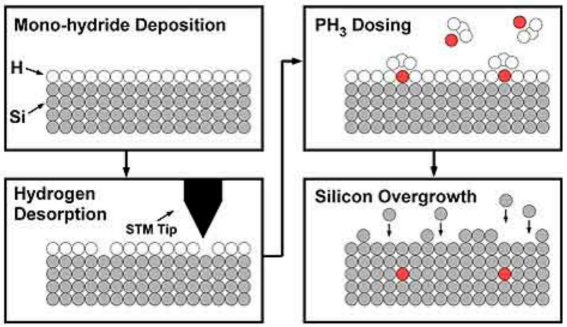
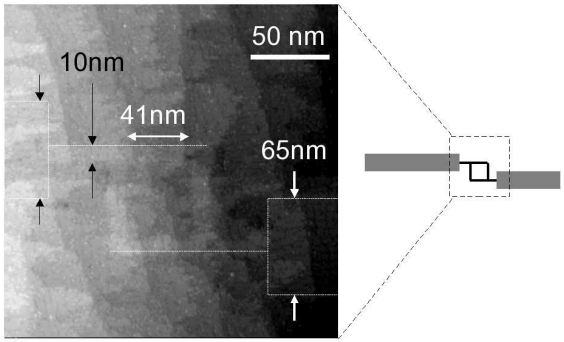


J. O'Brien, *et al.*, Univ. New South Wales, Sydney



Aharonov-Bohm ring of P atoms connected to pre-implanted contacts, and overgrown with Si on Si (100); TC. Shen, J. Tucker, *et al.*, 2003

- Desorption of H with low energy electrons ($\sim 10\,\mathrm{eV}$) from the STM tip
- Advantage: atomic resolution
- Problems: encapsulation, dopant activation, device integration, surface chemistry sensitivity

Qubit arrays bottom up: STM hydrogen lithography

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PHYSICAL REVIEW B **76**, 085403 (2007)

One-dimensional conduction properties of highly phosphorus-doped planar nanowires patterned by scanning probe microscopy

Frank J. Rueß,[1,2,*] Bent Weber,[2] Kuan Eng J. Goh,[1,2] Oleh Klochan,[2] Alex R. Hamilton,[2] and Michelle Y. Simmons[1,2]

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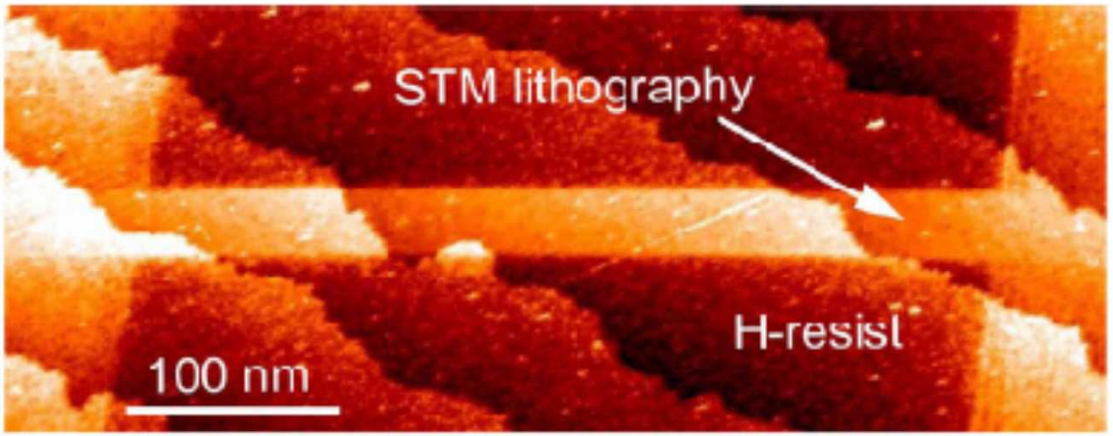
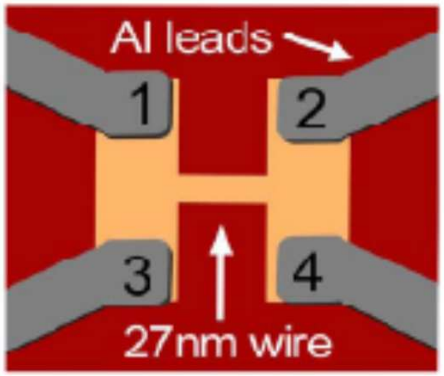
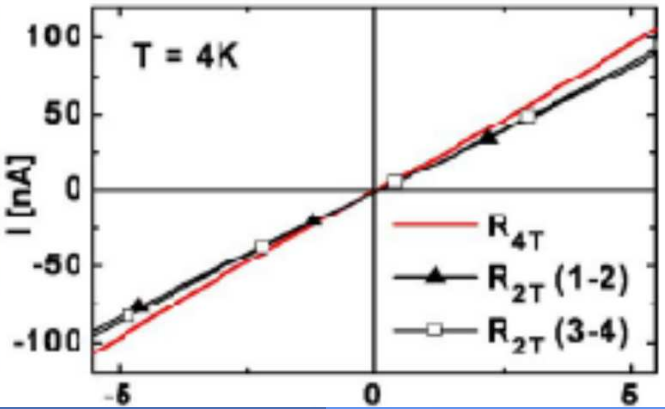
(Received 28 December 2006; revised manuscript received 2 April 2007; published 2 August 2007)







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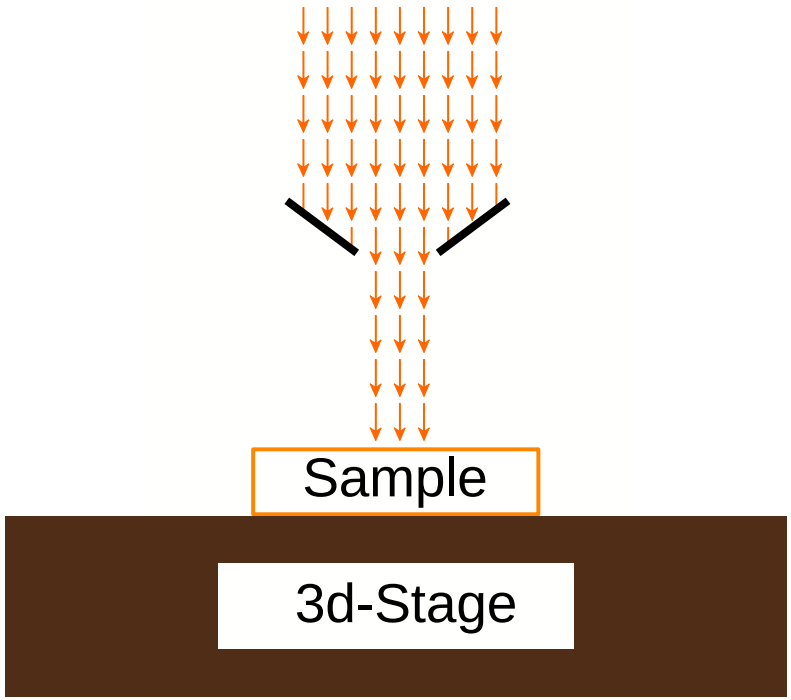
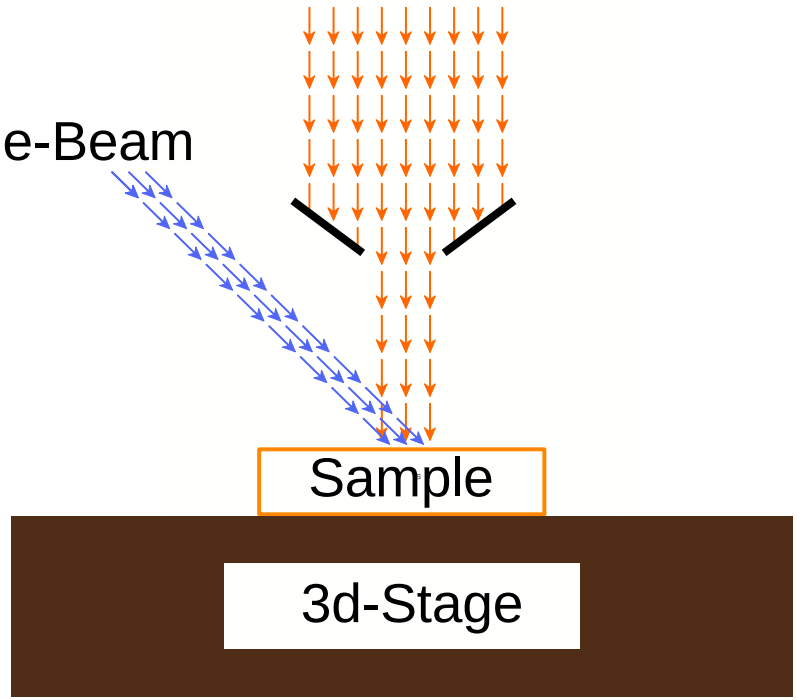
Single donor placement – Implantation

The idea



- Ion beam, e.g. FIB
- Combined with an e-beam
- Scanning probe

The idea



- Ion beam, e.g. FIB
- Combined with an e-beam
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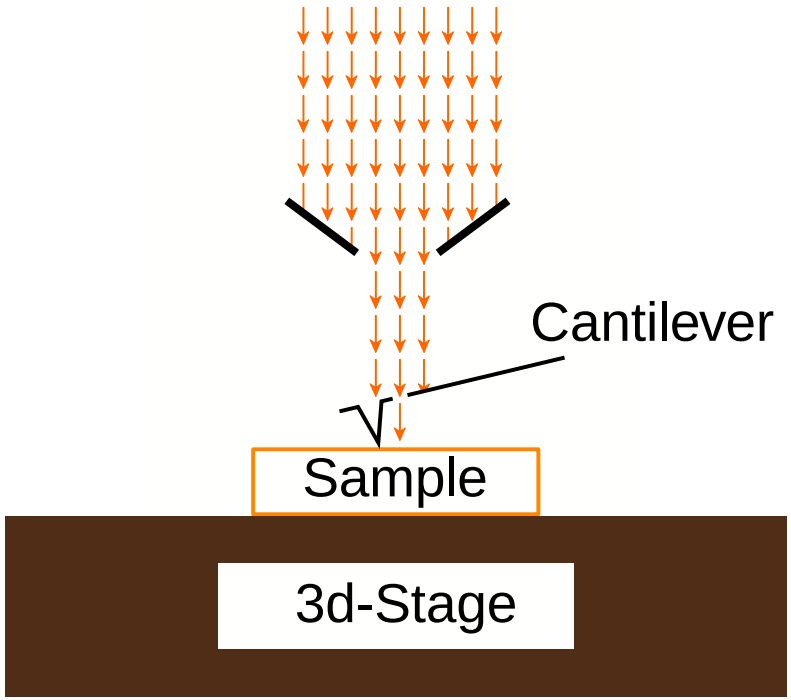
The idea



- Ion beam, e.g. FIB
- Combined with an e-beam
- Scanning probe

Standard atomic force microscope (contact mode)

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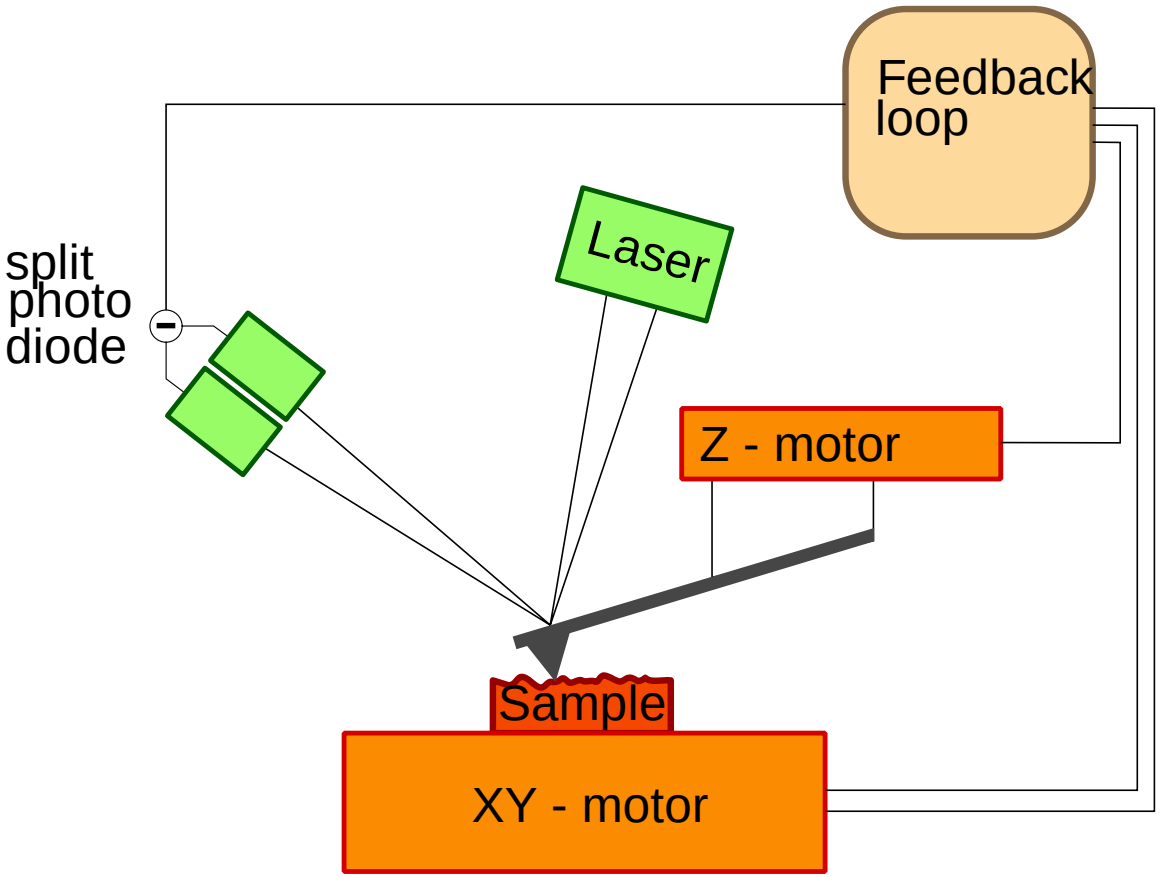

Piezo-resistive cantilever

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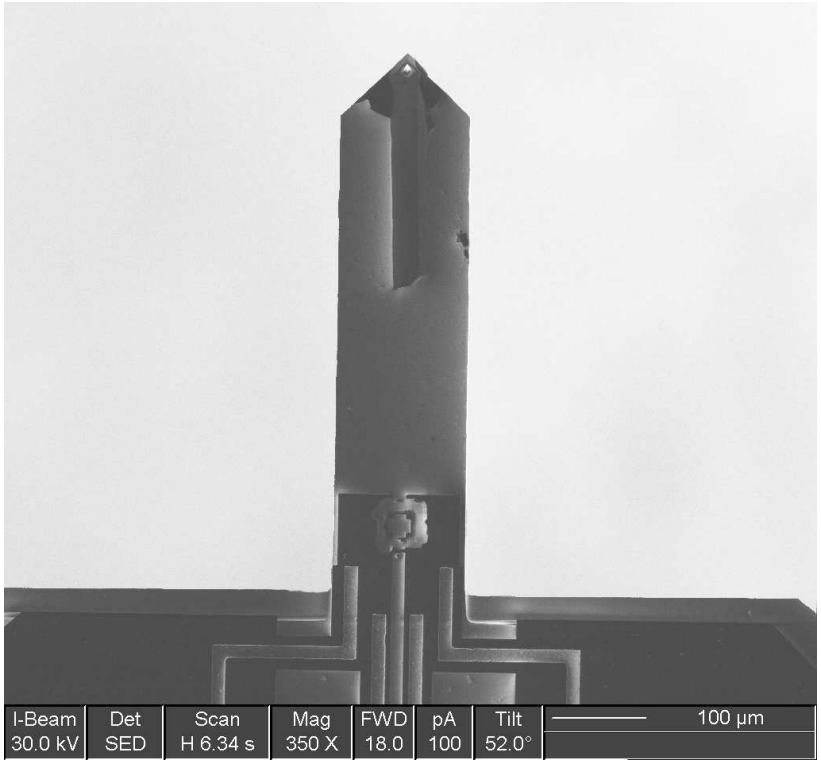
- No optical elements, compact and UHV-compatible
- Using commercially available cantilevers glued onto piezo-resistive ones



Piezo-resistive cantilever

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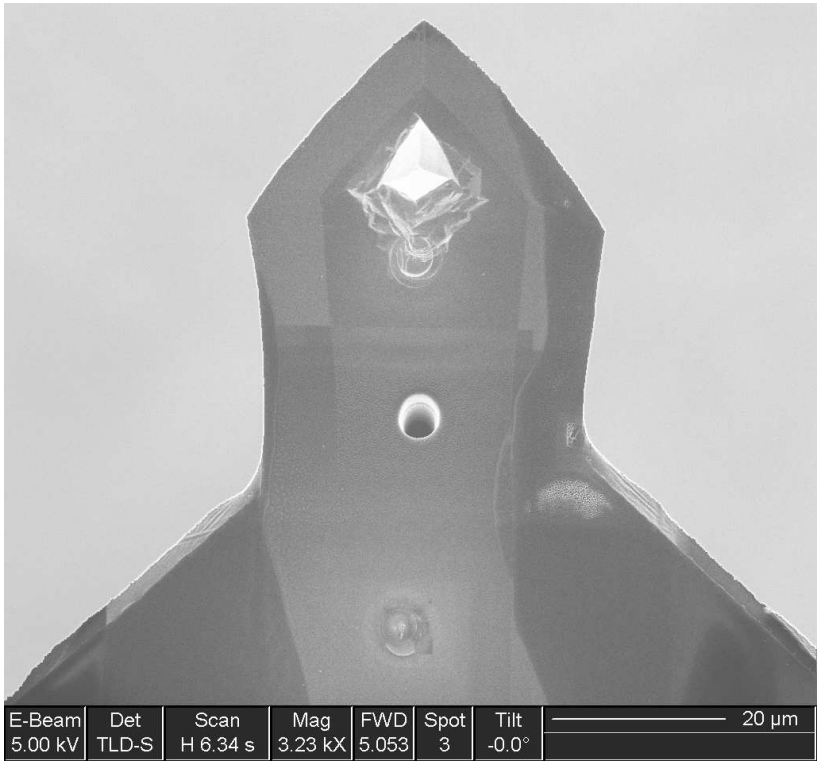
- Holes drilled with a FIB, you can see three holes from several micro-meters down to 100 nm.



Setup

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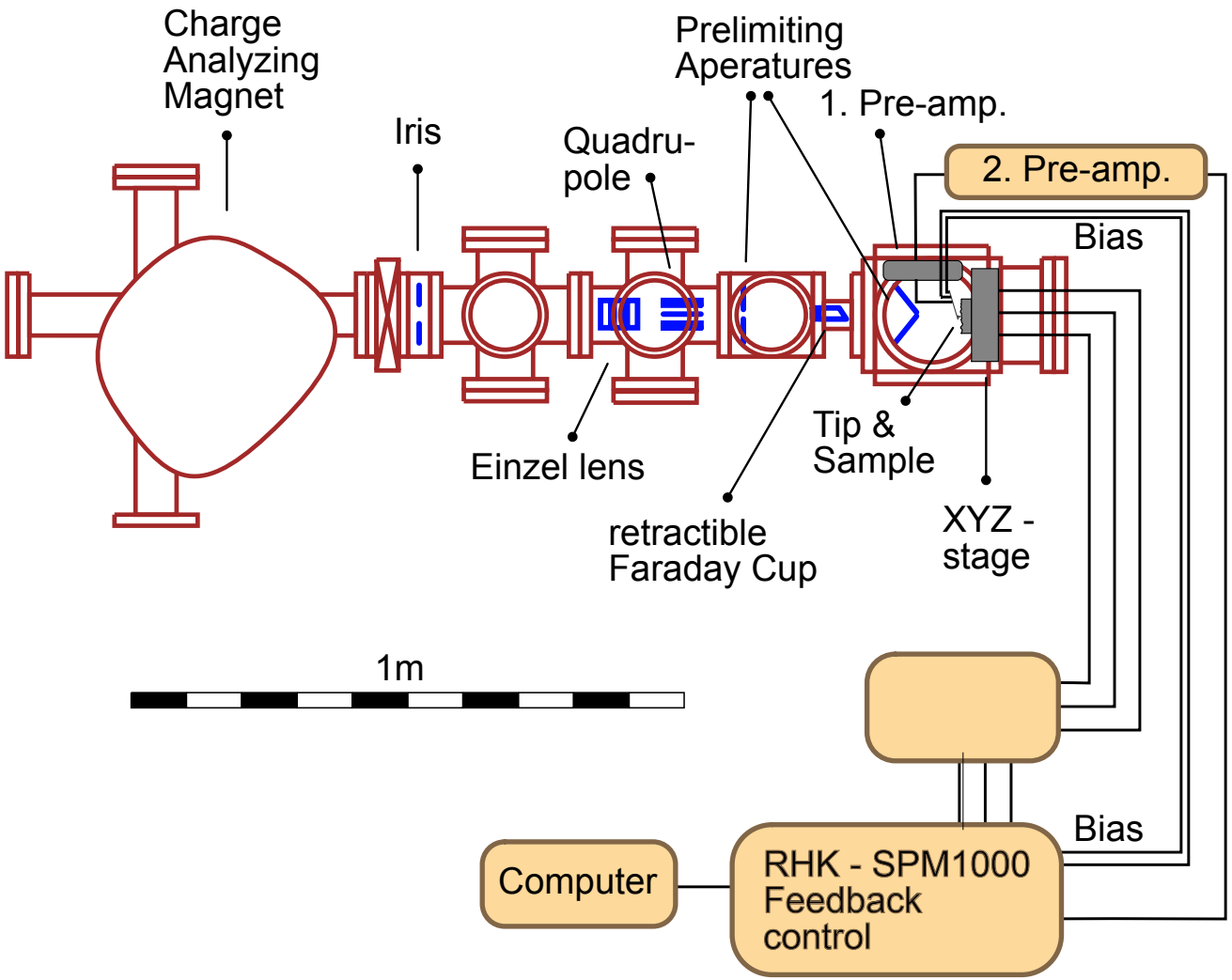

Ion beams

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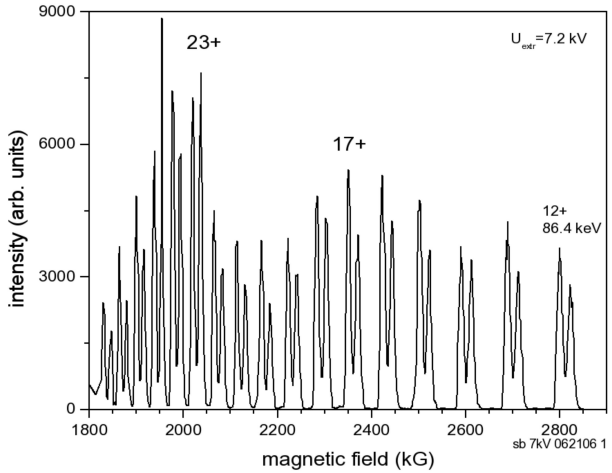
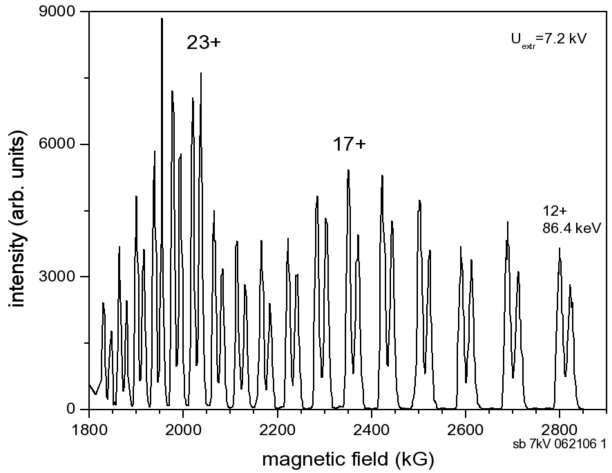


$$m\frac{v^2}{r} = qvB, \quad \frac{1}{2}mv^2 = qeU$$

- Low density plasma source for low ion charge states and molecular ions, e.g. $^{15}N^{2+}$, Ar^{1to3+}, 1 to 15 keV
- ECR (Electron Cyclotron Resonance) source, for low to medium ion charge states, e.g. Sb^{3to10+}, 3 to 150 keV
- EBIT (Electron Beam Ion Trap) for medium to high ion charge states, e.g. Sb^{4to40+}, 10 to 500 keV

Ion beams



$$B = \frac{\sqrt{2eU}}{r}\sqrt{\frac{m}{q}}$$

- Low density plasma source for low ion charge states and molecular ions, e.g. $^{15}N^{2+}$, Ar^{1to3+}, 1 to 15 keV
- ECR (Electron Cyclotron Resonance) source, for low to medium ion charge states, e.g. Sb^{3to10+}, 3 to 150 keV
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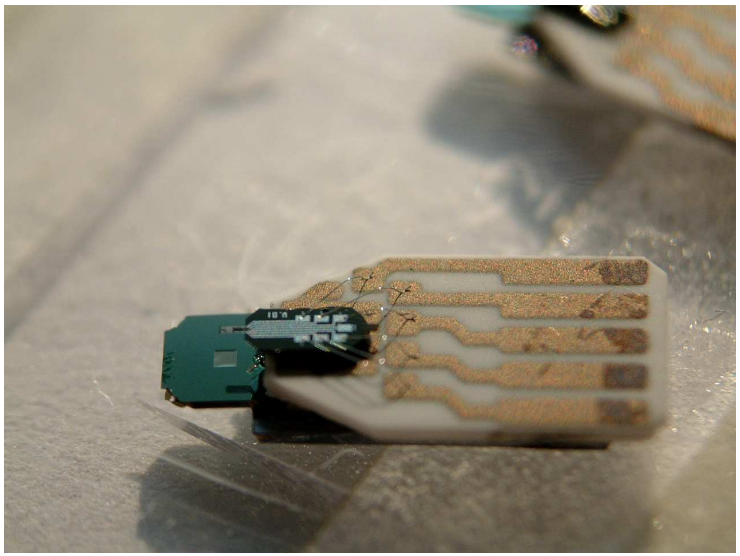
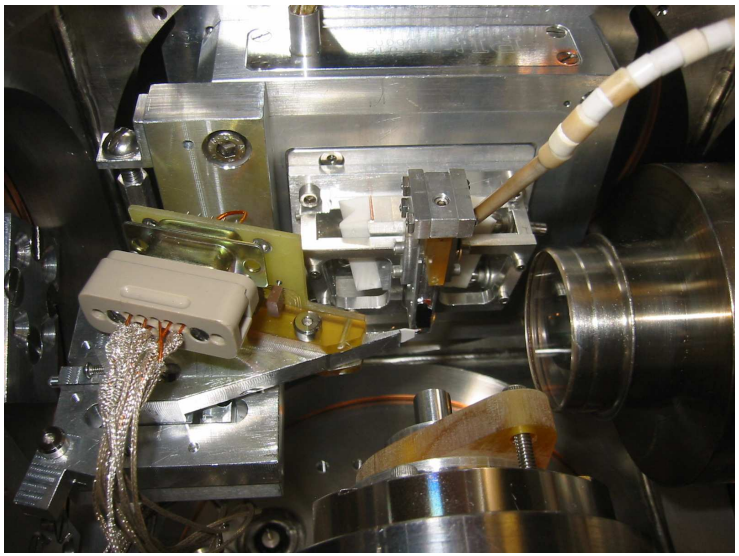
AFM





- SII-SPM setup connected to high vacuum beam line
- Scanning range of target stage is $0.1 \times 0.1\mathrm{mm}^2$
- Probe tip can be moved across a distance of 1 mm
- Piezo-cantilevers co. I. Rangelow, Kassel University
- Holes down to 2-5 nm diameter by FIB and TEM processing

Implantation results

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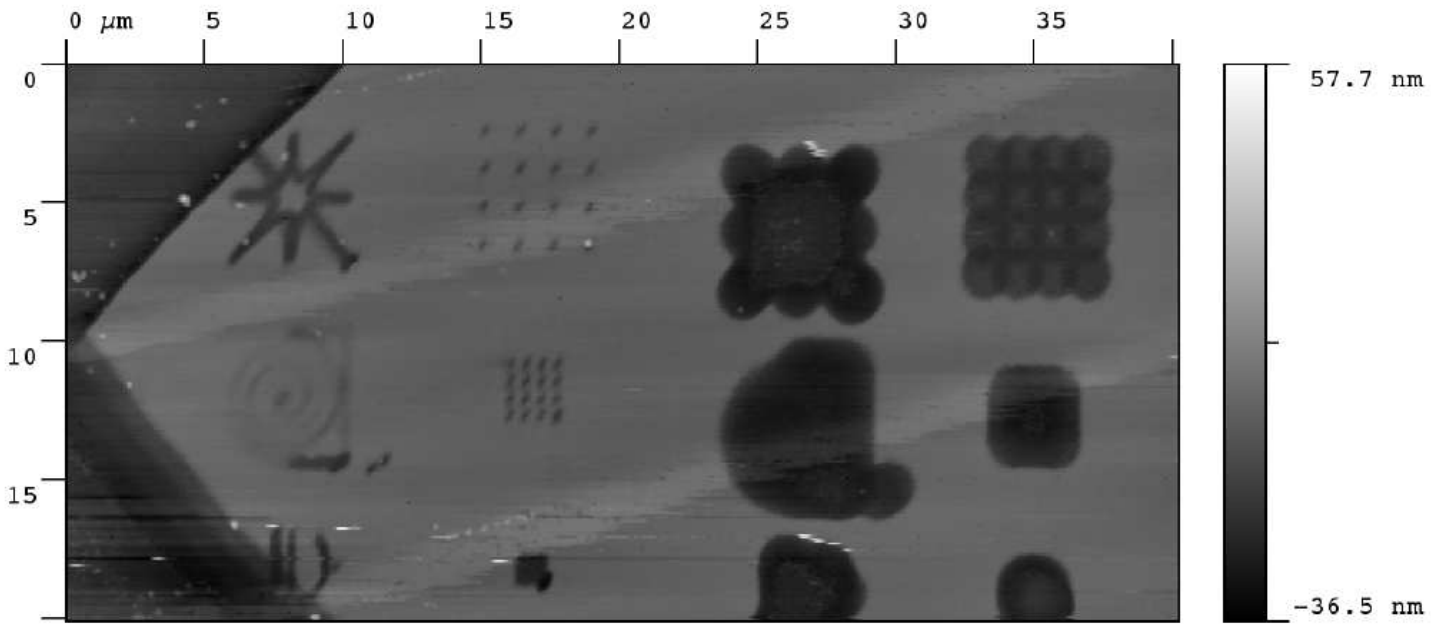

- A selection of patterns, roughly 120 nm wide; ion beam Ar^{2+}, 6 keV

Ultimate limit in dopant placement by ion implantation?

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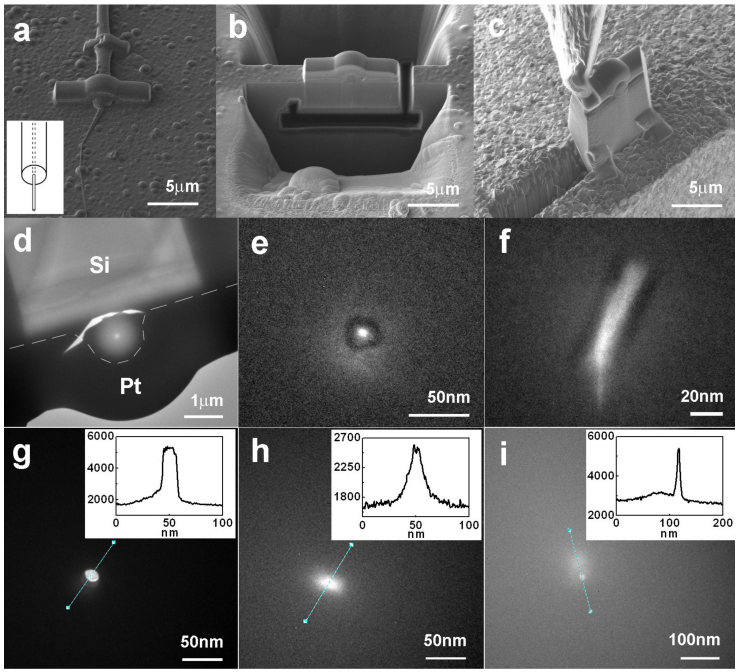

Electron transport through a single CNT, Images from Lee Chow, Univ. Central Florida, Appl. Phys. Lett. **91**, 103101 (2007); tests with ions in progress

- Straggling: minimize with low energy and high Z, can get $< 5\,\mathrm{nm}$
- Diffusion/segregation: Sb stays put
- Spot size for CNTs $\sim 1 - 20\,\mathrm{nm}$
- A few nm placement accuracy is possible!
- (Can also use $< 10\,\mathrm{nm}$ e-beam apertures in aFETs, but CNT collimators would work on any unstructured sample)

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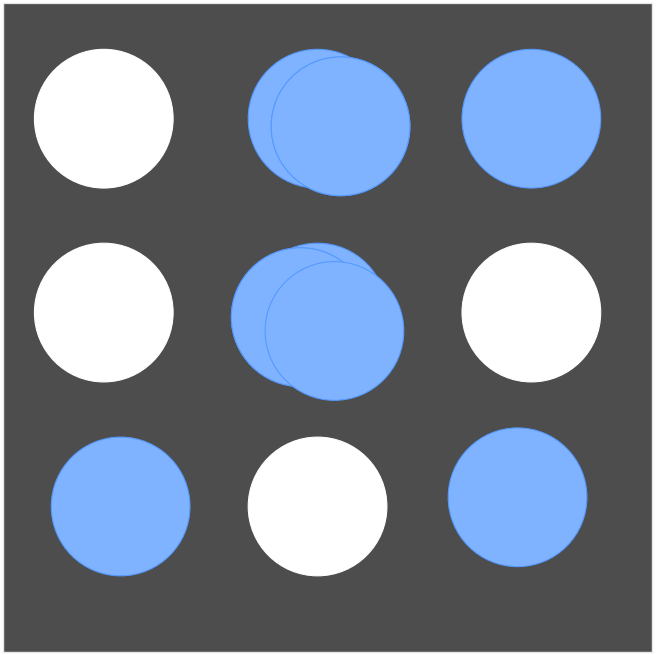
Single ion implantation

Beating statistics

Poisson distribution



- Distribution of probabilities for implantation of ions where the implantation probability is small ($\ll 1$) for each incident ion and the number of incident ions is large ($\gg 1$)
- If on average, one ion is implanted, then the probability for two adjacent ion hits is only 13%

Implantation with single ion detection

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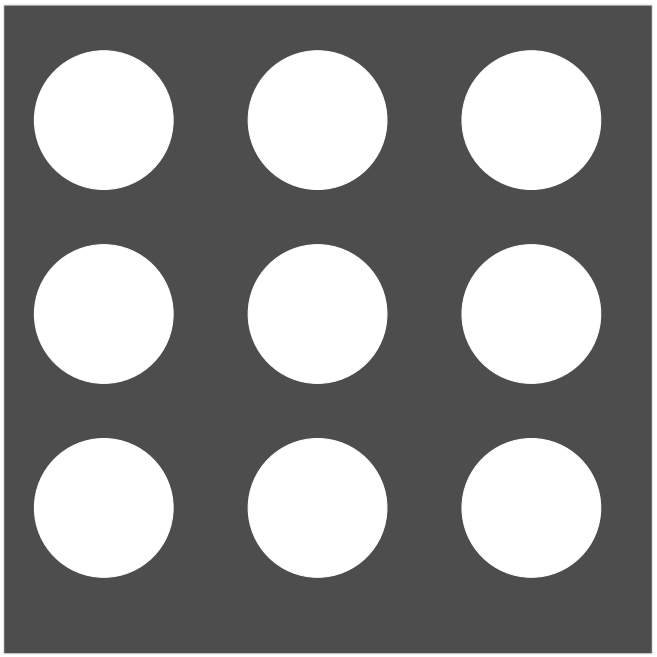
- Need single ion detection for each implantation

Detect every ion



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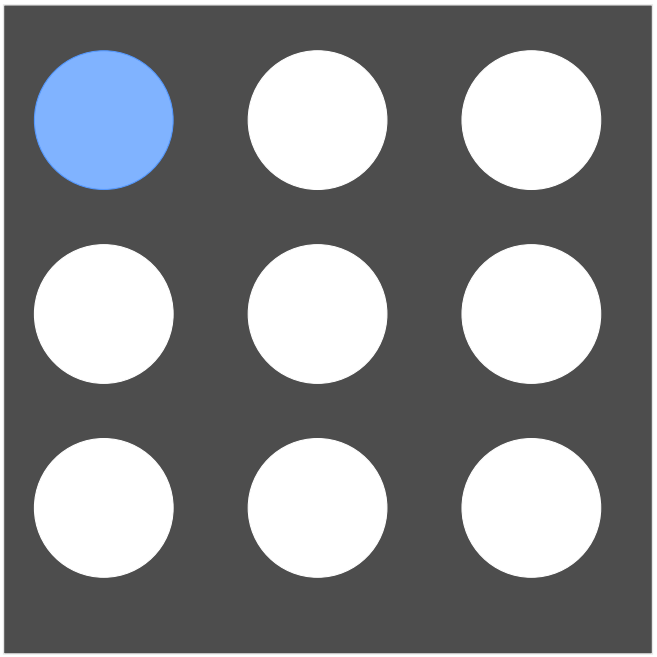

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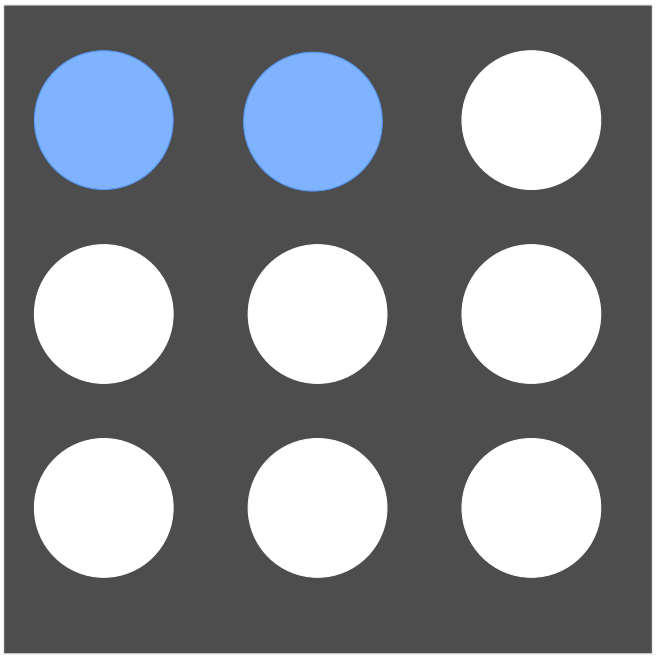

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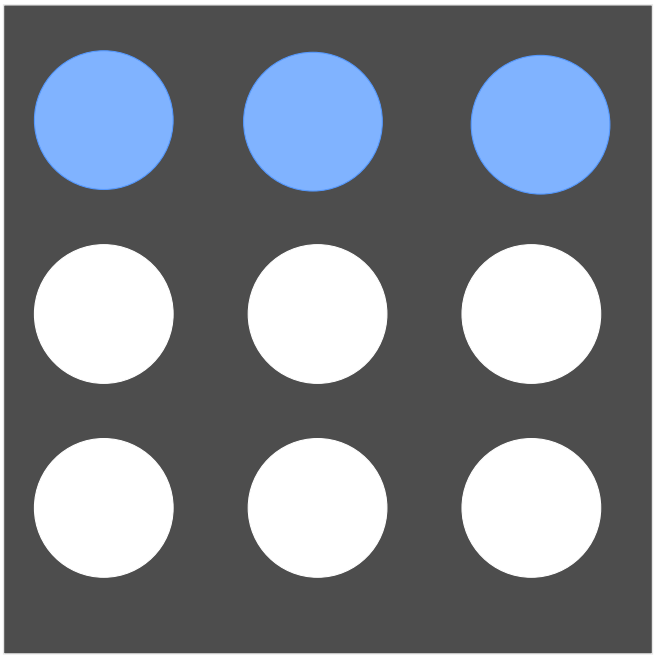

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- Need single ion detection for each implantation

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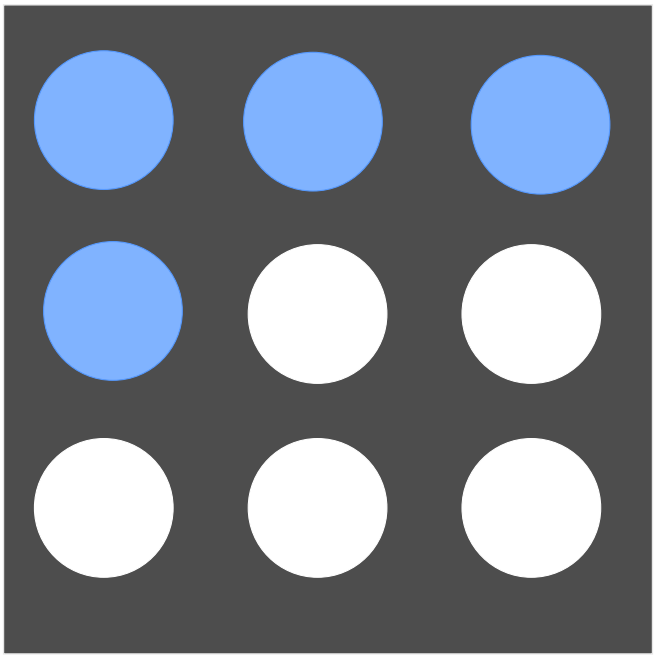

How to detect ions?

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Detection schemes:

- Use kinetic energy (potential energy can help): collect electron-hole pairs in a diode structure
- Look at secondary electrons
- Sense implantation damage: implant into transistor and sense change in source-drain current

Ion beam-induced charge

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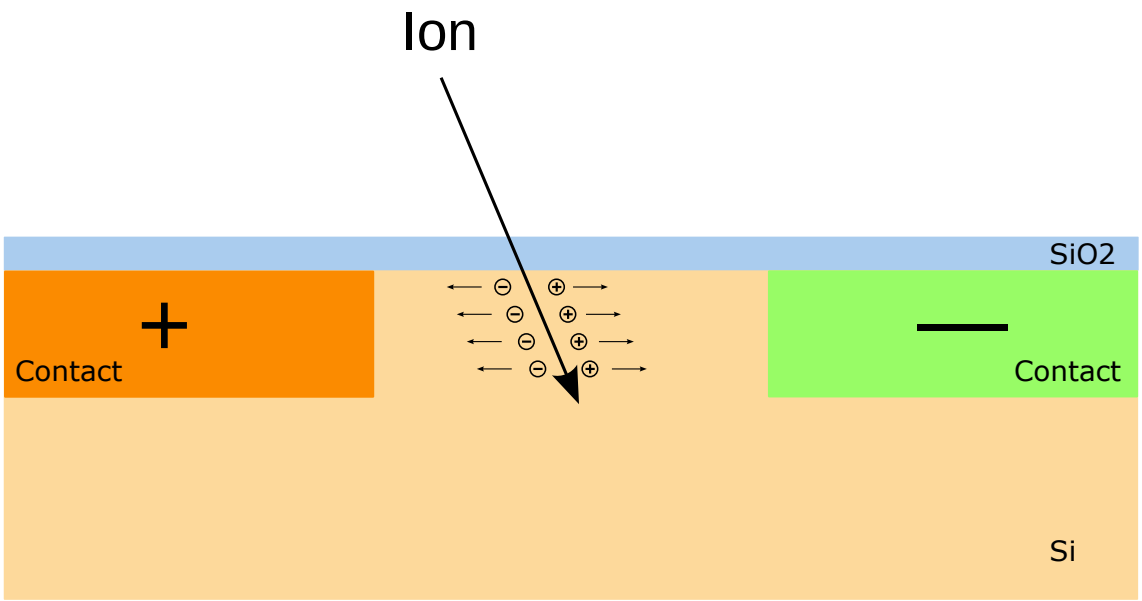

- Jamieson *et al.* can detect single ion hits for 14 keV P^+

Secondary electrons

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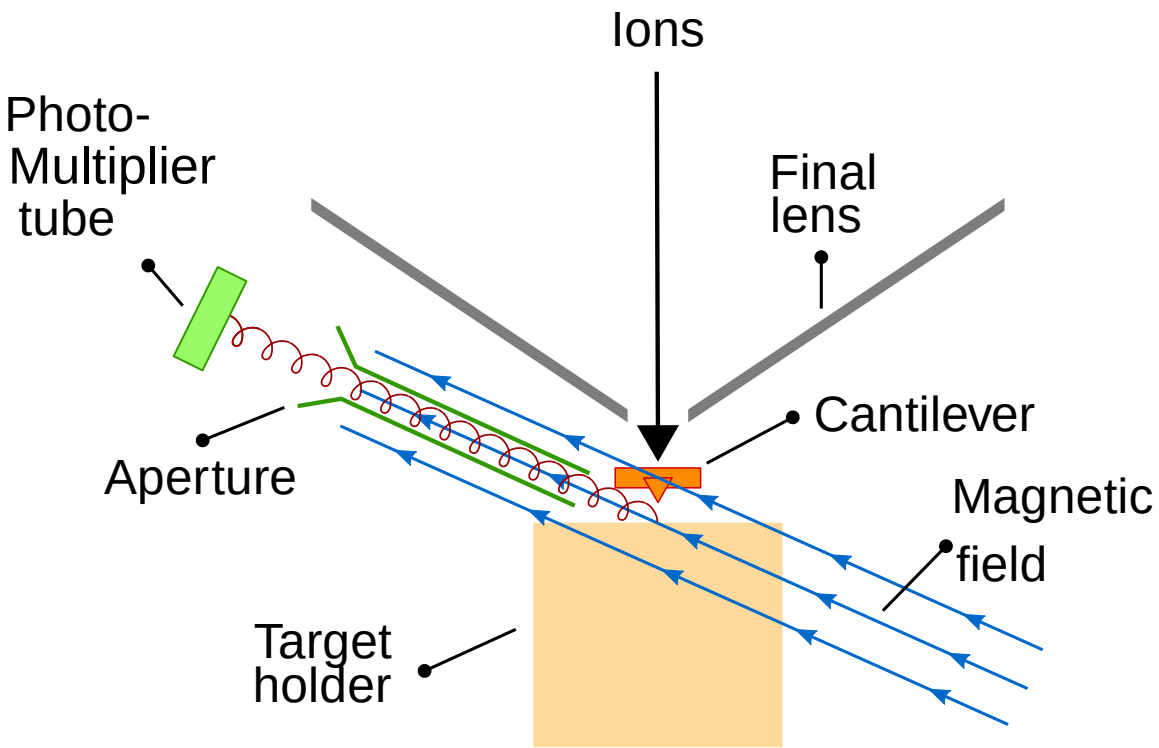

- Universal: should work for any material, any ion
- Highly charged ions create 10-100 secondary electrons on impact

Single ion detection in readout transistors through impact induced mobility changes

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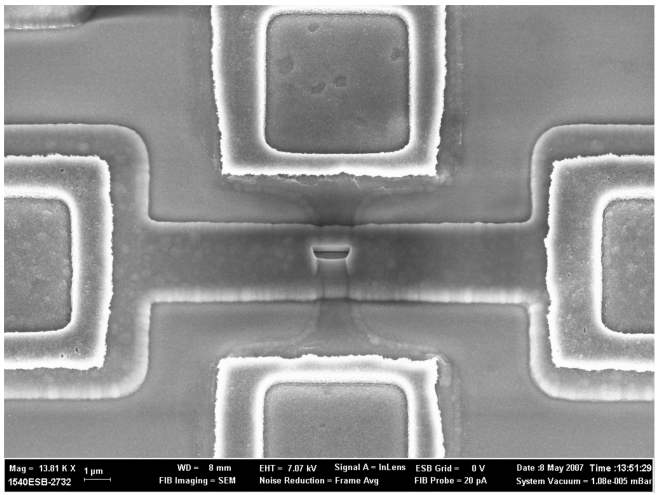

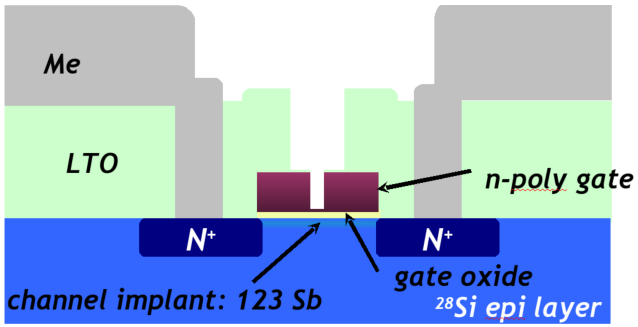

- Use transistors made at the UCB Microlab
- Open a hole in the gate using a FIB

Single ion detection in readout transistors through impact induced mobility changes

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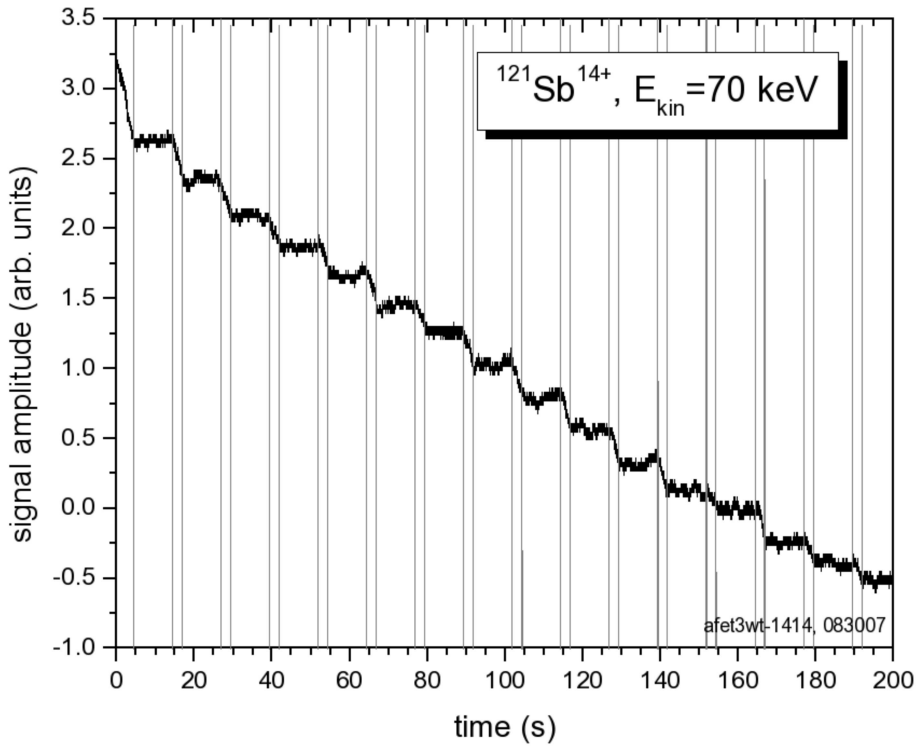

- Single ion doping of transistor channels through detection of current transients from single ion impacts ($dI \sim 20\,{}^{\mathrm{nA}}/_{\mathrm{ion}}$ in $2 \times 2\,\mu\mathrm{m}$ aFETs)

Single ion detection in readout transistors through impact induced mobility changes

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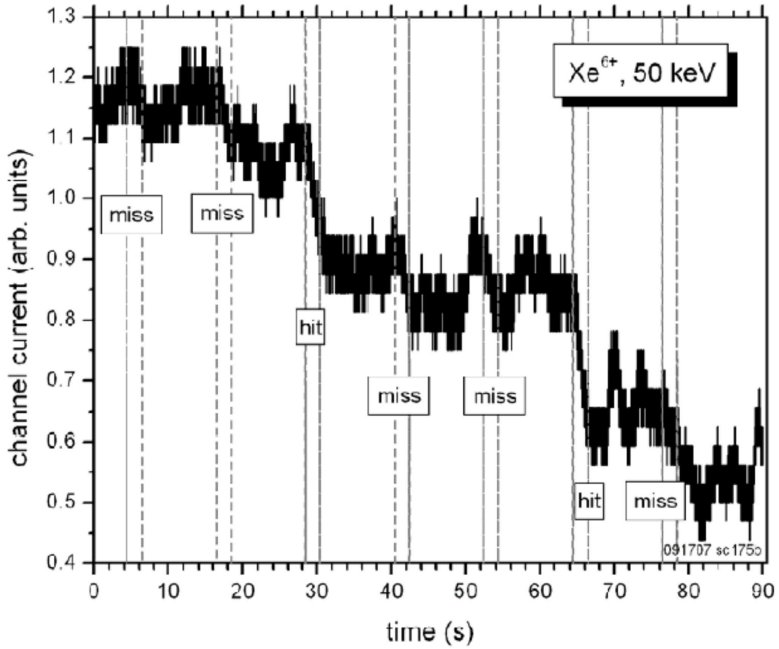

- Room temperature measurements of ion-induced current changes in $2 \times 2\,\mu\mathrm{m}$ FETs
- Can greatly improve single impact amplitude with some cooling and smaller devices
- Appl. Phys. Lett. **91**, 193502 (2007)

Single ion detection in readout transistors through impact induced mobility changes

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advantages

- Room temperature measurements
- Use existing structure that we plan to use for spin-readout
- Works for different ions

disadvantages

- Detector has to be integrated into target
- Not universal for all materials

Single ion detection in readout transistors through impact induced mobility changes

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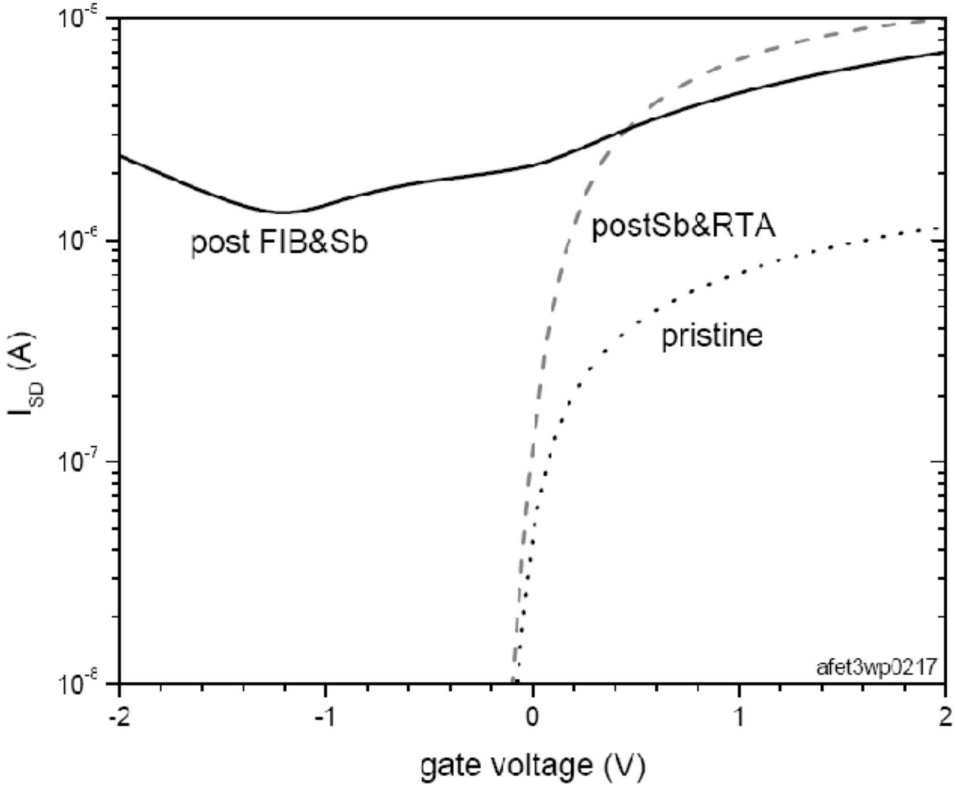

- Important to be able to anneal after implant
- Poly and tungsten electrodes allow annealing post single ion implantation of readout transistors
- No shift in threshold voltage

Initialization

Initialization

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- Polarization at low temperature, in strong magnetic field, $kT \ll g\mu_B B$
- kT (0.3 K) = 0.026 meV, $g\mu_B B$ (5 T) = 0.58 meV
- Initialization by just waiting long enough

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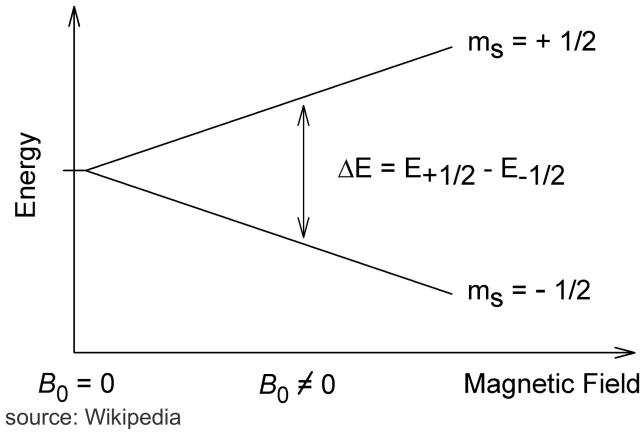
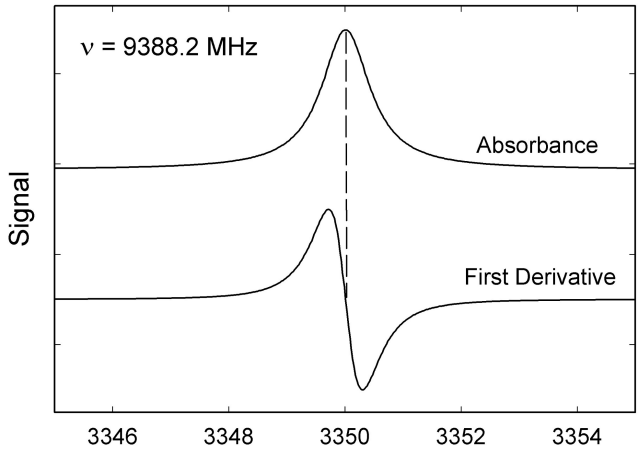
Decoherence times

Electron spin resonance



source: Wikipedia



source: Wikipedia

- X-Band: 10 GHz, 330 mT
- Scan magnetic field with fixed microwave frequency

electron spin resonance

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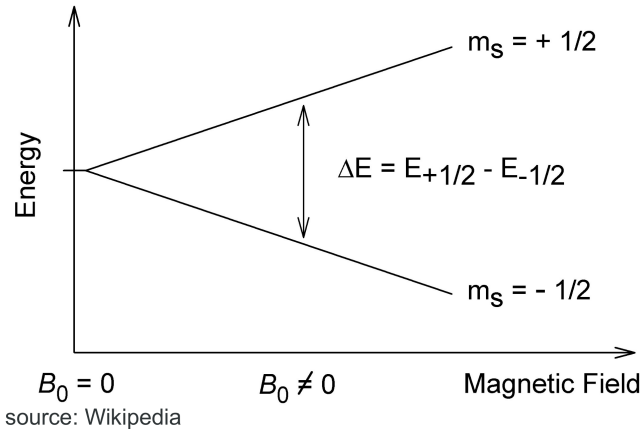
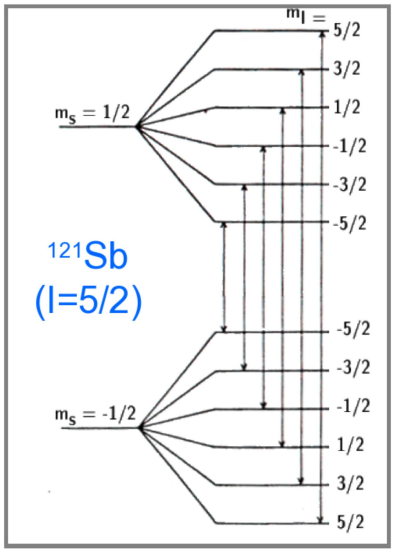
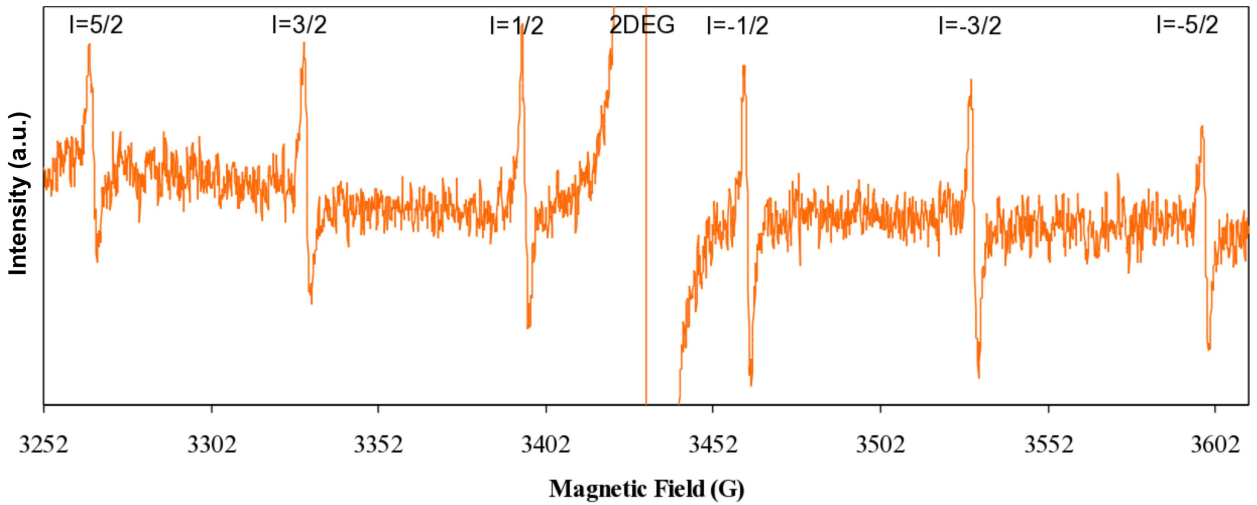


source: Wikipedia





First ESR data on ^{121}Sb implanted ^{28}Si epilayers with thermal SiO_2 barriers

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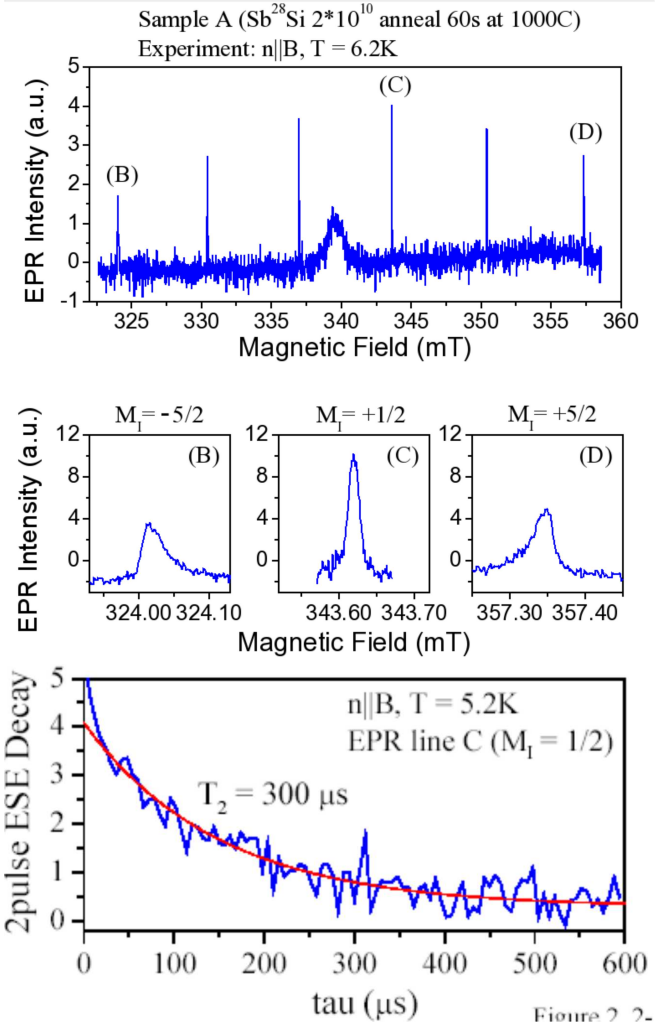

- In collaboration with Steve Lyon, Princeton use Sb due to P contamination in commercial ^{28}Si, at $5 \times 10^{13}\,/\mathrm{cm}^3$ level
- $T_2 = 0.3\,\mathrm{ms}$ at 5 K ($T_1 = 10\,\mathrm{ms}$), indication that electron spins are affected by coupling to the SiO_2/Si interface
- First step in optimization of pre-device structures by ensemble ESR

Decoherence times of donor electron spins in silicon: limits due to ^{29}Si

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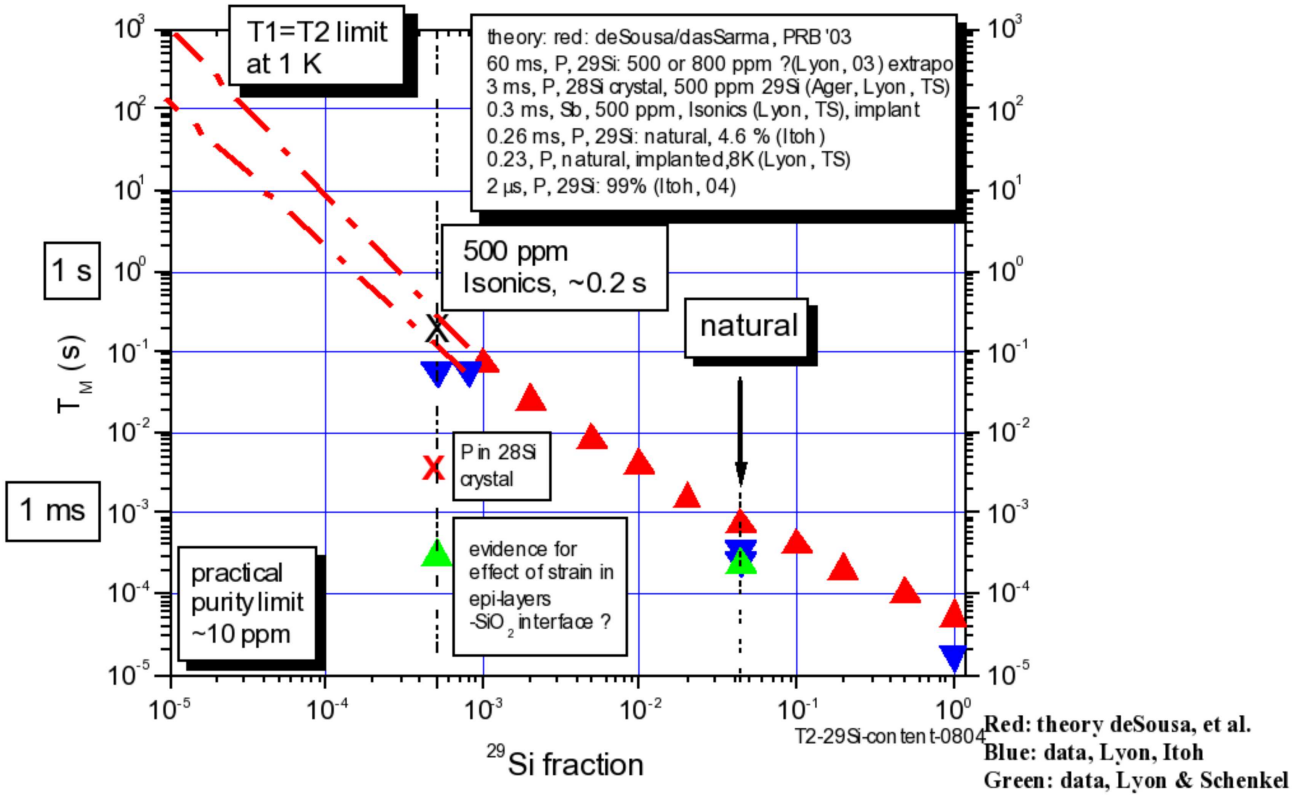

Surface effects on Sb donor electron spin coherence

Interface	Energy [keV]	T_1 [ms]	T_2 [ms]
SiO_2/Si	120	14 ± 2	0.30 ± 0.03
H/Si	120	16 ± 2	0.75 ± 0.04
SiO_2/Si	400	16 ± 1	1.5 ± 0.1
H/Si	400	14 ± 1	2.1 ± 0.1

- Fluctuation of trapping-centers at the Si/SiO_2 interface (weak)
- Spin-flips of paramagnetic centers at the Si/SiO_2 surface DOMINANT
- Hydrogen nuclear spins at passivated Si-H surface (very small)
- Appl. Phys. Lett. **88**, 112101 (2006), Theory: R. de Sousa, arXiv:0705.4088

Gates

Stark tuning of donor spin resonance: proto A-gate

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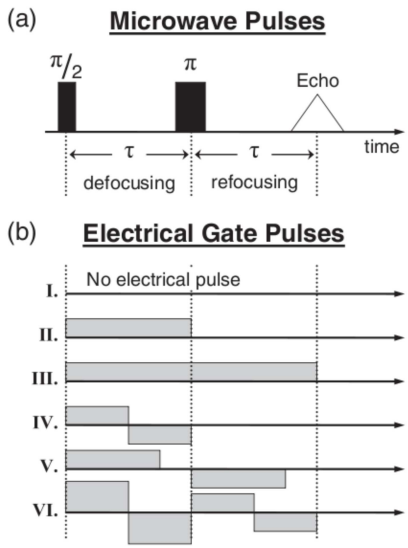
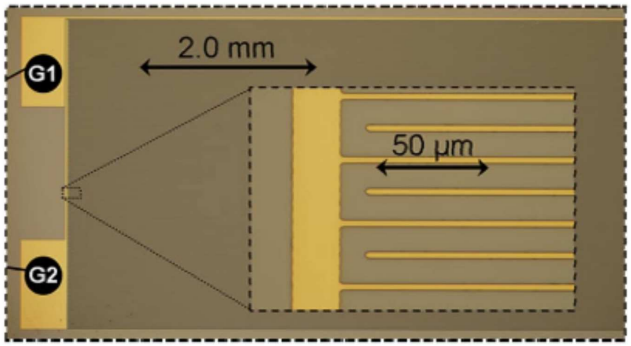
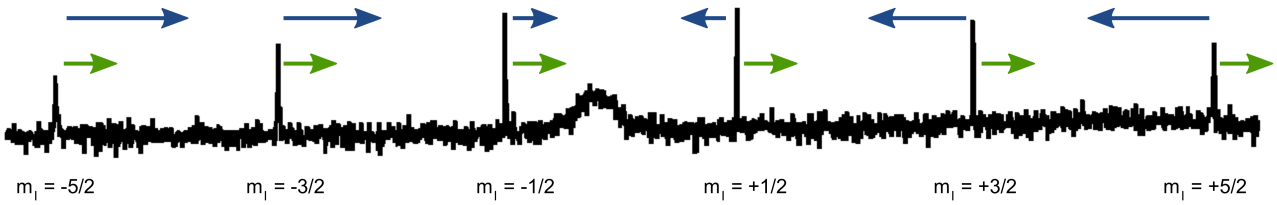




Expect phase shift from two components:

- $\sim E^2 B_0$
- $\sim E^2 m_I$



Stark tuning of donor spin resonance: proto A-gate

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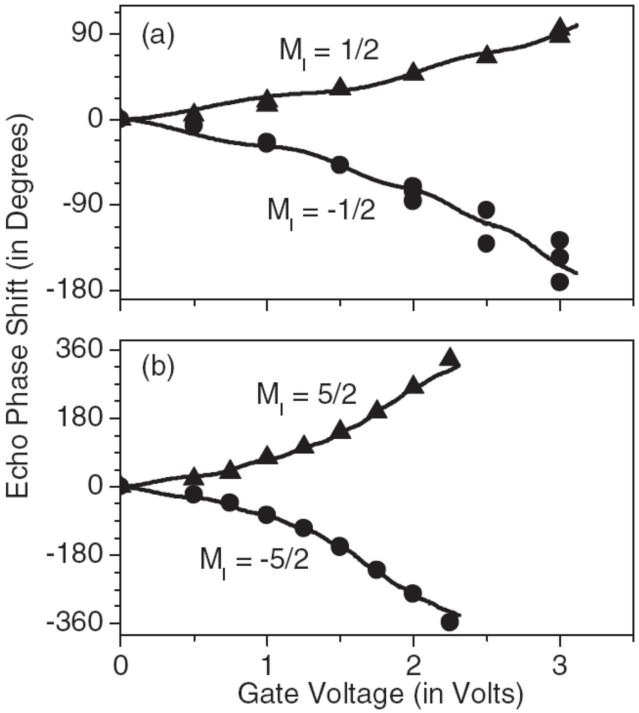

Experiments:

- Lateral gates to apply field
- Long, narrow gates to avoid microwave absorption
- Measure echo phase shifts from donor resonance shift

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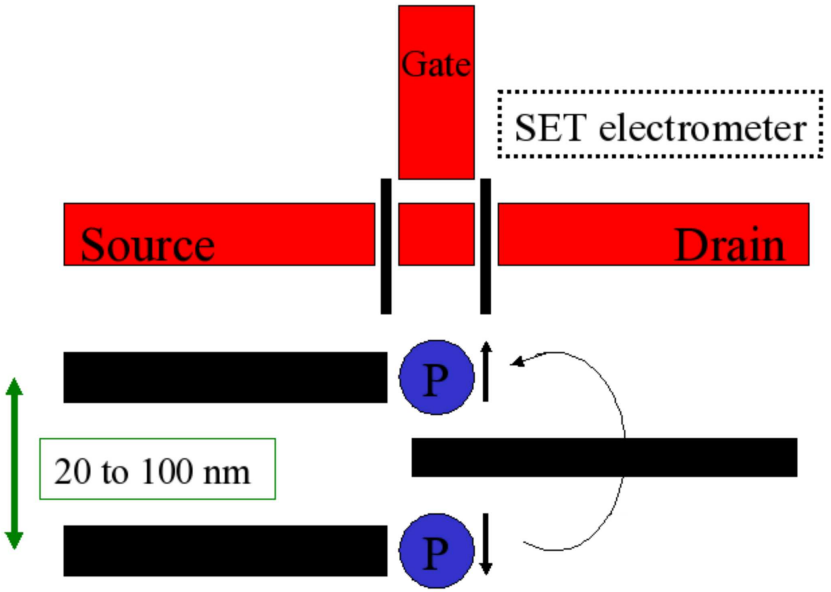
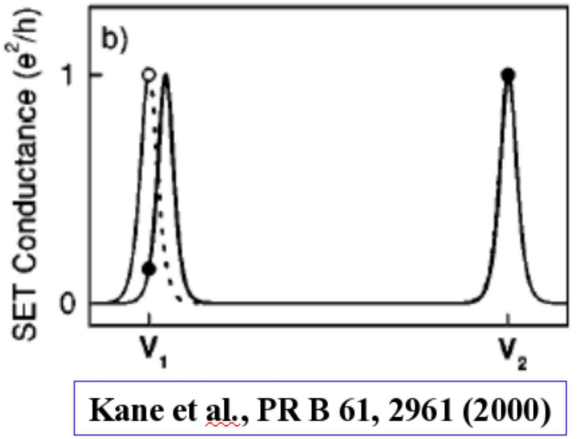
Basic building block to access the physics of the ^{31}P qubit

Two ^{31}P atoms aligned with control gates and SETs





Kane et al., PR B 61, 2961 (2000)

- Gate control of single spins and readout through spin-dependent charge transfer between ^{31}P atoms (based on exclusion principle)

Si-SETs in SOI with 10 nm line widths

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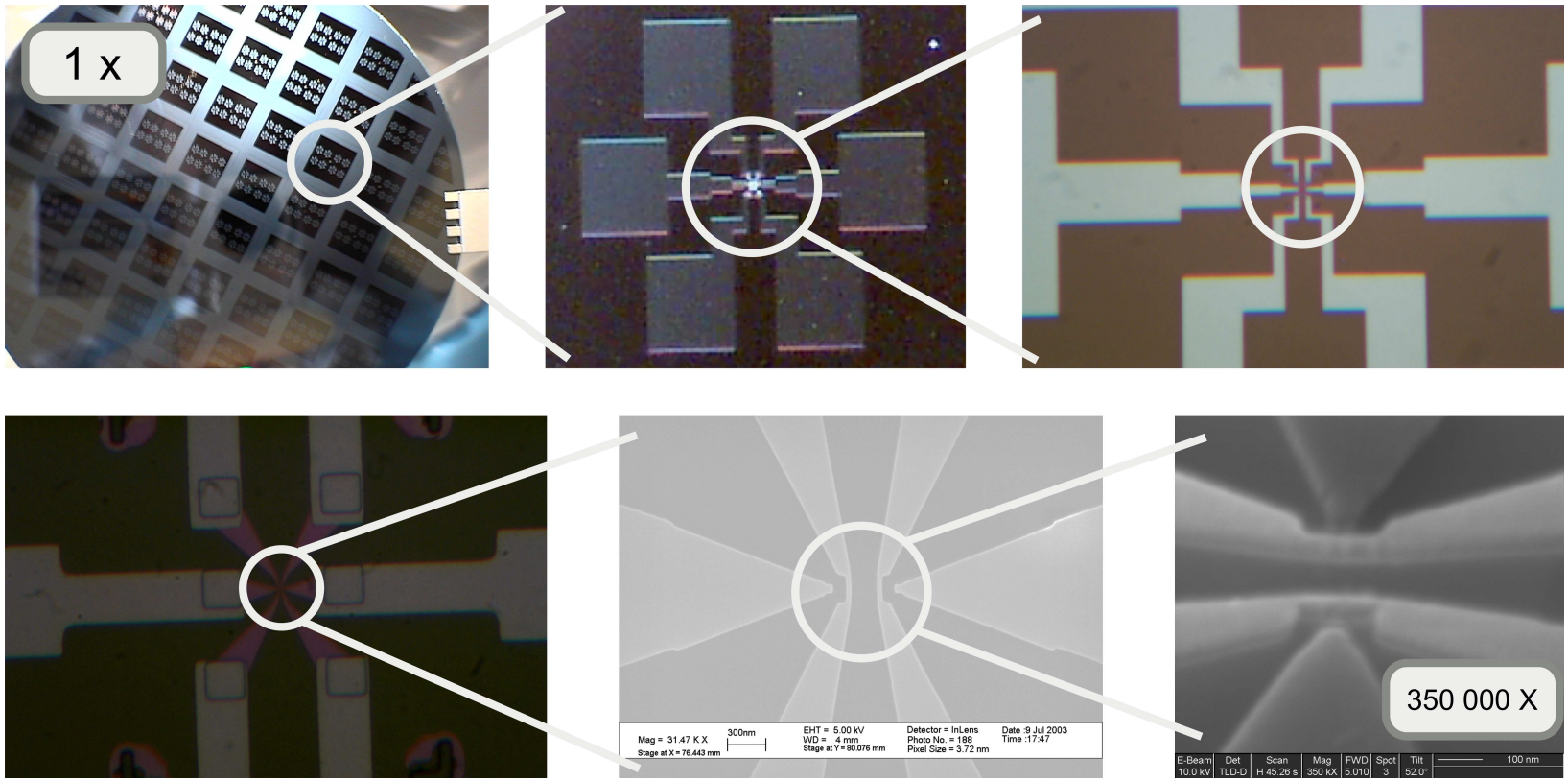
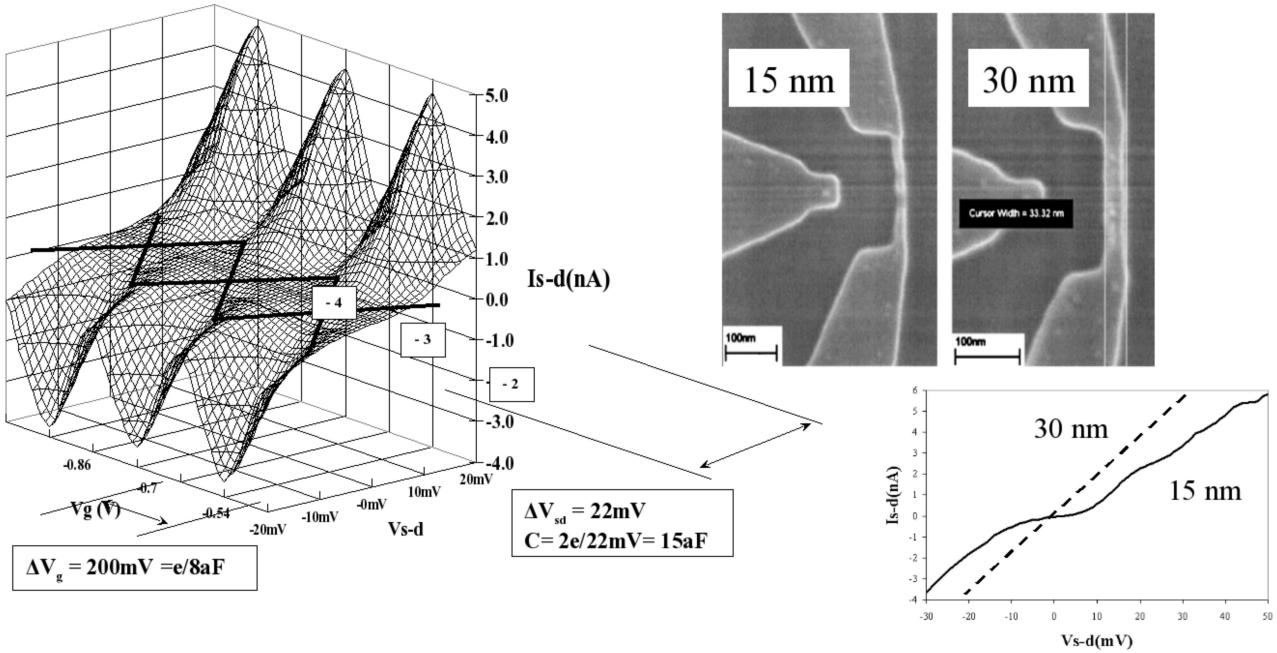


Silicon nanowire SETs

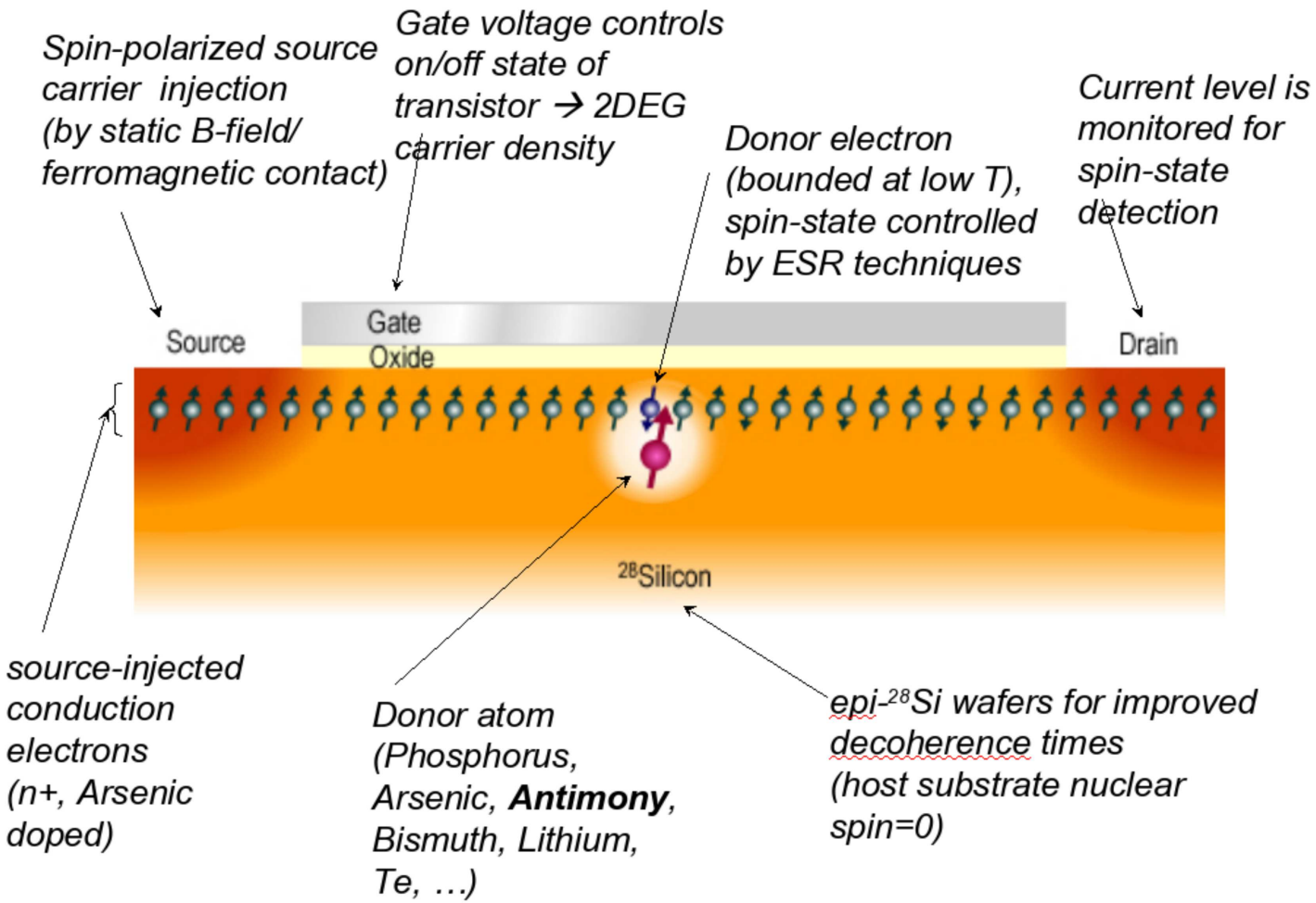
Direct lithographic access to 15 nm wires in SOI without stress-limited oxidation



- 15 nm lines in silicon by e-beam lithography and dry etching
- SET islands and tunnel junctions form by dopant segregation during source-drain implant anneals
- Issue: electronic defects at interfaces will cause decoherence of nearby qubits
- S.J. Park *et al.*, J. Vac. Sci. Technol. B **22**, 3115 (2004)

Spin-dependent transport (SDT)in FETs

Schematics of SDT in single-donor aFETs



Single spin readout via spin dependent transport in FET channel

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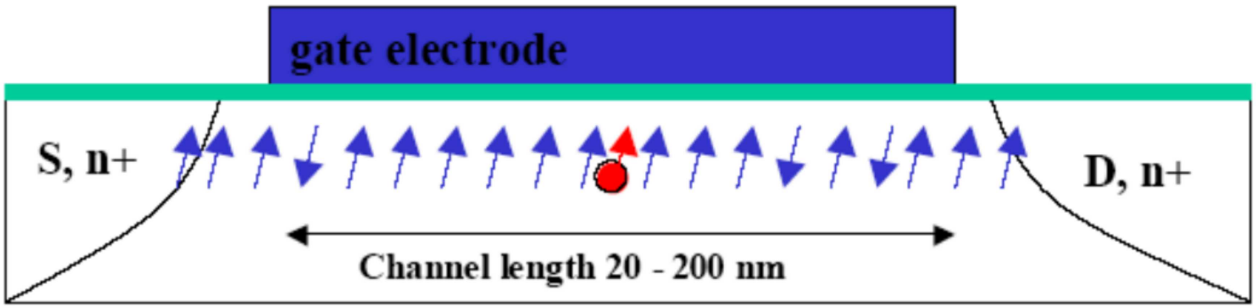

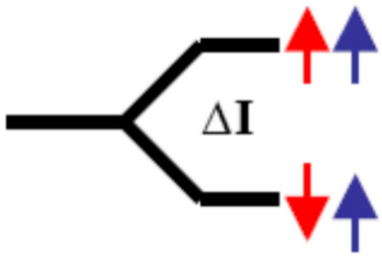

$$\frac{\Delta I_{\uparrow\uparrow}}{I_0} \approx \text{const.} \times \sigma_{tri}$$

$$\frac{\Delta I_{\downarrow\uparrow}}{I_0} \approx \text{const.} \times \left(\frac{\sigma_{tri} + \sigma_{si}}{2}\right)$$

$$\sigma_{si} - \sigma_{tri} \geq 4 \times 10^{-13}\,\text{cm}^{-2}$$

- injected spins will be (mostly) down, donor spins will be up or down
- for in-up – donor-up: only triplets can form (until spins flip in scattering)
- for in-up – donor-down: singlets will form 50% of the time, and triplets will form 50% of the time
- Scattering contributions from neutral impurities has to be about comparable to all other scattering mechanisms
- demonstrated for 10^8 spins by Ghosh, and Silsbee, (1992)

Electrical detection of magnetic resonance (EDMR)

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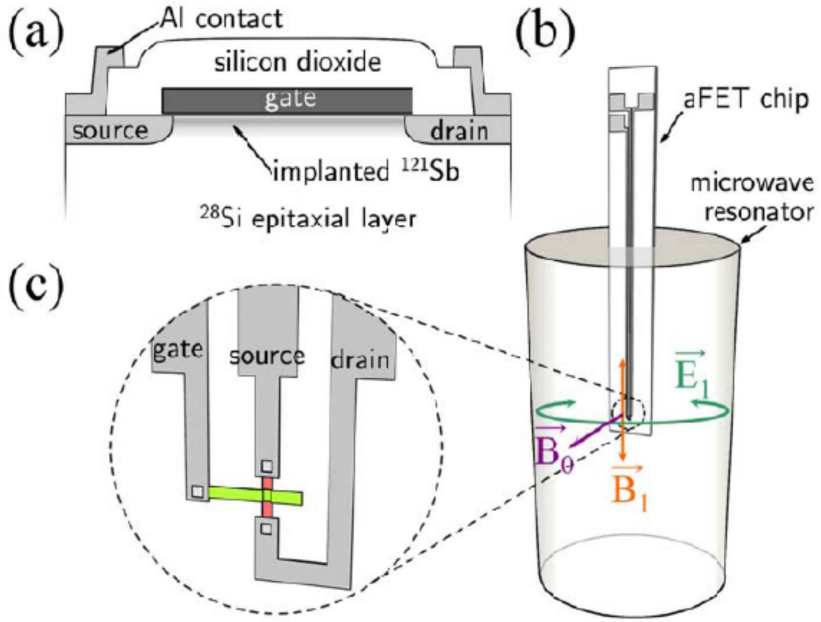

a) Schematic cross-section of an aFET
b) Device placement and field orientations in the ESR microwave resonator
c) Magnified view of an aFET chip

- Cheuk C. Lo, *et al.*, Appl. Phys. Lett., **91**, 242106 (2007), arXiv:0710.5164

Measurements

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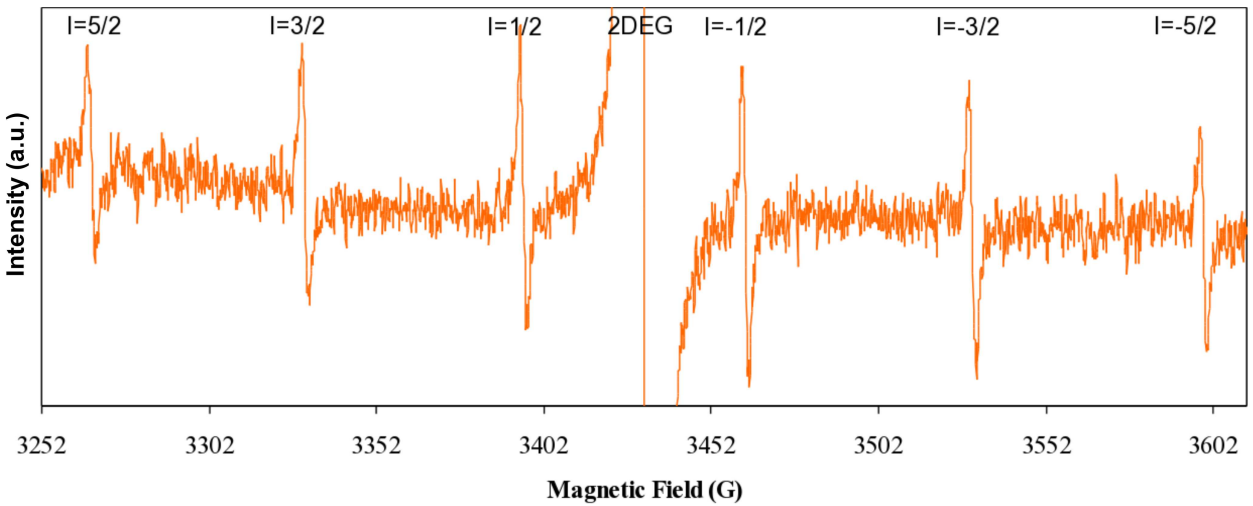

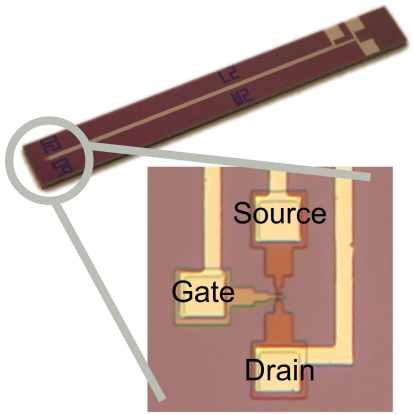

- 1st observation of SDT by EDMR in fully functional transistors
- ^{28}Si implanted with ^{121}Sb donors.
- $\sim 10^6$ donors in a $20 \times 160\,\mu\mathrm{m}^2$ device.
- From line width of 1 G, we can estimate $T_1 \gg 100\,\mathrm{ns}$.
- Test bed for spin physics and scaling!

Projective single spin measurements by EDMR?

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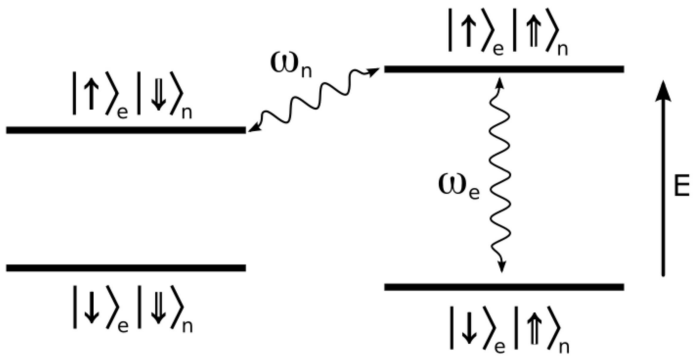
- Due to efficient spin exchange between conduction electrons and bound donor electrons, spin dependent scattering alone does not allow projective measurements of the donor electron spin state
- Need ability to SWAP quantum information from the electron to the nuclear spin
- Position of electron spin resonance lines depends on nuclear spin state through hyperfine coupling
- Detecting the presence or absence of selected hyperfine lines in EDMR constitutes a quantum non-demolition measurement of the nuclear spin state
- Requirements are optimized signal amplitudes and nuclear spin relaxation times $> 1\,\mathrm{ms}$, longer then shot noise limited measurement times
- Next stop: single spin measurements in 50 nm scale transistors



4 levels of the electron-nuclear spin system

- M. Sarovar, *et al.*, arXiv:0711.2343

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Many qubits

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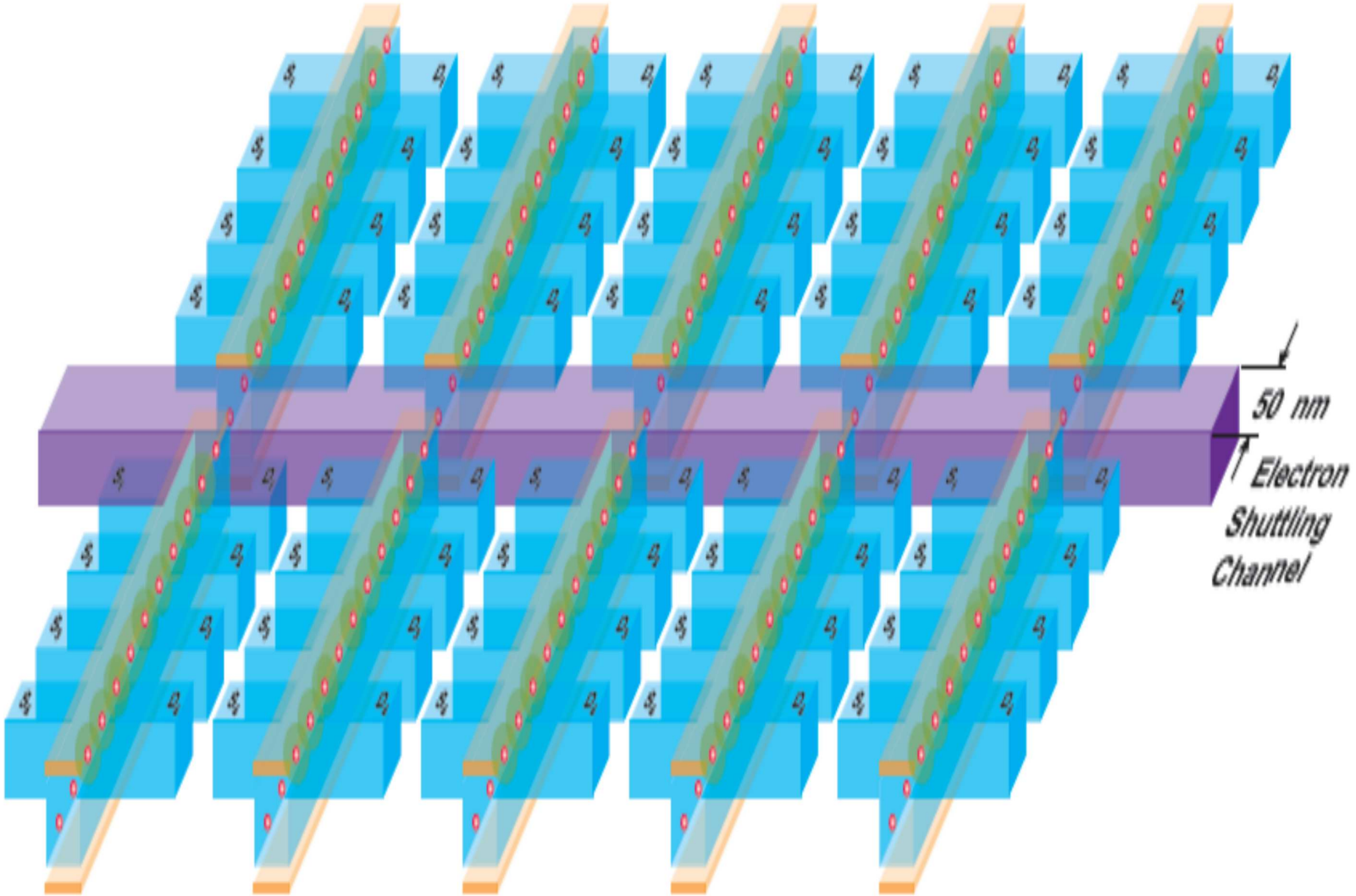
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