Exploration of quantum computer architectures with donor spin qubits in silicon

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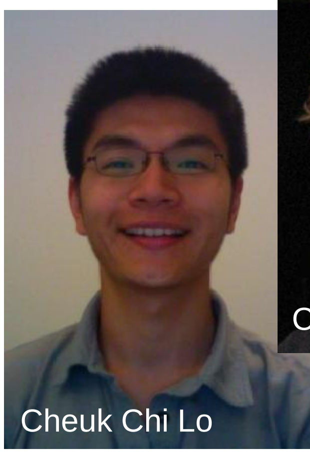
Center for Beam Physics Seminar, LBNL, August 10, 2012

http://www-ibt.lbl.gov

Acknowledgments

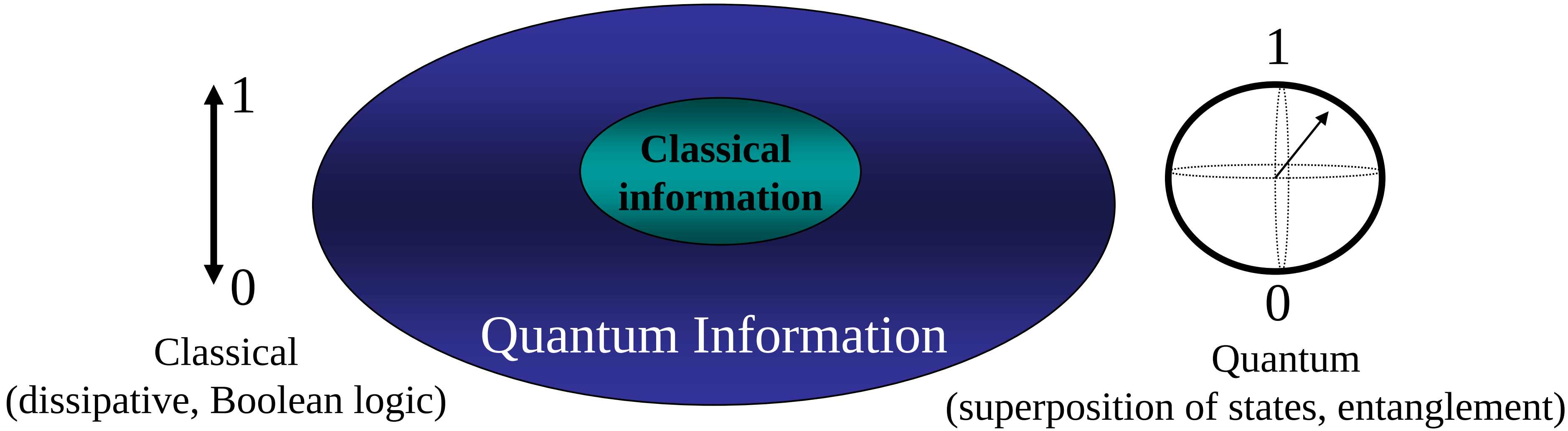
- **PostDocs**
  - Christoph Weis (LBNL)
  - Cheuk Chi Lo (LBNL /UC Berkeley)
- **Graduate students**
  - Michael Ilg (LBNL)
  - Julian Schwartz (LBNL)



- **Si-QC Team members**
  - Jeff Bokor, UC Berkeley & Molecular Foundry, LBNL
  - Steven Lyon, Princeton University
  - Alexei Tyryshkin, Princeton University
  - Birgitta Whaley, UC Berkeley
  - John Morton, University College London
- **Special thanks to**
  - Staff of the
    - •UC Berkeley Nanolab
    - •National Center for Electron Microscopy and the ALS at LBNL
    - •The Molecular Foundry at LBNL
    - • The National High Magnetic Field Lab, Tallahassee (esp. Jan van Tol)

This work is supported by NSA and DOE

The Quest for Quantum Computing



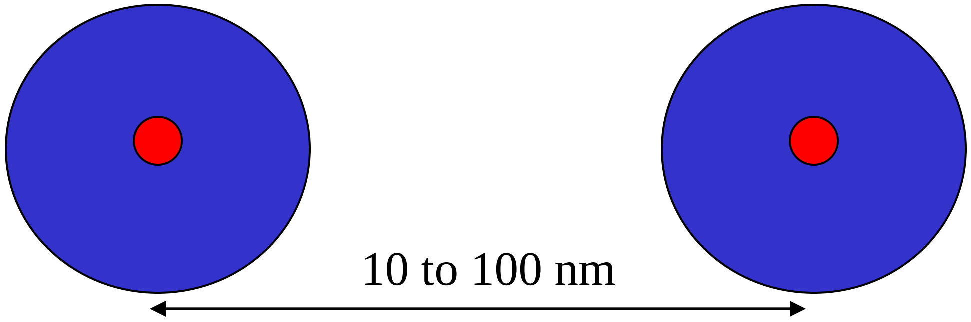
- Flavors of quantum computing approaches[1]
  - Quantum circuit model
  - Measurement based quantum computing
  - Adiabatic quantum computing
  - Topological quantum computing
  - …

[1]see e. g. "Quantum computers: Definition and implementations", C. A. Perez-Delgado and P. Kok, Phys. Rev. A 83, 012303 (2011)

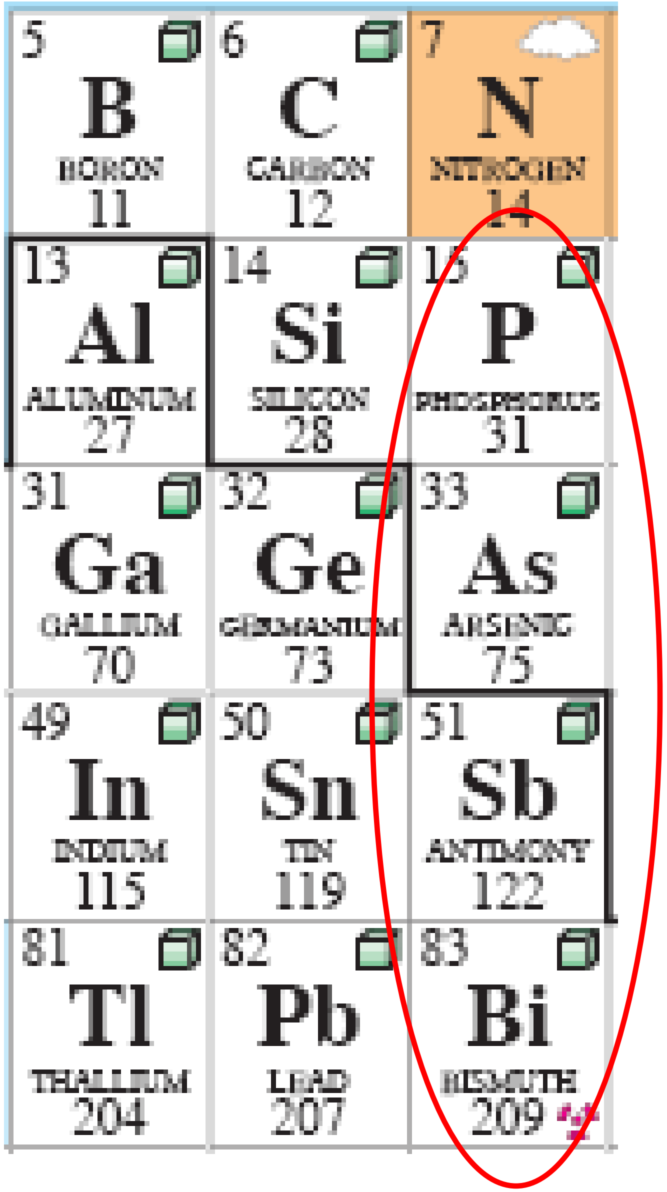
Criteria for physical implementation of a quantum computer (DiVincenzo)

1. Well defined extendible qubit array – stable memory
2. Initialization in the "000…" state
3. Long decoherence time (>10^4 operation time, to allow for error correction)
4. Universal set of gate operations (not, cnot)
5. Read-out: Single-quantum measurements (projective measurement)
6. Efficient quantum communication (form, transmit and convert "flying qubits")

Nuclear and electron spins in silicon are promising qubit candidates



Donor electron spin qubits in silicon



^{31}P ("natural quantum dot")

Si: [Ne].$3s^2$.$3p^2$

P: [Ne].$3s^2$.$3p^3$

- $3p^3$ binding energy: 45 meV
- 100% abundant isotope with I=1/2
- ^{28}Si matrix can be prepared with I=0

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(DiVincenzo)

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   → protection of donor electron and nuclear spin coherence, "clock-transitions"

4. *Universal set of gate operations (not, cnot)*

   → Stark shift measurements (proto nuclear spin control gate)

   → electron-nuclear spin state transfer

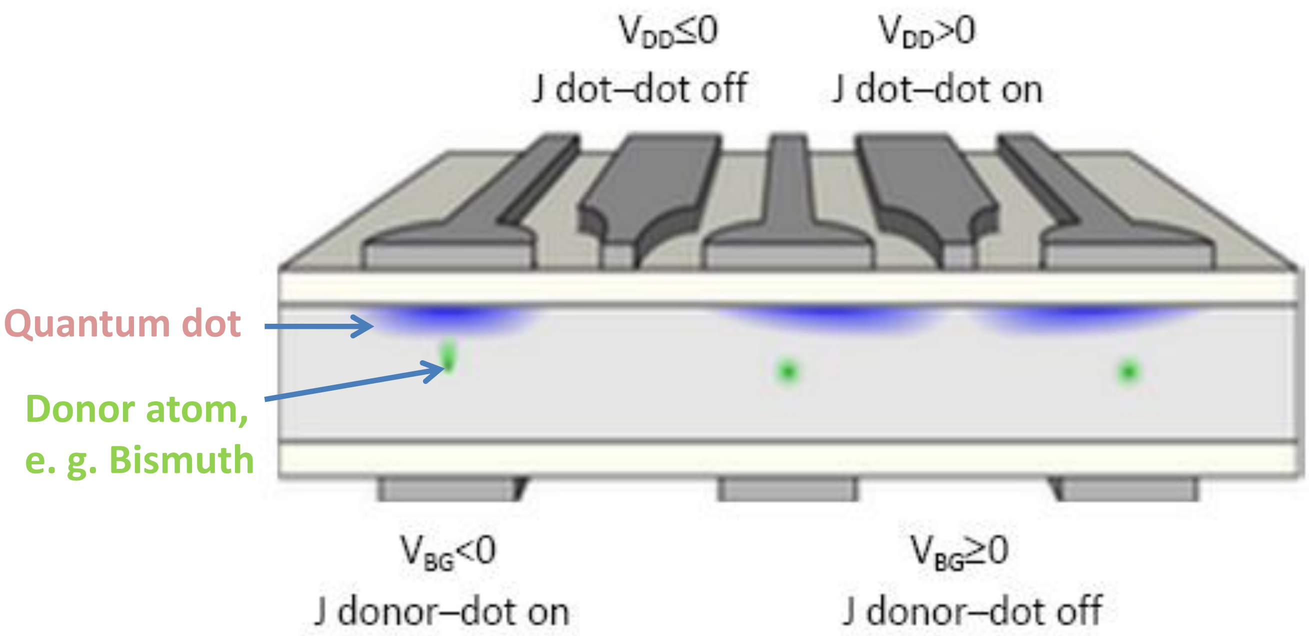
5. *Read-out: Single-quantum measurements (projective measurement)*

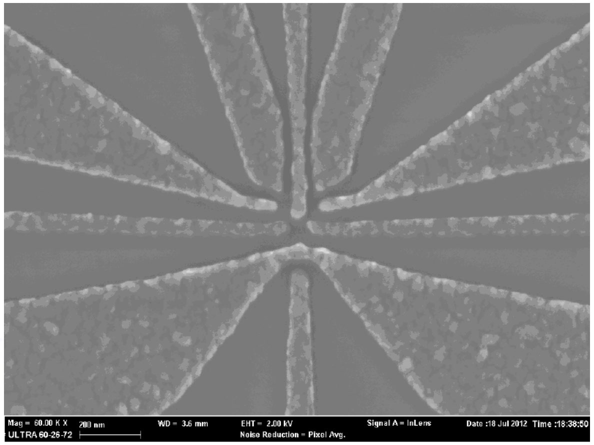
   → spin dependent transport in transistors

6. *Efficient quantum communication ("flying qubits")*

   → electron shuttling

Exploration of spin qubits in donor – quantum dot devices





- SEM image of a prototype donor-dot device

- Donor electron spins couple to donor nuclear spins for long term quantum memory
- Quantum logic on donor electrons coupled to quantum dot electrons and between adjacent quantum dots
- Quantum communication by coherent electron shuttling between quantum dots

"A spin qubit architecture with coupled donors and quantum dots in silicon", T. Schenkel, C. C. Lo, C. D. Weis, J. Bokor, A. M. Tyryshkin, and S. A. Lyon, arXiv:1110.2228, "Single Atom Nanoelectronics" (T. Shinada, E. Prati, eds.), 2012, in press

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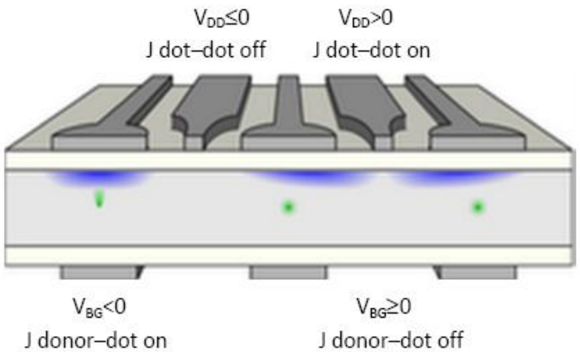
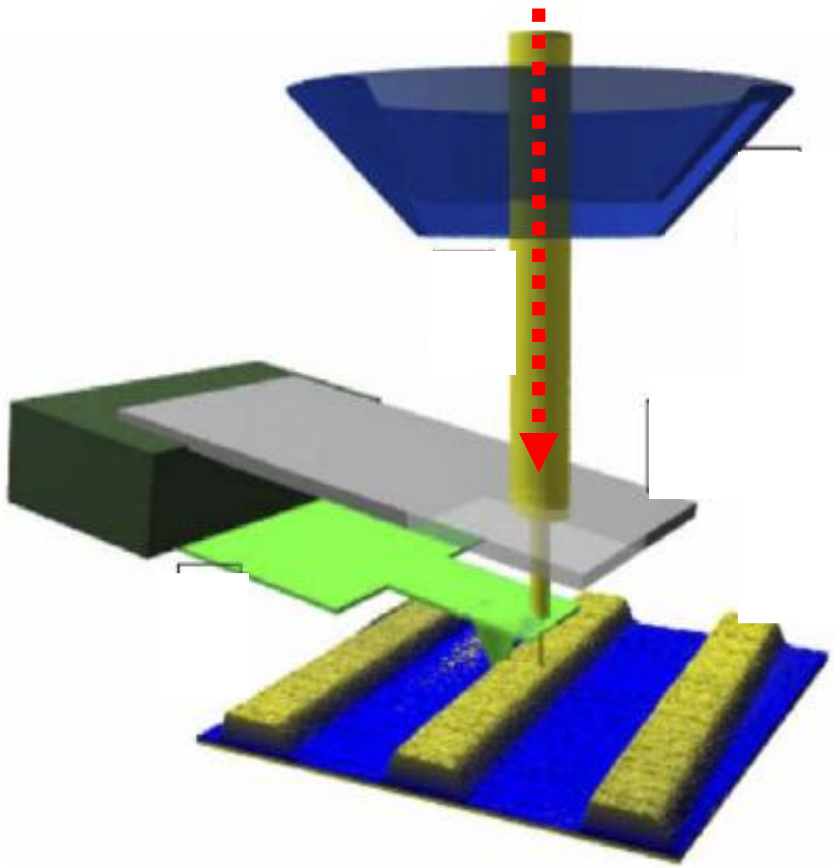
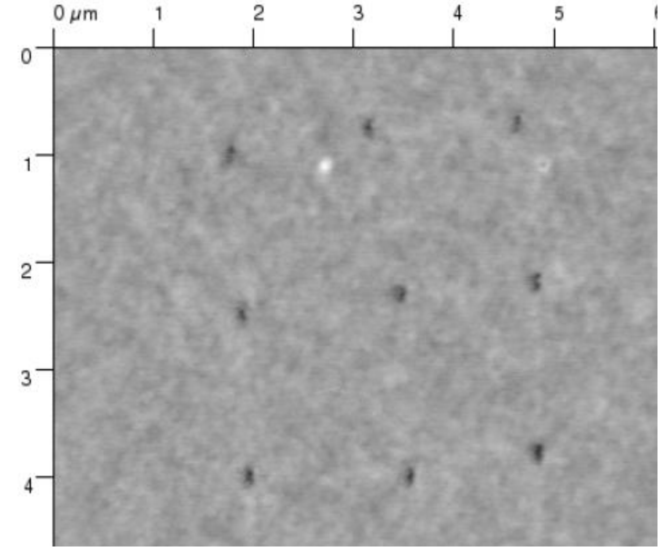


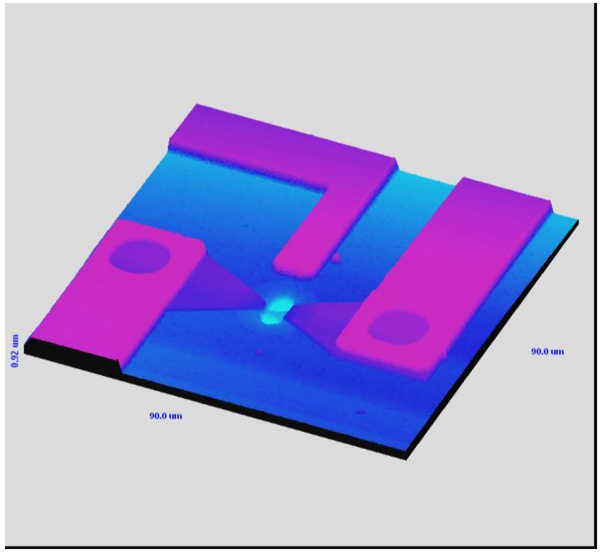
Single Ion Placement with Scanning Probe Alignment

- Non-destructive imaging and nm-apertures for nm-accuracy





array of 90 nm dots in PMMA from ion implantation with scanning probe alignment



in situ scanning probe image of a FinFet

A. Persaud, et al.,
Nano Letters 5, 1087 (2005)

Single Ion Implantation with Non-contact Scanning Probe Alignment

Motivation

•develop a non-contact scanning probe integrated with ion beams for high resolution imaging and alignment of single dopant ions to spin readout transistors

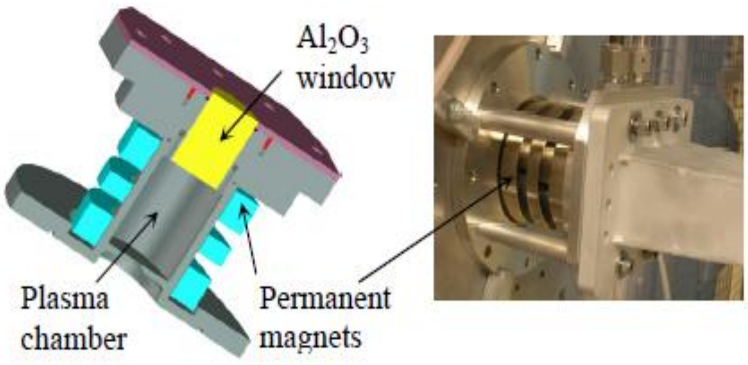
•develop a versatile ion source and beam line integrated with the scanning probe

Approach

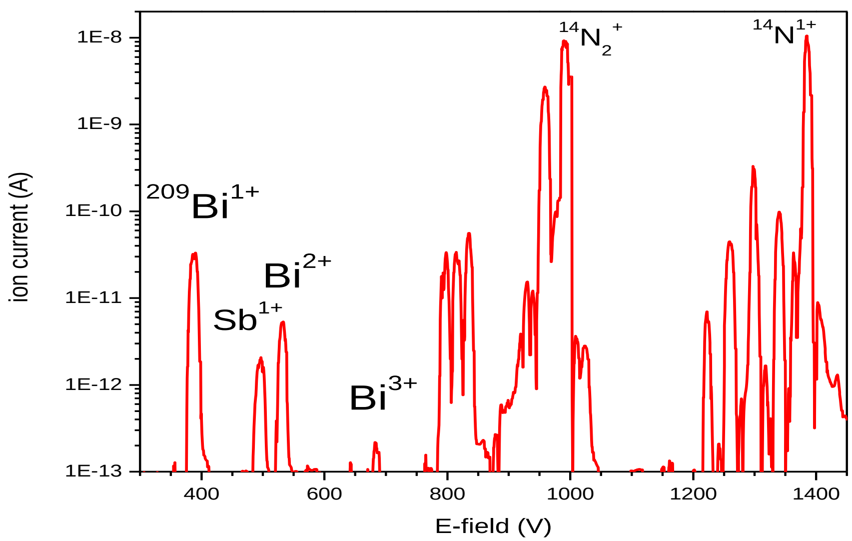
•piezoresistive force readout and actuated cantilevers for non-contact imaging

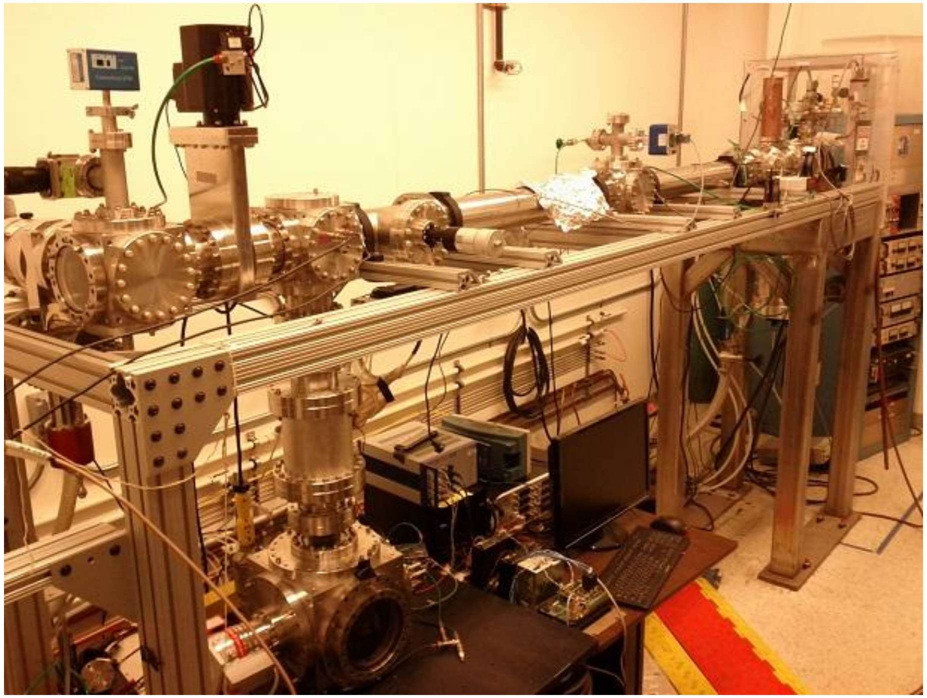
•FIB processing for nano-apertures and imaging tips

•microwave driven permanent magnet ion source for donor ion beam formation

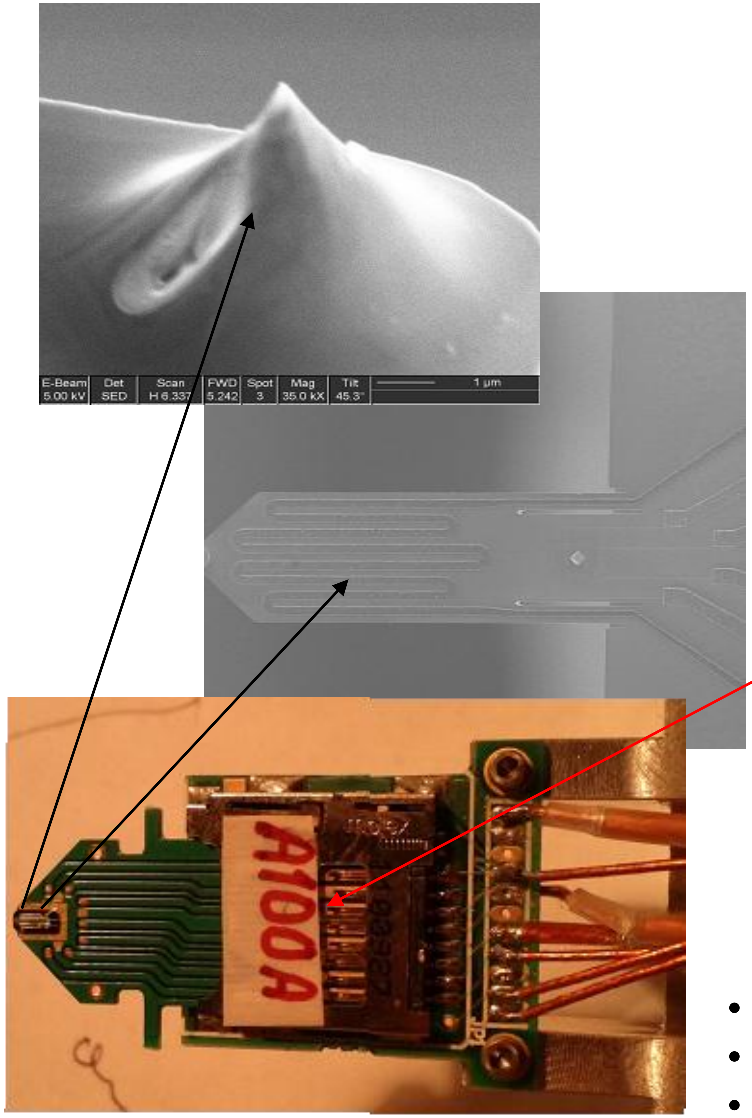


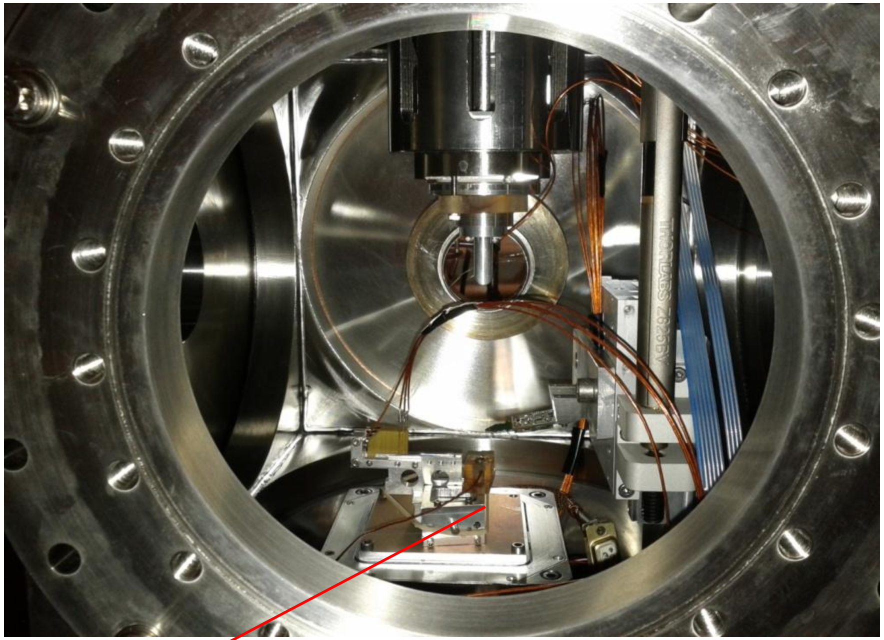
- Microwave driven ion source (2.45 GHz)
- co. Qing Ji

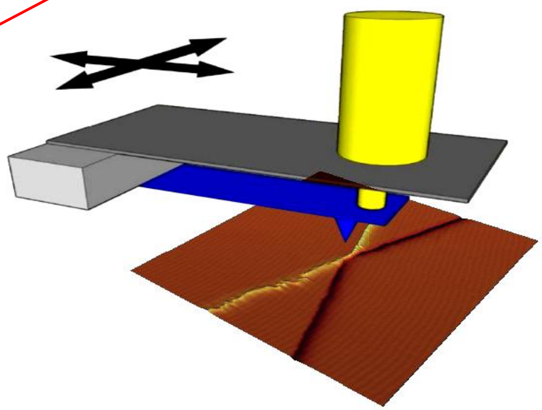




Setup for Ion Implantation with Scanning Probe Alignment

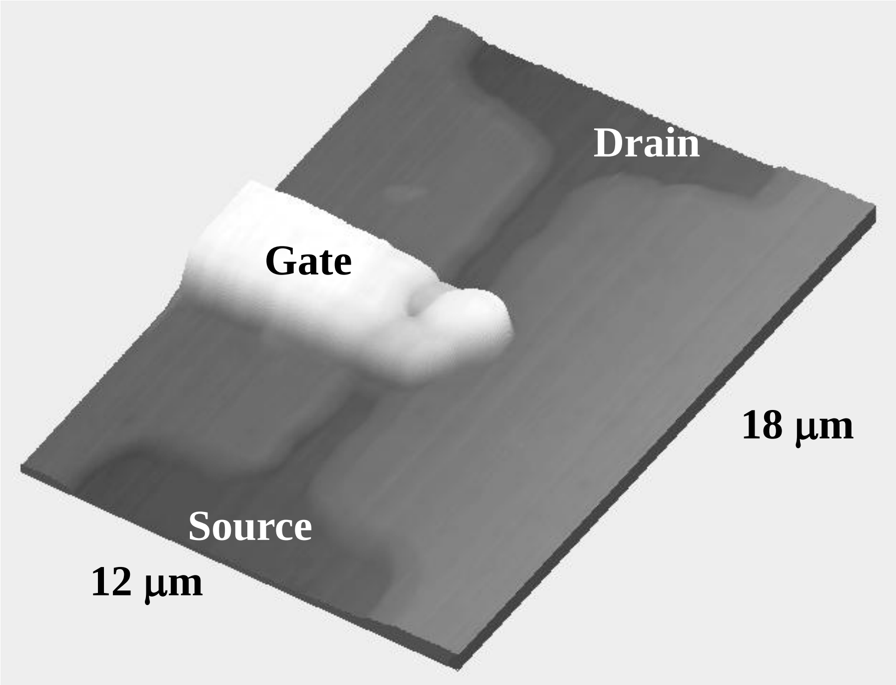


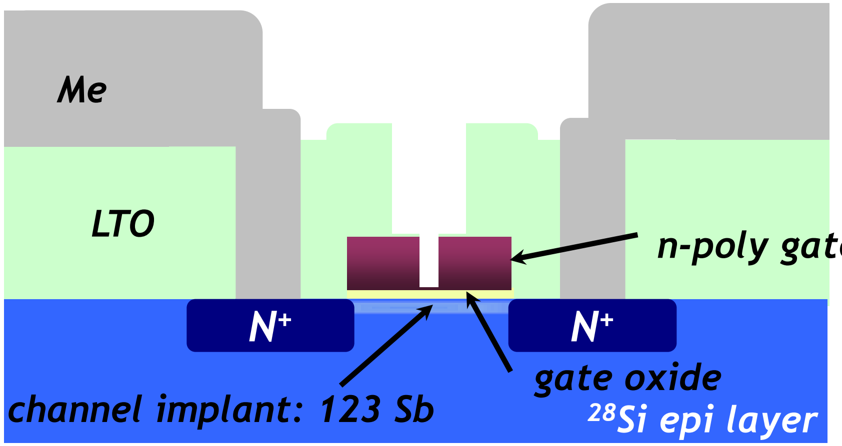


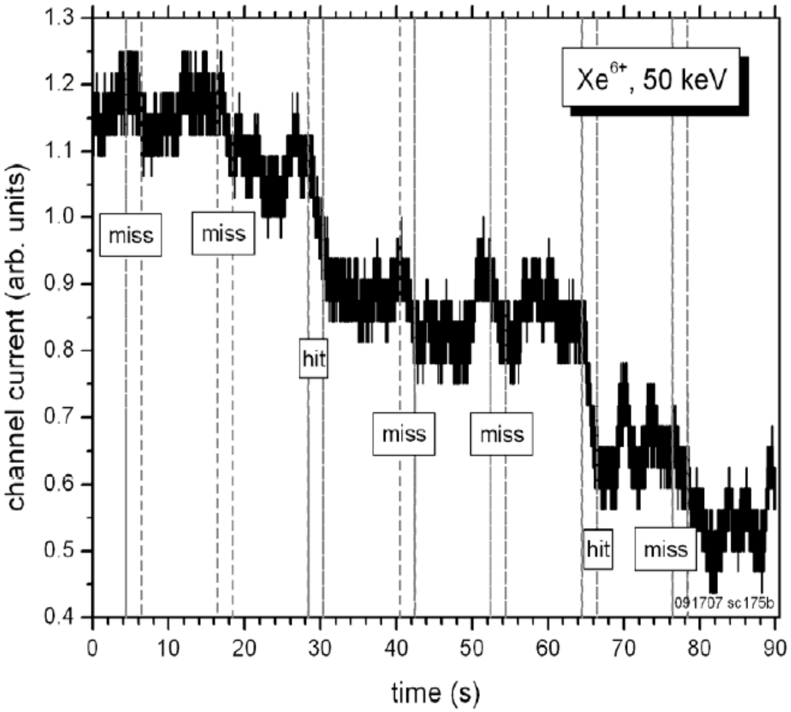


- camera and 5x5 cm range x-y stages for coarse alignment
- scan range of target piezo-stage is 30 x 30 µm
- Piezoresistive scanning force microscope technology in close collaboration with **Prof. Ivo Rangelow, Tech. Univ. Ilmenau**

Single Ion Detection in Readout Transistors through ion impact induced current changes





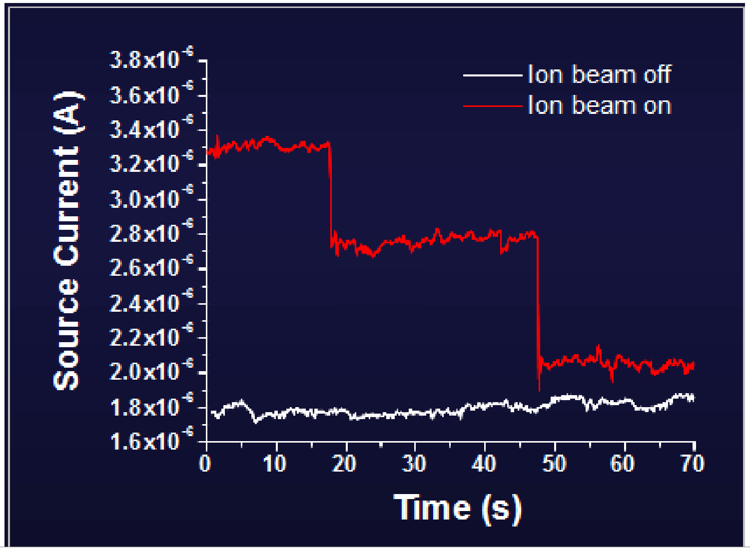


• single ion doping through detection of current transients from single ion impacts (dI~ few 10^{-4} dI/I, in 2x2 µm aFets)

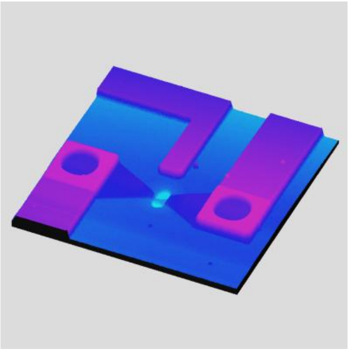
A. Batra et al., Appl. Phys. Lett. 2007

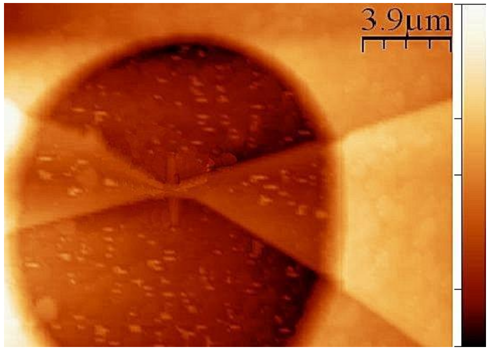
Single ion implantation demonstrations in 100 nm scale devices

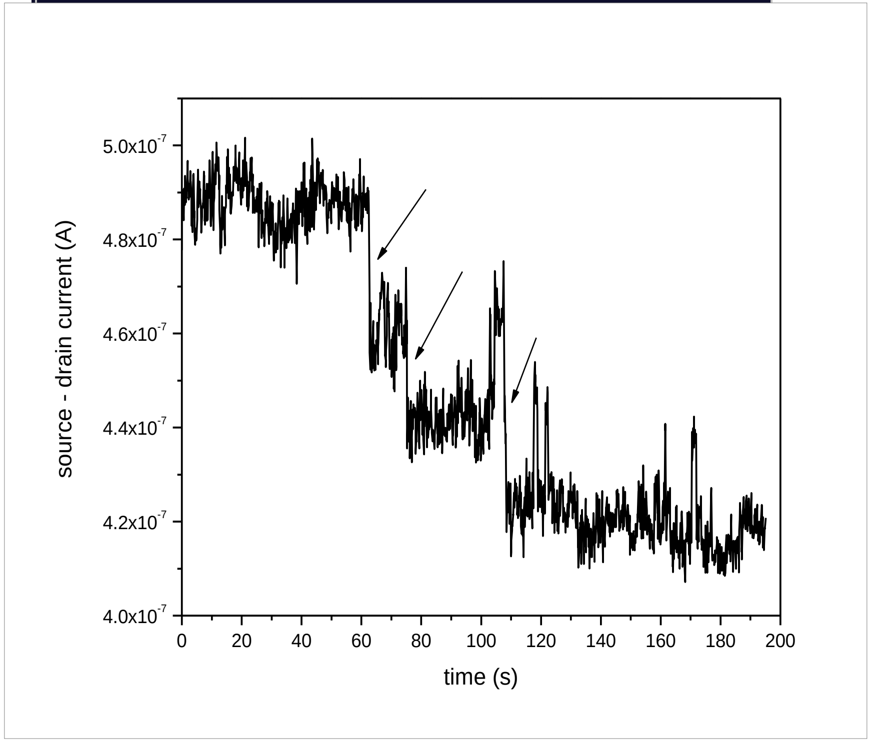
- Xe^{6+}
  - 48 KeV
  - 100 nm x 300 nm
  - Ion beam 1.3×10^{-13} A/mm^2
  - $\Delta I/I$ = 10 to 25%



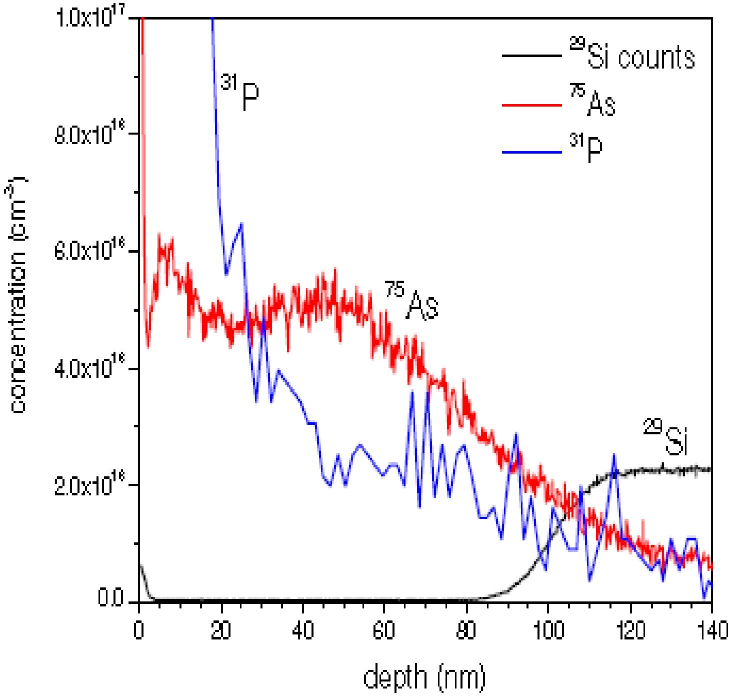
- Bi^{+}
  - 10 keV
  - 80x4000 nm
  - Ion beam 1.3×10^{-13} A/mm^2
  - $\Delta I/I$ ~5%

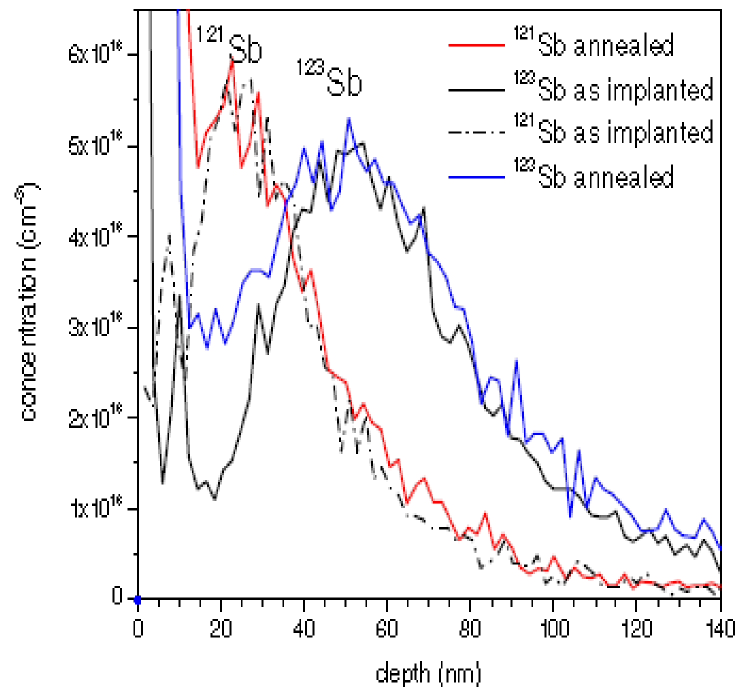


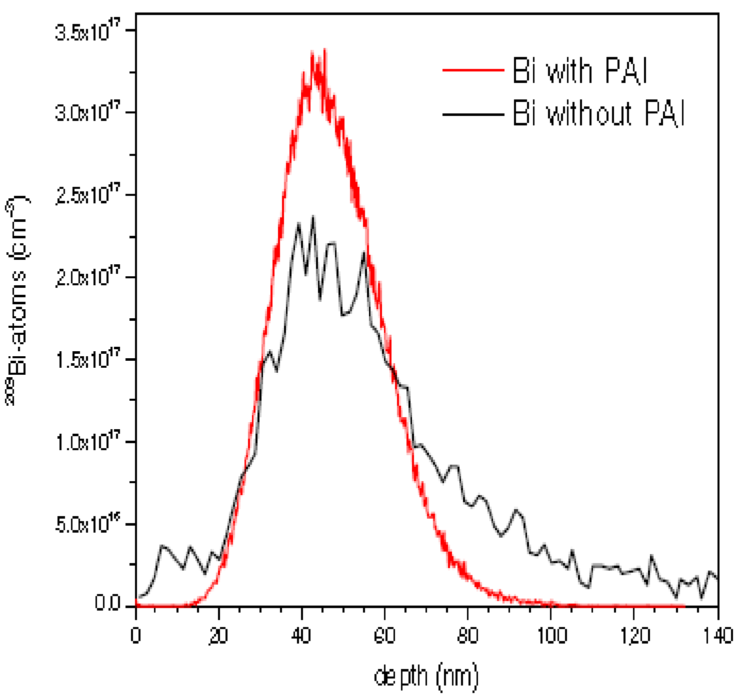




Depth profiles of ion implanted and annealed donors in silicon







- **minimal straggling and diffusion for Bismuth**

• P (blue, 58 keV, 4x1011 cm-2, 7 degree, 920 C, 10 s)
and As (top, red, 120 keV, 4x1011 cm-2, 7 , 920 C, 10 s), Sb and Bi implanted into silicon. 121Sb: 60 keV, 2x1011 cm-2, 123Sb, 120 keV, 4x10 cm-2 (850 C, 10 s) Bi: 120 keV, 1012 cm-2 (with PAI: annealed at 600 C for 4 min., without PAI, annealed at 650 C for 9 min).

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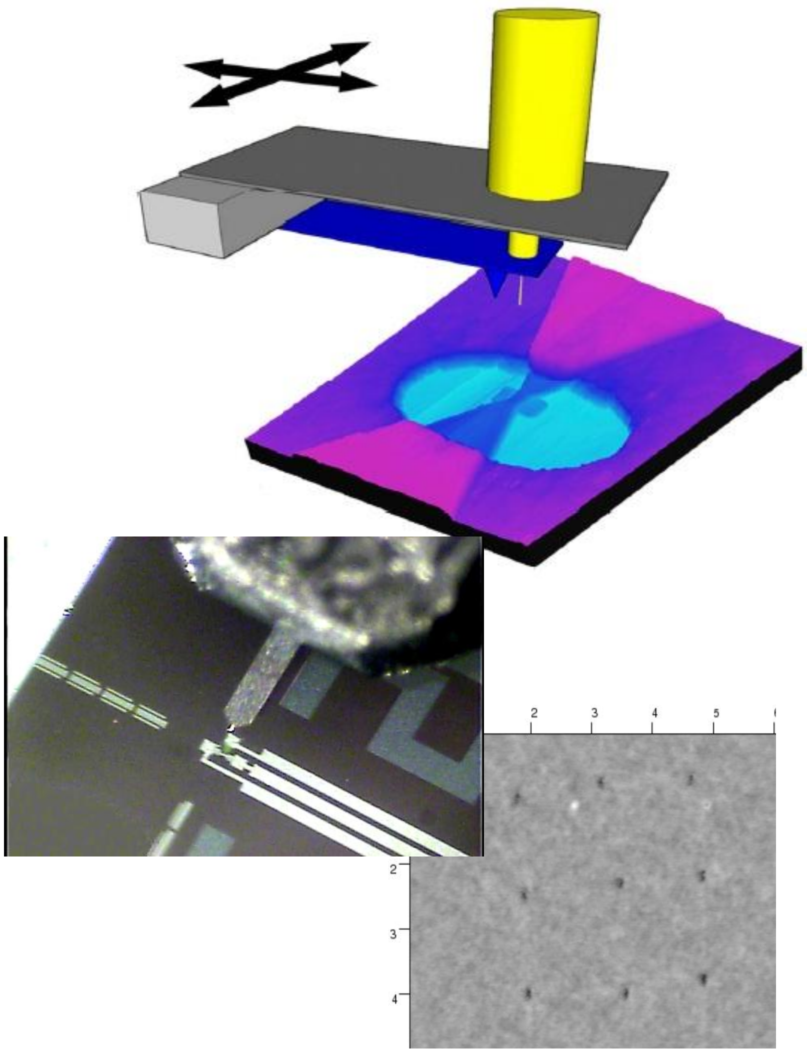

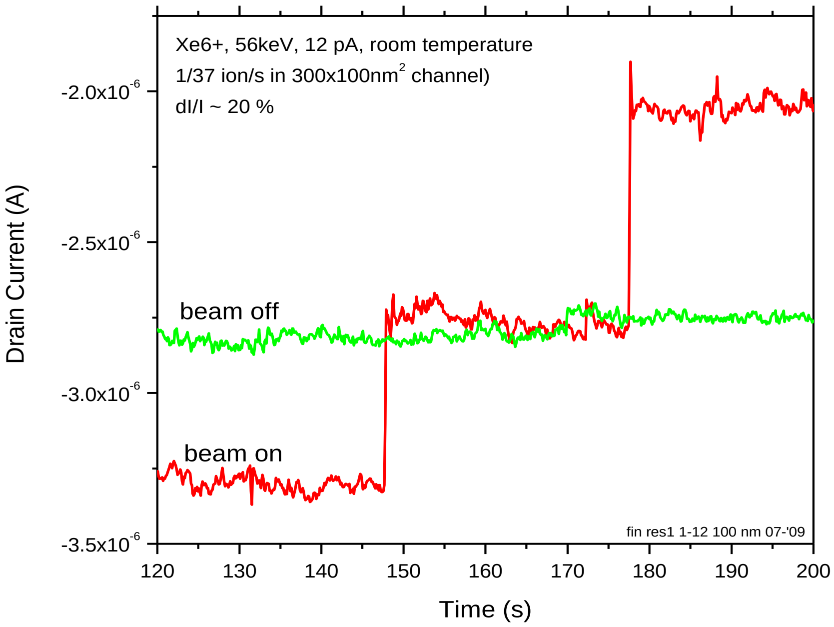

- **qubit array formation by single ion implantation with scanning probe alignment**
- non-destructive imaging with nm-accuracy
- T. Schenkel, et al., Nucl. Instr. Meth. B 267, 2563 (2009)
- C. D. Weis, et al., NIM B 267, 1222 (2009)
- A. Batra, et al., APL 91, 193502 (2007)

Criteria for physical implementation of a quantum computer (DiVincenzo)

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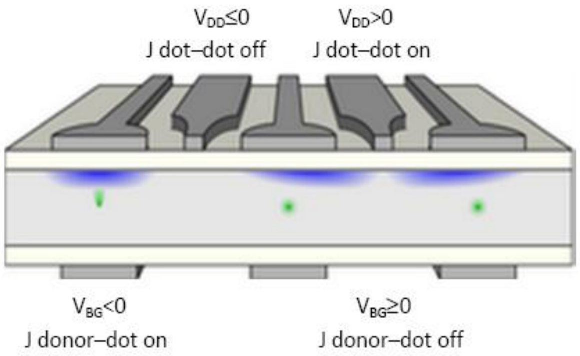
   → spin dependent transport in transistors

6. *Efficient quantum communication ("flying qubits")*

   → electron shuttling



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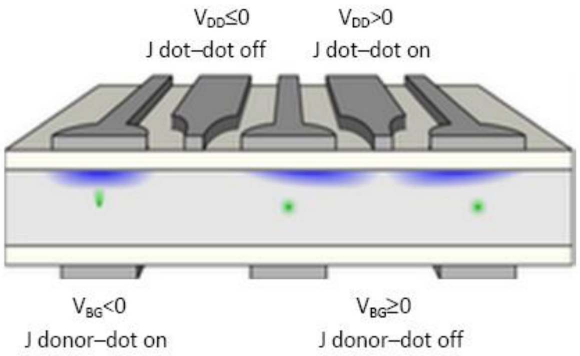
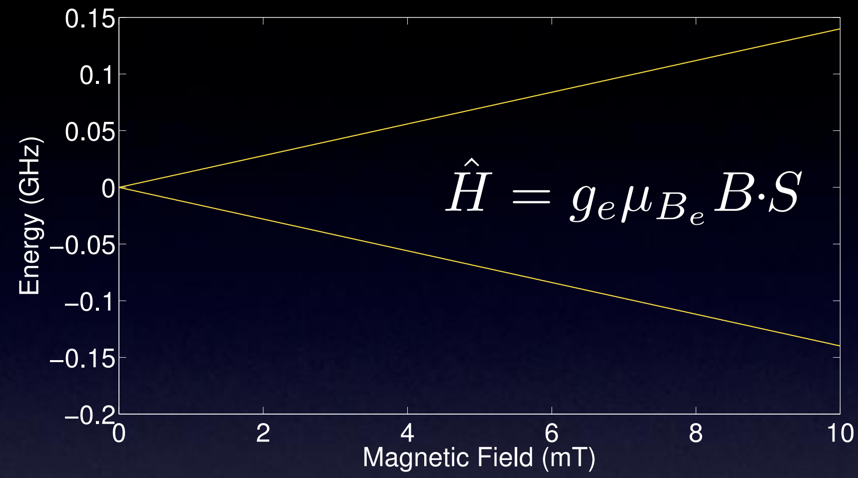
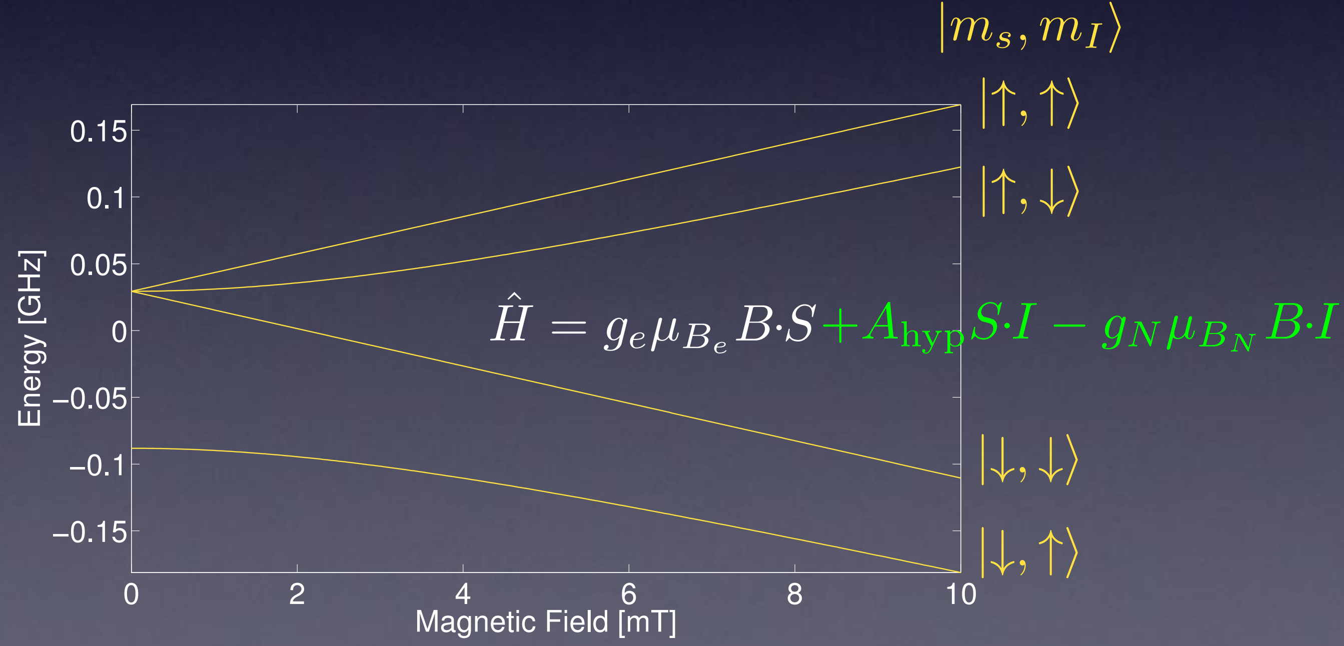


The degenerate electron energy levels split in a magnetic field.

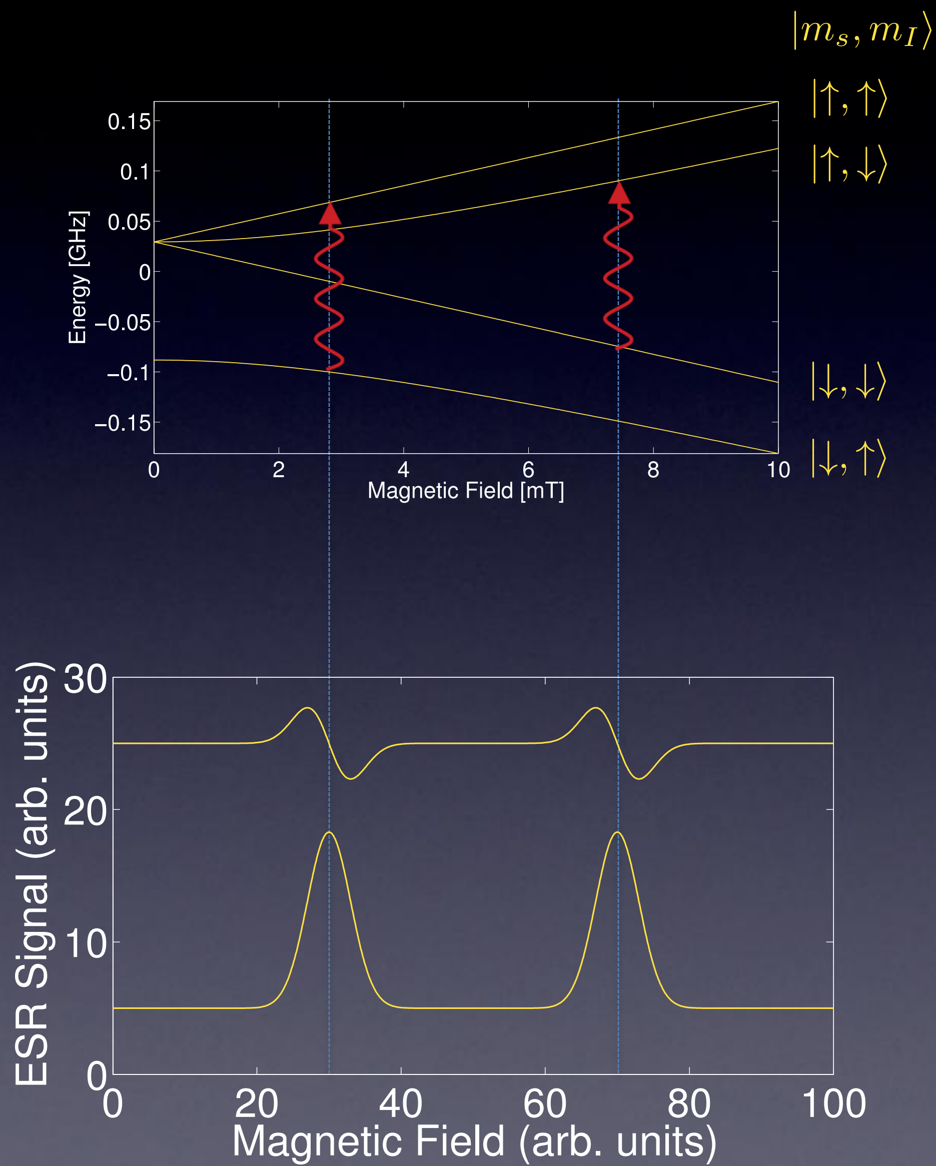
Free Electron



Electron bound to [31]P



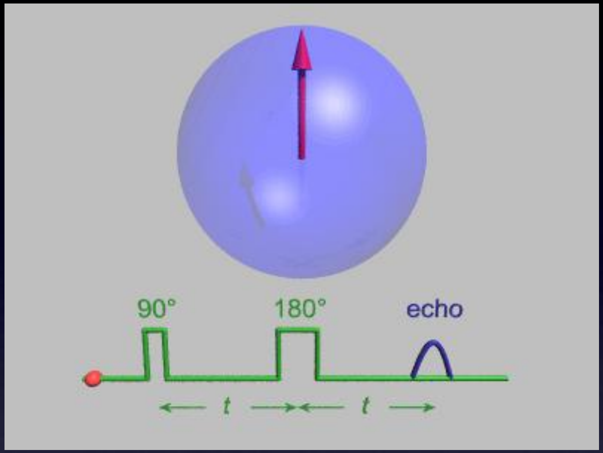
Paramagnetic centers are identified via their microwave absorption spectrum.



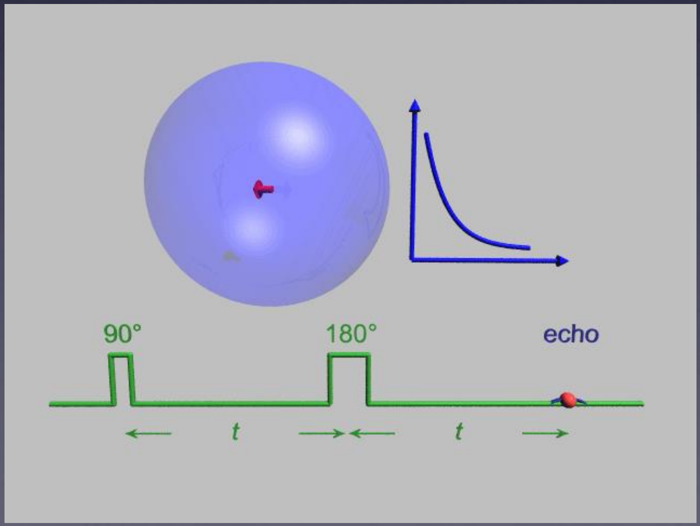
Microwaves,
e.g. 10GHz

Species	*I*	*A (MHz)*
^{31}P	1/2	*117.53*
^{75}As	3/2	*198.35*
^{121}Sb	5/2	*186.802*
^{123}Sb	7/2	*101.518*
^{209}Bi	9/2	*1475.4*

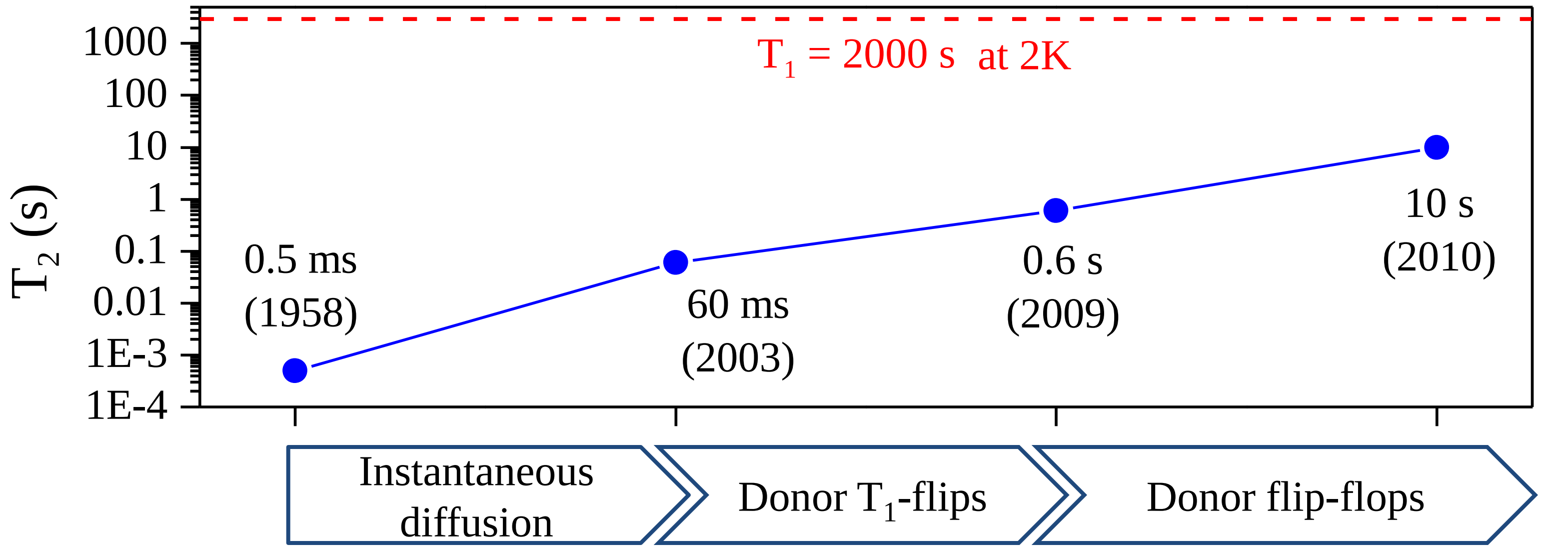
Electron spin coherence times are determined via pulsed ESR measurements.



Source: Wikipedia



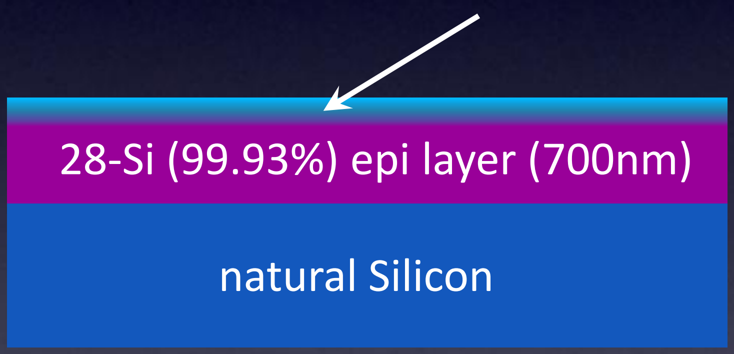
Isolated Donor $T_2 \geq 10$ seconds in ^{28}Si at 2 K



- T_1 spin-lattice relaxation time
- T_2 spin-spin relaxation time (phase coherence)
- $2T_1 \geq T_2$

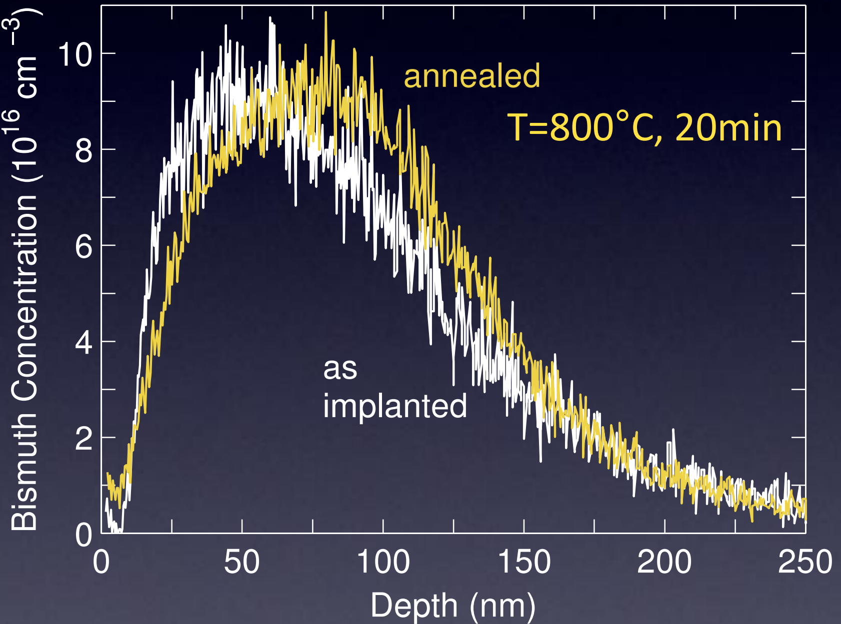
• A. M. Tyryshkin et al., Nature Materials, 2012

Bismuth is implanted into isotopically enriched silicon-28 for measurements of electron spin coherence



(Natural Si > 10 kΩcm for measurements of electrical activation)

Secondary Ion Mass Spectroscopy



Total fluence: $1.1{\times}10^{12}$ cm^{-2}

E_{kin} = 40, 80, 120, 200 and 360keV

Energy level splitting for bismuth in silicon.

$$\hat{H} = g_e \mu_{B_e} B \cdot S + A_{\text{hyp}} S \cdot I - g_N \mu_{B_N} B \cdot I$$

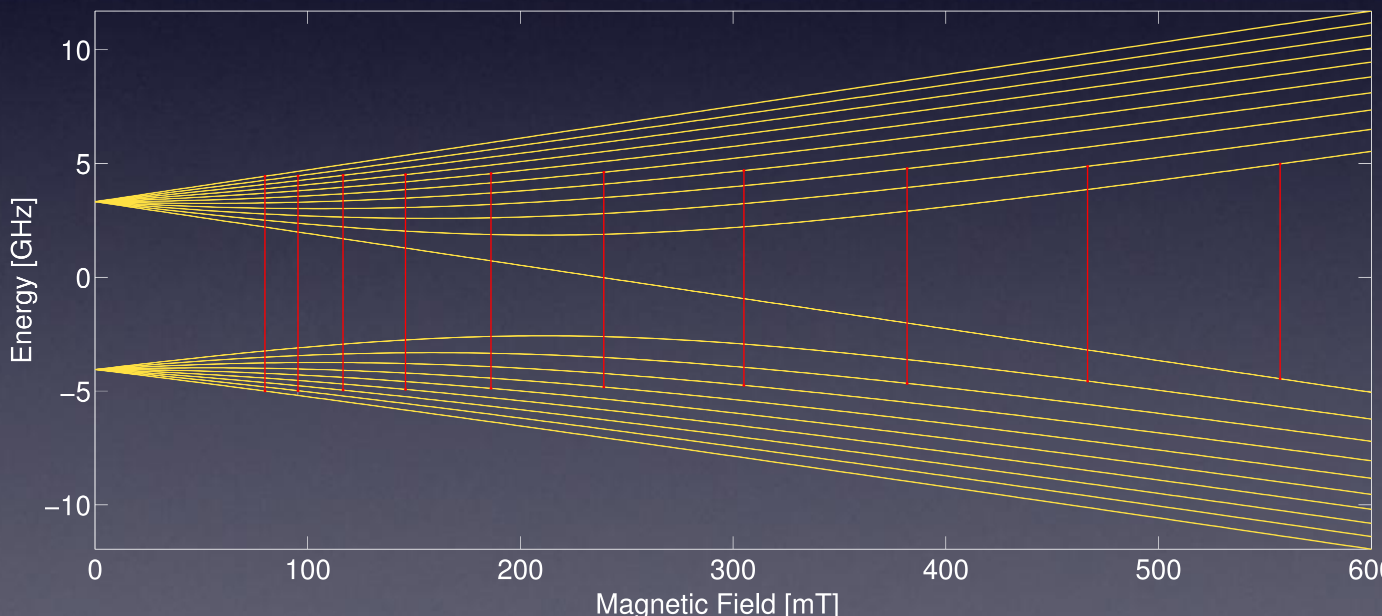
$$E_{\pm} = -\frac{A}{4} - g_N \mu_N B m \pm \left(I + \frac{1}{2}\right) \frac{A}{2} \sqrt{1 + \frac{2m}{I + \frac{1}{2}} \alpha + \alpha^2}$$

$$\alpha = \frac{g_e \mu_e B + g_N \mu_N B}{A(I + \frac{1}{2})}$$

$$m = m_s + m_I$$

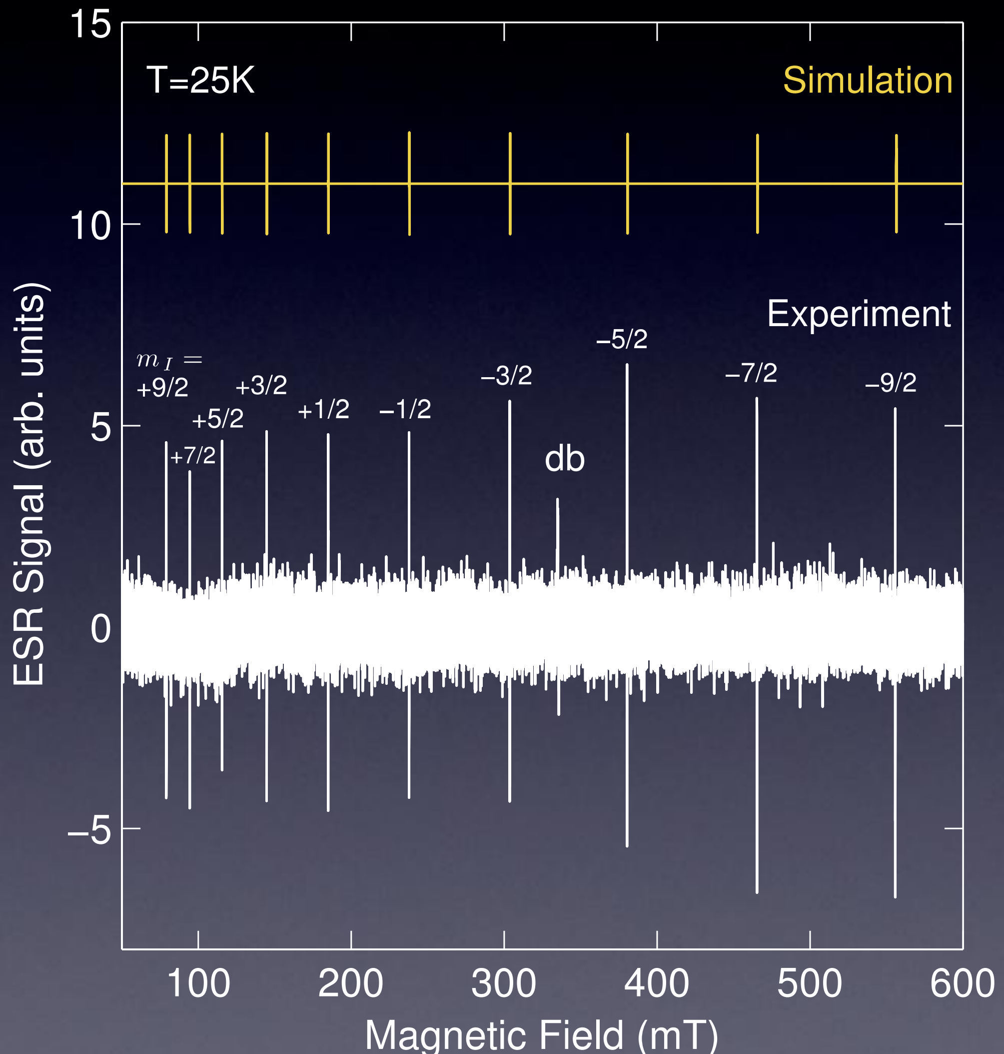
$$ZFS = A(I + 1/2)$$

$ZFS_{Bi} = 63 \times ZFS_P$



Cw-ESR measurements confirm electrically active Bismuth

Five stacked samples ≈ 1.5x1012 Bi atoms



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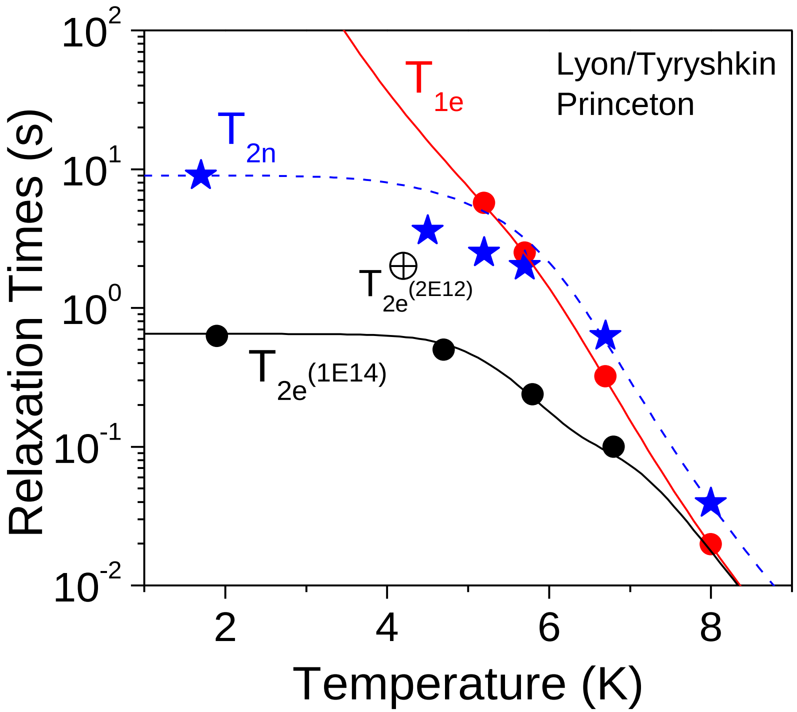
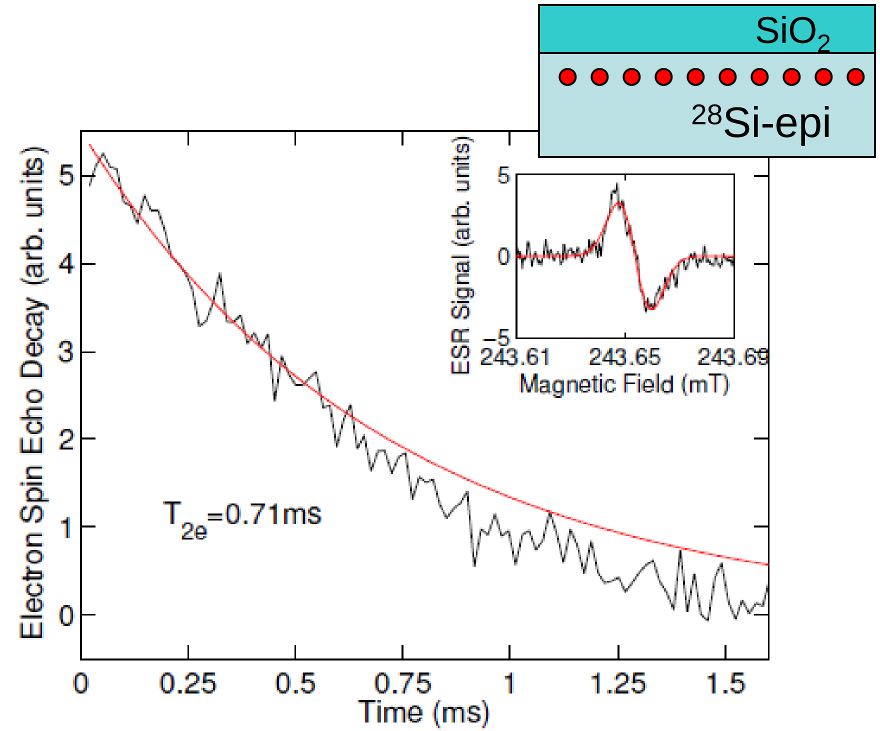
3. **Long decoherence time** (>10^4 operation time, to allow for error correction)





"Electron spin coherence exceeding seconds in high-purity silicon", A. M. Tyryshkin, S. Tojo, J. J. L. Morton, H. Riemann, N. V. Abrosimov, P. Becker, H. J. Pohl, T. Schenkel, M. L. W. Thewalt, K. M. Itoh, and S. A. Lyon, **Nature Materials** 11, 143 (2012)

- idealized case of isolated donors ($2{\cdot}10^{12}$ -10^{14}cm^{-3})

"Electrical activation and electron spin resonance measurements of implanted bismuth in isotopically enriched silicon-28"
C. D. Weis, C. C. Lo, V. Lang, A. M. Tyryshkin, R. E. George, K. M. Yu, J. Bokor, S. A. Lyon, J. J. L. Morton, and T. Schenkel, **Appl. Phys. Lett**., 100, 172104 (2012)

- Coherence time much shorter than in idealized case due to higher donor concentration ($9{\cdot}10^{16}$ cm^{-3}) near a noisy interface

Bismuth T_{2e} times are comparable to other implanted donor species at similar dopant concentration per hyperfine line.

Interface	Peak dopant depth (nm)	Apparent activation ratio	T_1 (ms) at 5.2 K	T_2 (ms) at 5.2 K
SiO_2	50	(3.4%)	15±2	0.3±0.03
H–Si	50	—	16±2	0.75±0.04
SiO_2	150	100%	16±1	1.5±0.1
H–Si	150	—	14±1	2.1±0.1

T. Schenkel, et al., Appl. Phys. Lett. 88, 112101 (2006)

Implanted Bismuth:
T_{2e}=0.7ms

-next: T_{2e} at "clock transitions", where df/dB=0, expected to be insensitive to surface magnetic noise
-preliminary results (Steve Lyon, Princeton): T_{2e} at clock transition in these same Bismuth samples is over ten times longer than at standard electron spin transitions
→ insensitivity to surface magnetic noise is very exciting for bismuth donor qubit integration near surfaces in devices !

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   → Stark shift measurements (proto nuclear spin control gate, Bradbury et al. Phys. Rev. Lett. (2006))

   → electron-nuclear spin state transfer; theory: Sarovar et al. PRB (2008), experiments: Morton et al., Nature (2008)

5. *Read-out: Single-quantum measurements*

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6. *Efficient quantum communication ("flying qubits")*

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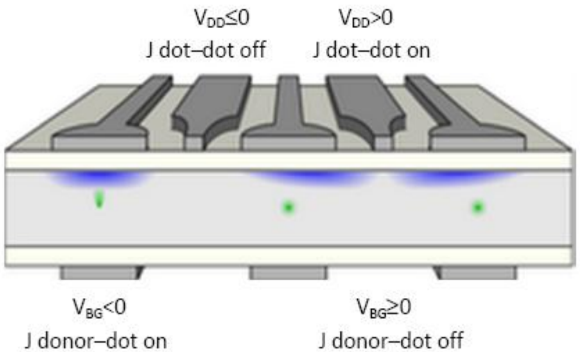

Criteria for physical implementation of a quantum computer **(DiVincenzo)**

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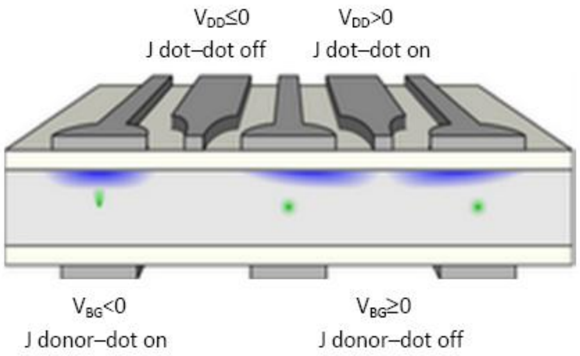
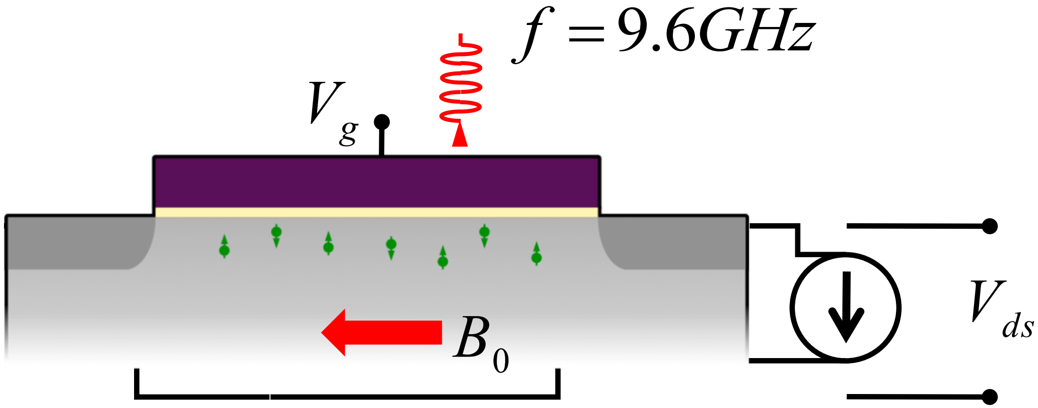
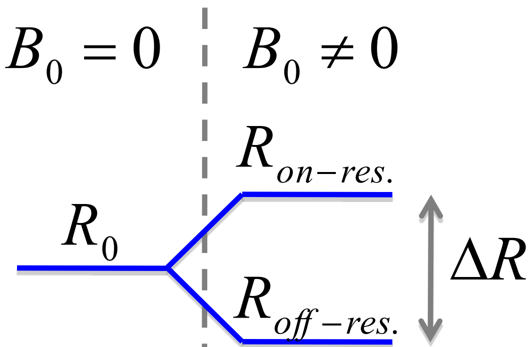
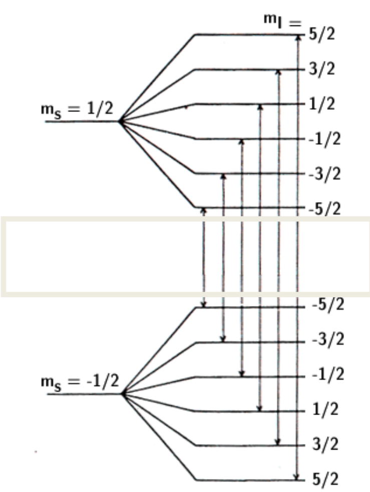


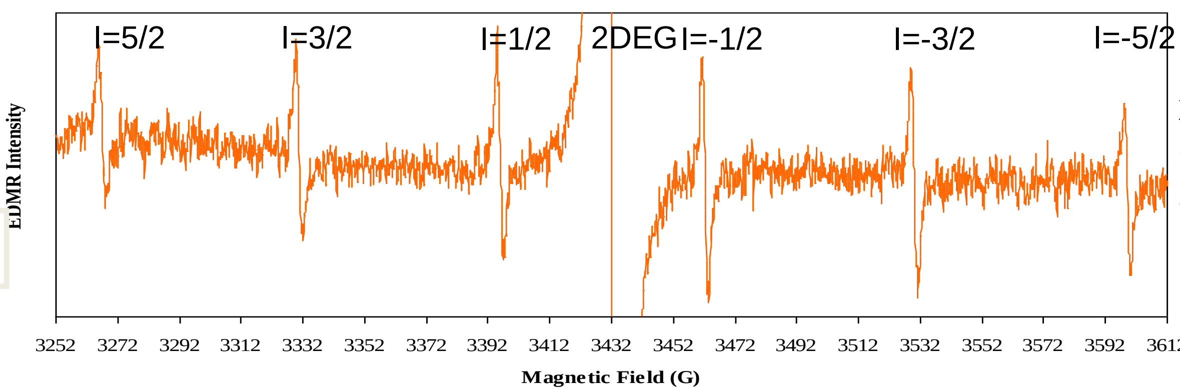
Probing donor spins with Electrically-Detected Magnet Resonance (EDMR)

- Accumulation-mode Field Effect Transistors (aFETs)
  - Neutral donors in channel, gate-tunable conduction electron (2DEG) density (polarization)
  - Strength of EDMR (vs. tunneling): spectroscopic signature of donor species and optimization for scaling from large ensembles to single donor
  - Access to small spin numbers and probing of spin quality







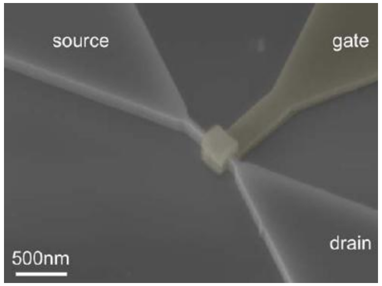


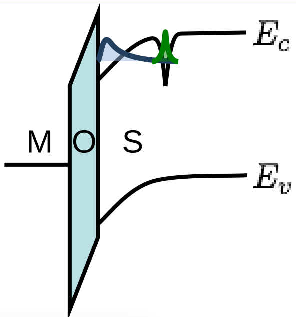
x-band EDMR with ^{121}Sb implanted aFets at 5 K

- **C. C. Lo, et al., Appl. Phys. Lett. (2007)**
- **C. C. Lo, et al., Phys. Rev. Lett (2011)**

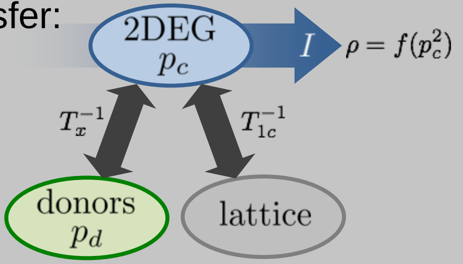
Readout of donor electron spins in silicon transistors

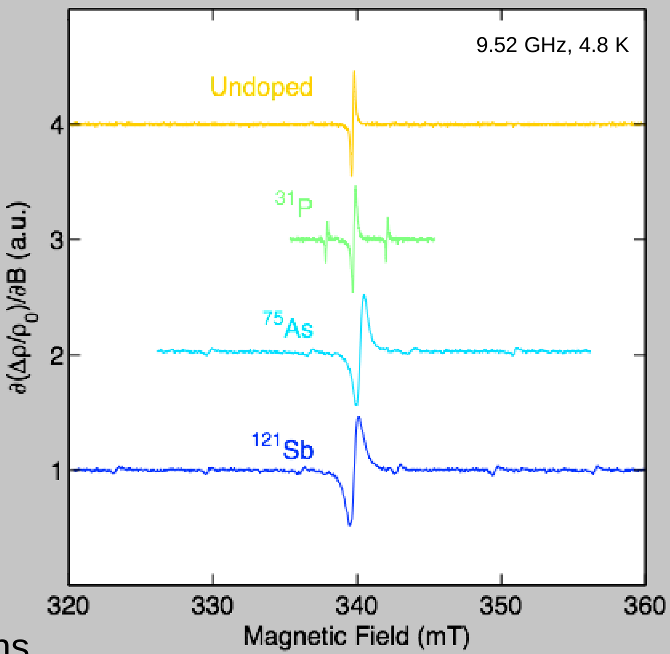
- spin flips change transistor currents
- but not by much ($dI/I \sim 10^{-6}$ at x-band)





- Electrons in a two dimensional electron gas (2DEG) and donor electrons are detected through measurements of current changes that are resonant with spin transitions
- Donors detected via polarization transfer:





- Achieved sensitivity of a few thousand spins

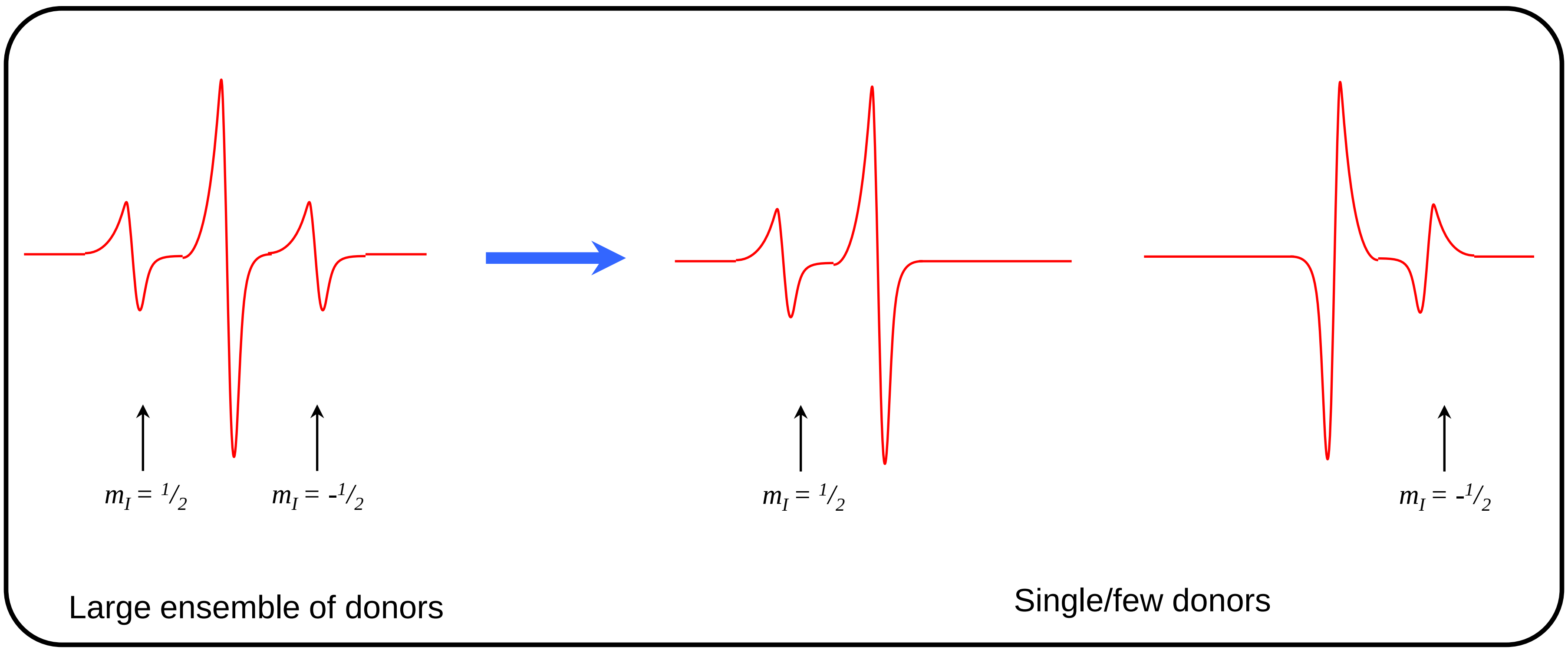
- "Electrically detected magnetic resonance of neutral donors interacting with a two-dimensional electron gas", C. C. Lo, V. Lang, R. E. George, J. J. L. Morton, A. M. Tyryshkin, S. A. Lyon, J. Bokor, T. Schenkel, ***Phys. Rev. Lett.*** 106, 207601 (2011)
- C. L. Lo, et al**., Appl. Phys. Lett.** 100, 063510 (2012)

- An alternative approach using spin dependent tunneling achieved single donor spin detection (Morello et al., Nature, '10)

Readout for single donor electron and nuclear spin by EDMR

- transfer quantum information from electron to nuclear spin[1]
- measure nuclear spin population by detecting presence/absence of a spectral line
- need to measure within nuclear spin flip time
- repeat entire procedure $\rightarrow$ get values of α and β for electron spin qubit with correct statistics

$$|\Psi_e\rangle = \alpha|\uparrow\rangle_e + \beta|\downarrow\rangle_e$$



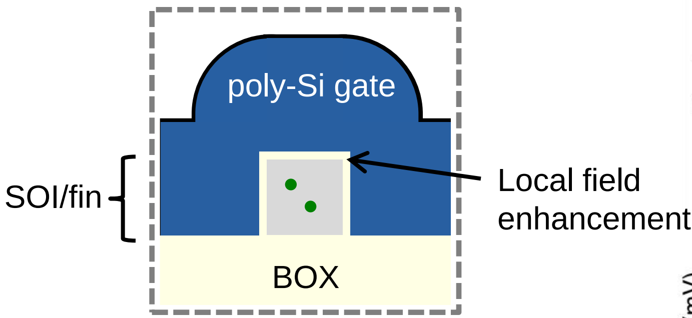
[1]Morton et al., Nature, (2008)

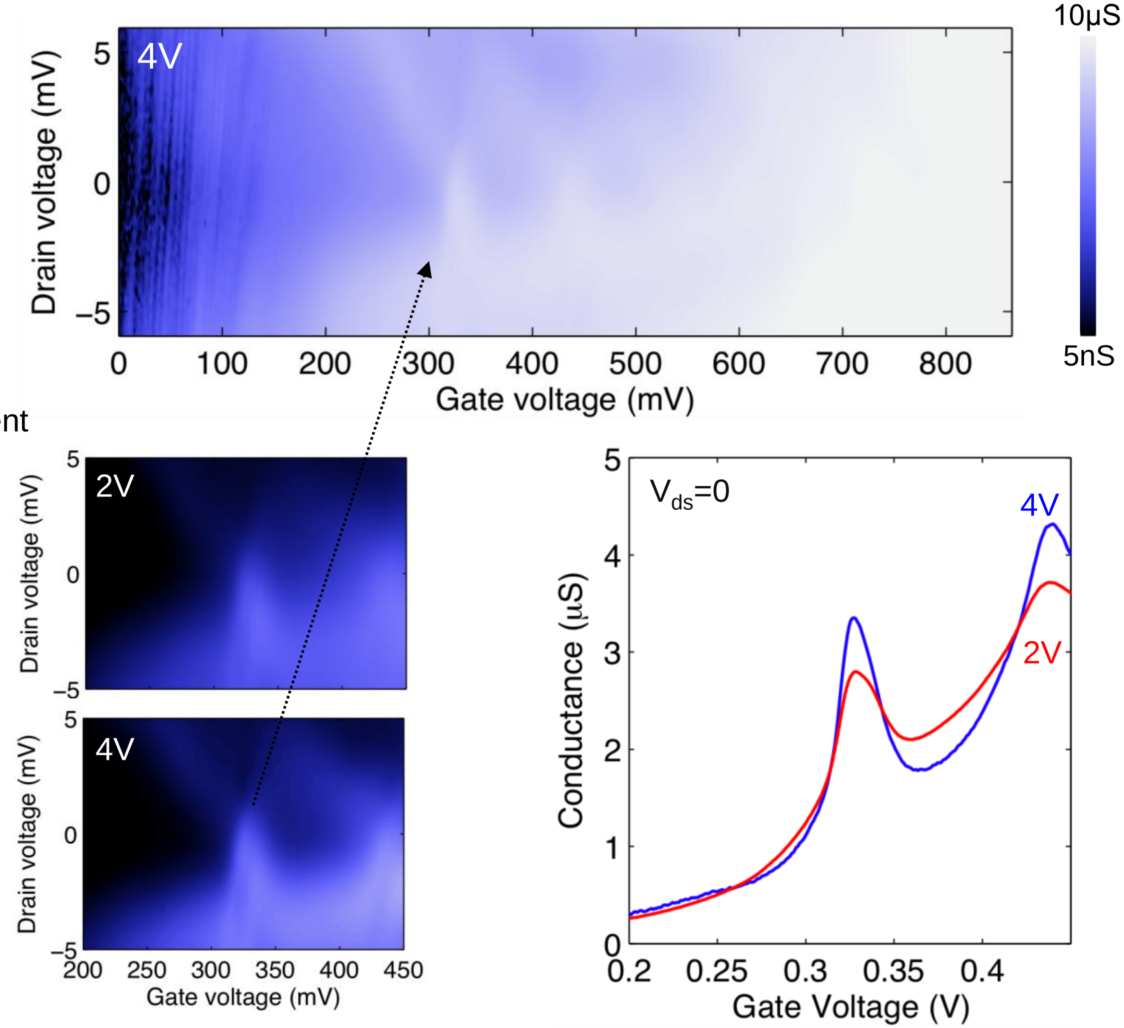
Theory: M. Sarovar, et al. Phys. Rev. B 78, 245302 (2008)

Evidence for transport through single donor atoms (4.2K)

- several devices show strong resonance peaks *after* turn-on:

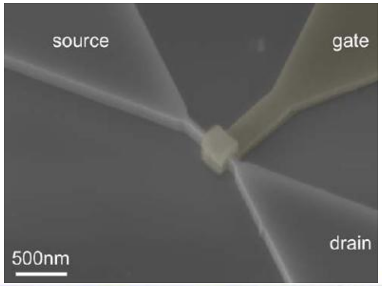
- Corner effects in FinFETs

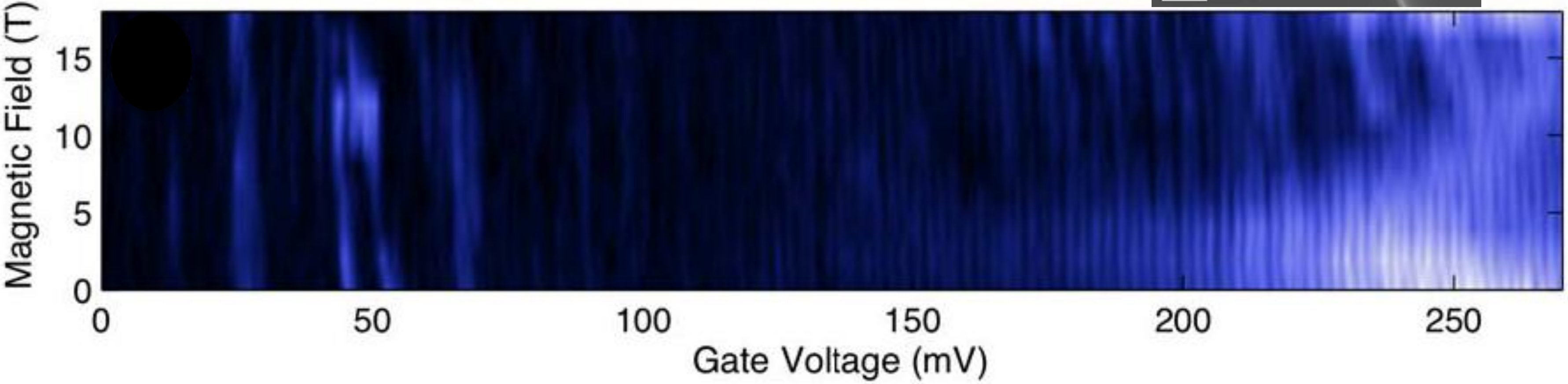


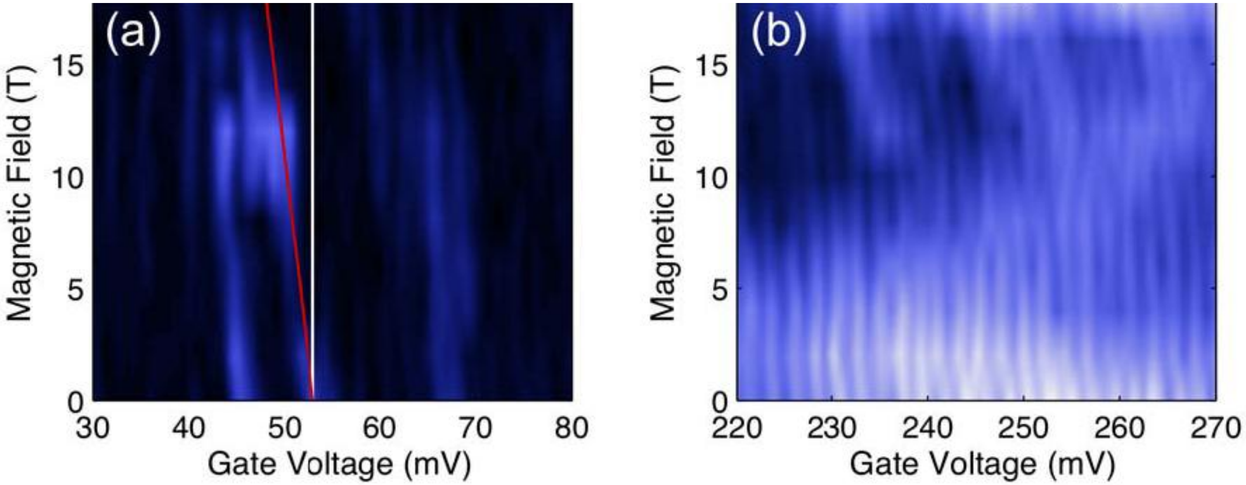


$$l_l = 76\text{nm}, w_l = 50\text{nm}$$

Readout – Find single donor transport resonances in FinFets and run ESR on these for single nuclear spin state detection (within T_{1n})







Magneto transport, l = 100 nm, w = 50 nm triple gate FinFet. Bottom: (a) sub-threshold regime with isolated transport resonances. Some showing a strong magnetic field dependence, corresponding to the Zeeman shift of paramagnetic states, either donor or defect states (red line). (b) Same bias window at higher gate voltage. Coulomb oscillations of the multi-electron quantum dot do not exhibit strong magnetic field dependence at all. T~0. 1 K. Experiments at National High Magnetic Field Lab, Tallahassee.

But we did not succeed in detecting spin resonances on single dopant transport features.

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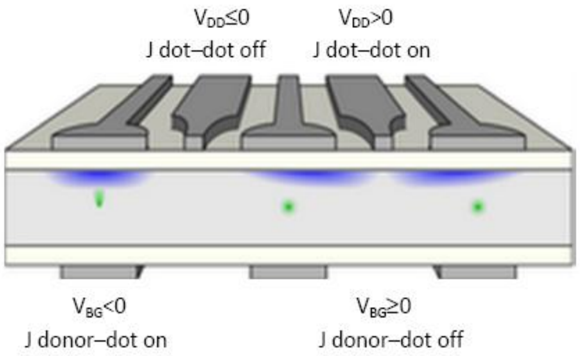
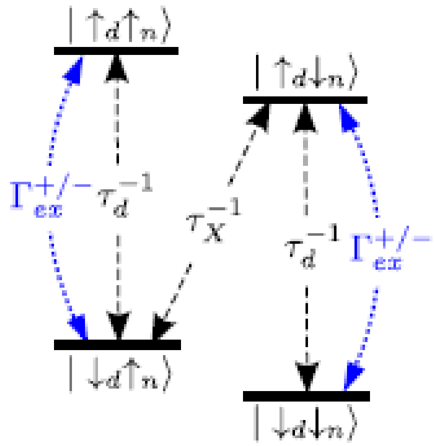
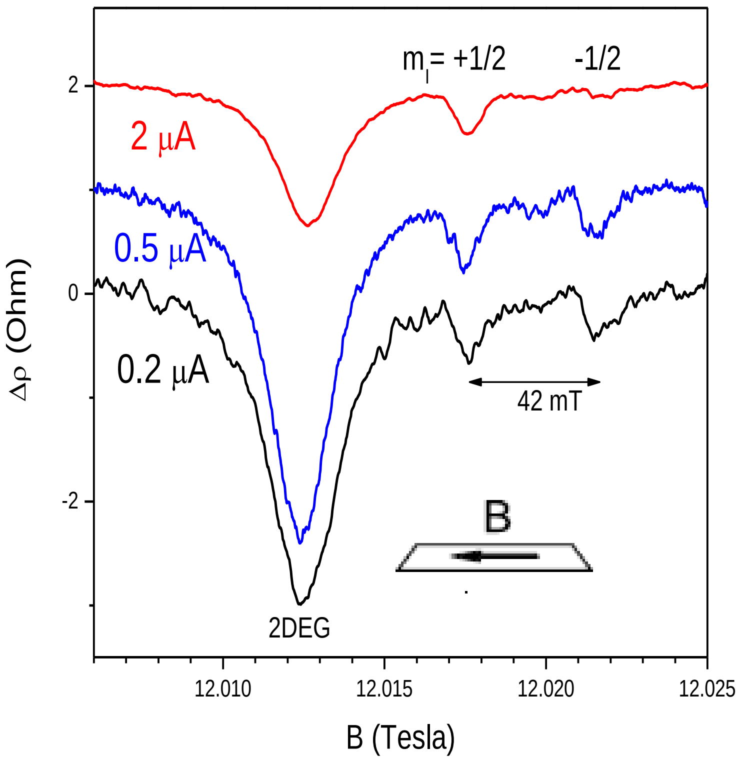


All-electrical nuclear spin polarization of donors



- “hot” 2DEG electrons from high source-drain bias fields, rapid exchange scattering leads to difference in spin and lattice (phonon) temperatures
- Nuclear polarization detected by EDMR
- 5K, 300GHz radiation and in-plane B-field (co. J. van Tol, NHMFL, Tallahassee)



$$\tau_X \sim \frac{1}{B^2 T A^2 I}$$

-τ_X: electron-nuclear spin flip-flop rate scaling
B: external magnetic field
T: temperature
A: hyperfine coupling strength
I: nuclear spin

- $P_n = {}^{(Y\uparrow n - Y\downarrow n)}/_{(Y\uparrow n + Y\downarrow n)}$ =66% for Phosphorus at 12 T (I=1/2, A=0.1 GHz)

→ **Expect for Bismuth at 0.3 T (I=9/2, A=1.5 GHz)**

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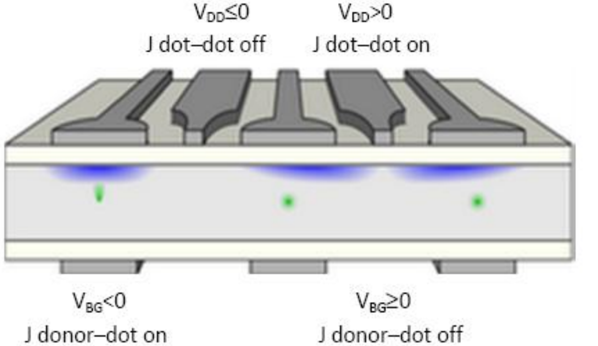
   → spin dependent transport in transistors

6. *Efficient quantum communication ("flying qubits")*
   → coherent electron shuttling, ensemble tests in back gated 28-SOI devices (in progress, co. J. Morton)



Outlook – Exploration of quantum computer architectures with donor spin qubits in silicon

1. *Well defined extendible qubit array – stable memory*

   → **single ion implantation of donor atoms**

2. ***Initialization in the "000…" state***

   → **nuclear spin polarization with electrical currents**

3. ***Long decoherence time (>10^4 operation time, to allow for error correction)***

   → **protection of donor electron and nuclear spin coherence, "clock-transitions"**

4. *Universal set of gate operations (not, cnot)*

   → Stark shift measurements (proto nuclear spin control gate)

   → electron-nuclear spin state transfer

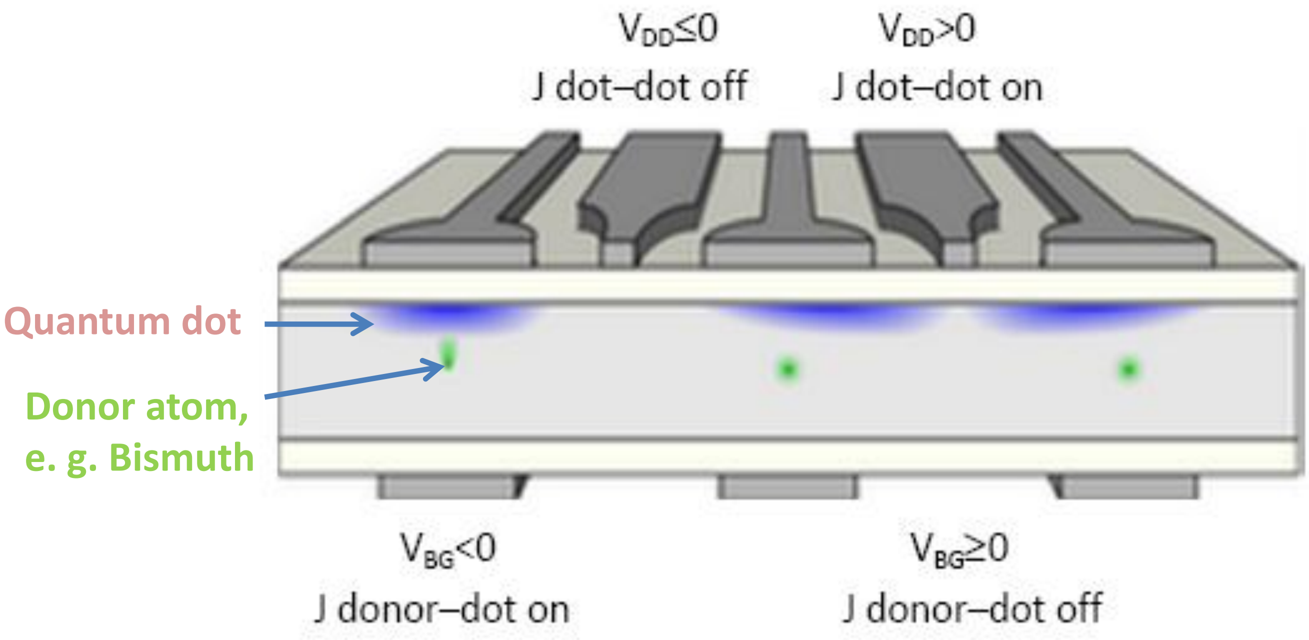
5. ***Read-out: Single-quantum measurements (projective measurement)***

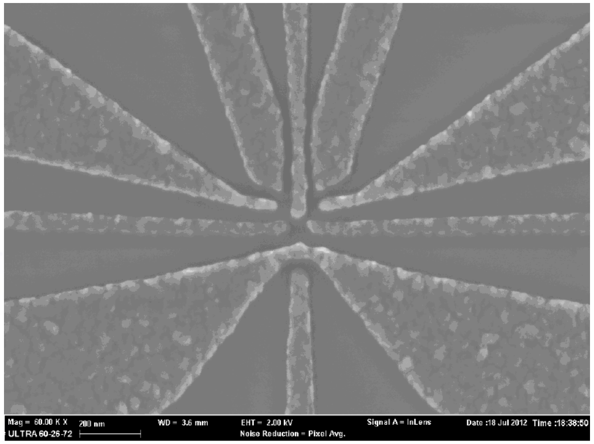
   → **spin dependent transport in transistors**

6. *Efficient quantum communication ("flying qubits")*

   → electron shuttling (in progress)

Outlook - spin qubits in donor – quantum dot devices





- SEM image of a prototype donor-dot device

- Donor electron spins couple to donor nuclear spins for long term quantum memory
- Quantum logic on donor electrons coupled to quantum dot electrons and between adjacent quantum dots
- Quantum communication by coherent electron shuttling between quantum dots

"A spin qubit architecture with coupled donors and quantum dots in silicon", T. Schenkel, C. C. Lo, C. D. Weis, J. Bokor, A. M. Tyryshkin, and S. A. Lyon, arXiv:1110.2228, "Single Atom Nanoelectronics" (T. Shinada, E. Prati, eds.), 2012, in press