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Shallow Donors in Silicon as Electron and Nuclear Spin Qubits

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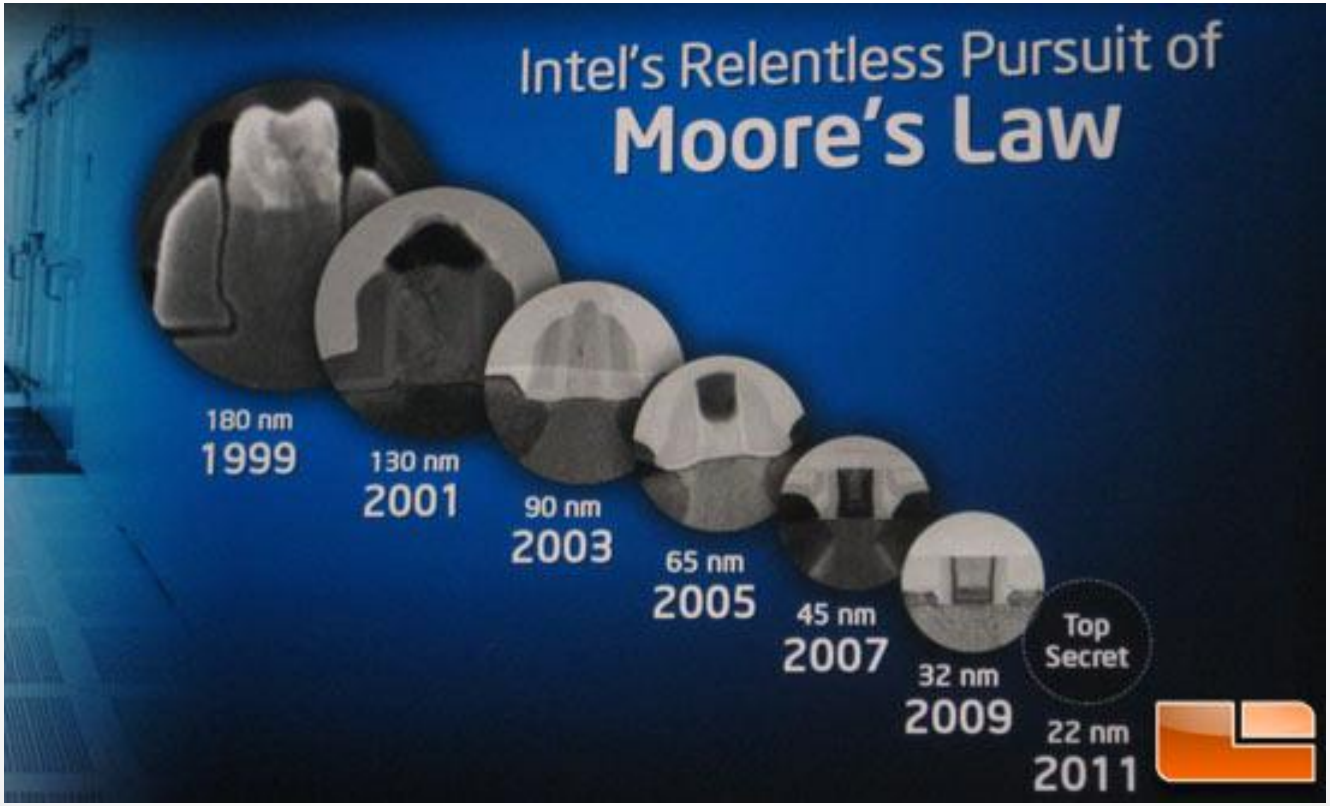
Overview

- Electronics – The end of Moore's law?
- Quantum computing
- Spin qubits
- Relaxation
- Manipulation
- Readout
- FEL EPR

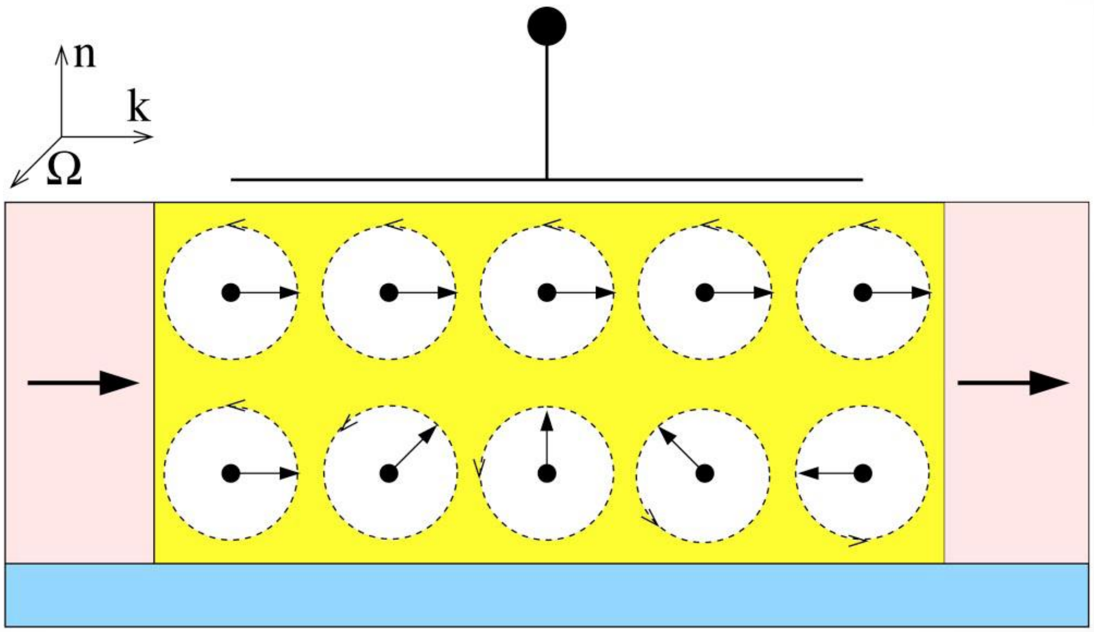
(Gordon) Moore's law

- "The number of transistors incorporated in a chip will approximately double every 24 months."



Spintronics

- Electronics depends on the charge of the electron
- Using the spin: **spin tr**ansport electr**onics**

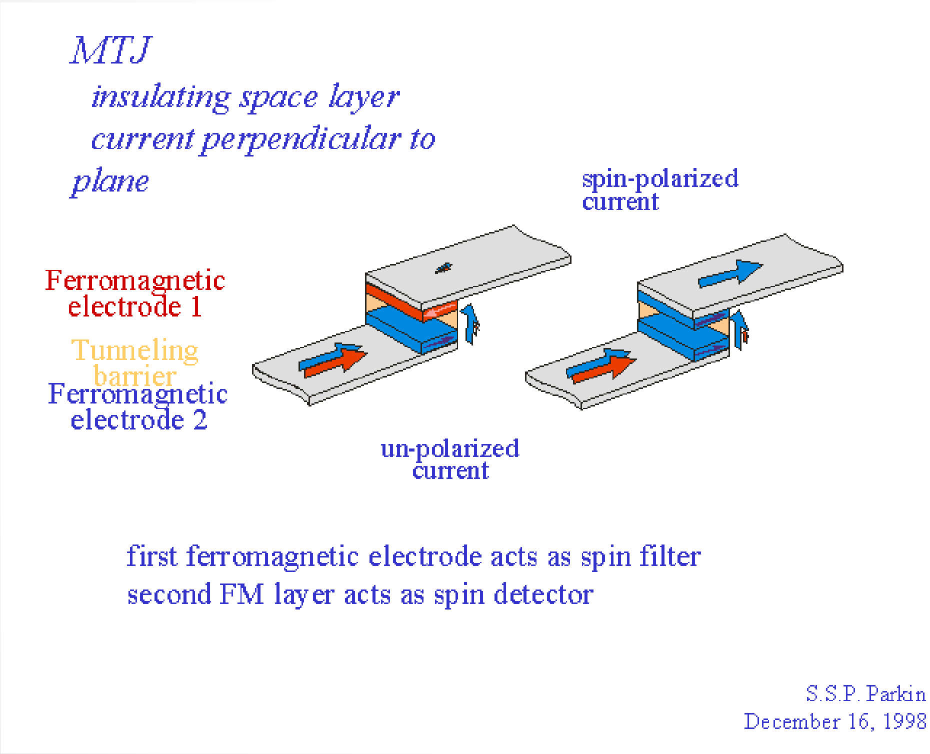


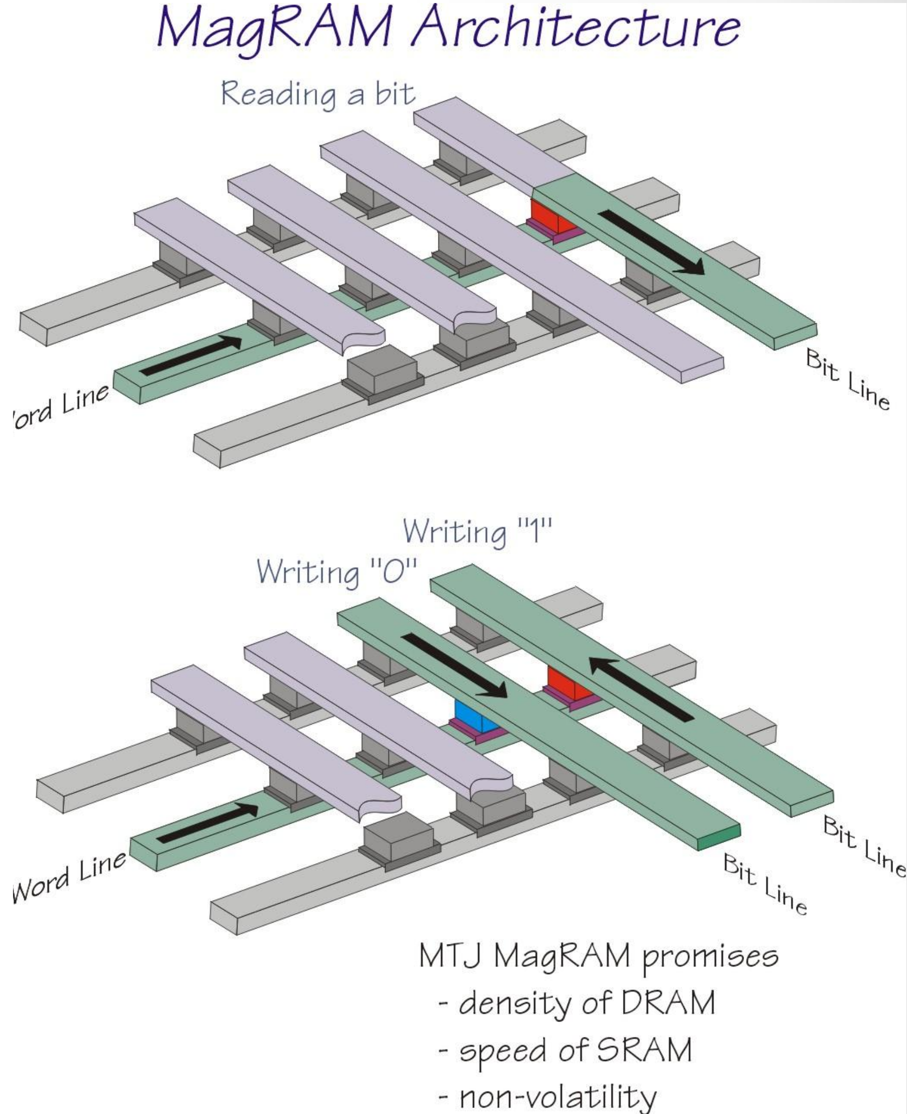
Source: Zutic et al. Rev Mod Phys 76 (2004), 323.

Datta-Das Spin Field Effect Transistor

Spintronics device MRAM

- Universal Memory





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Quantum Computer

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain.

Peter Shor:

Factorization of a prime number can be solved in many fewer steps in a quantum computer. (1994)

Requirements

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- Scalable quantum system that:
  - Can represent quantum information robustly (long-lived: long relaxation times)
  - Perform transformations (operations)
  - Prepare an initial state
  - Measure the results

→ SPINS

Magnetic moment of electron and nuclear spins is 'isolated' from the surroundings

Proposed schemes

- Superconductor-based quantum computers (including SQUID-based quantum computers)[18]
- Trapped ion quantum computer
- Optical lattices
- Topological quantum computer[19]
- Quantum dot on surface (e.g. the Loss-DiVincenzo quantum computer)
- Nuclear magnetic resonance on molecules in solution (liquid NMR)
- Solid state NMR Kane quantum computers
- Electrons on helium quantum computers
- Cavity quantum electrodynamics (CQED)
- Molecular magnet
- Fullerene-based ESR quantum computer
- Optic-based quantum computers (Quantum optics)
- Diamond-based quantum computer[20][21][22]
- Bose–Einstein condensate-based quantum computer[23]
- Transistor-based quantum computer - string quantum computers with entrainment of positive holes using an electrostatic trap
- Spin-based quantum computer
- Adiabatic quantum computation[24]
- Rare-earth-metal-ion-doped inorganic crystal based quantum computers[25][26

Quantum Computing

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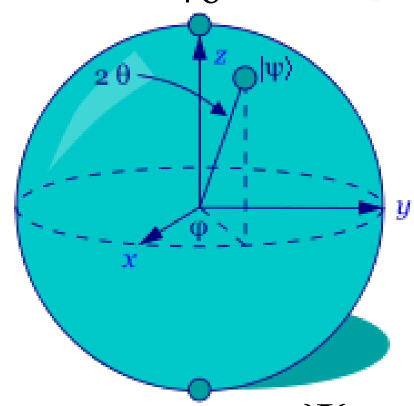
Bit

QuBit

1 or 0

|0>



|1>

$\Psi = \cos(\theta)|0\rangle + \exp^{-i\varphi}\sin(\theta)|1\rangle$

2 bits: 4 states: 00, 01, 10, 11

2 qubits: |00>, |01>, |10>, |11>,

$1/\sqrt{2}$ (|00> + |11>), $1/\sqrt{2}$ (|00> + |01>), …

½ (|00>-|01>+|10>-|11>), …

The EPR phenomenon

$$H = \mu_B B \cdot \mathbf{g} \cdot S + S \cdot \mathbf{D} \cdot S + \sum_j S \cdot \mathbf{A} \cdot I_j - \gamma_n I_j B + \sum_k J S_k \cdot S + S_k \cdot \mathbf{T_{dip}} \cdot S$$

Zeeman

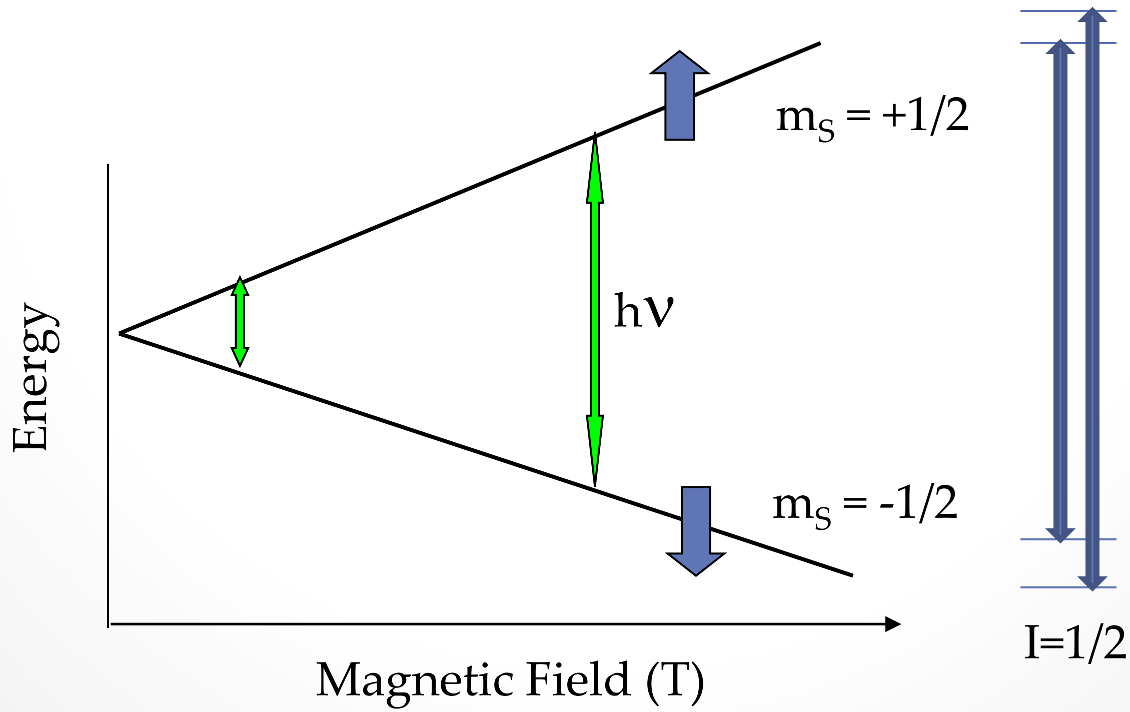
Hyperfine structure

Exchange

Fine Structure

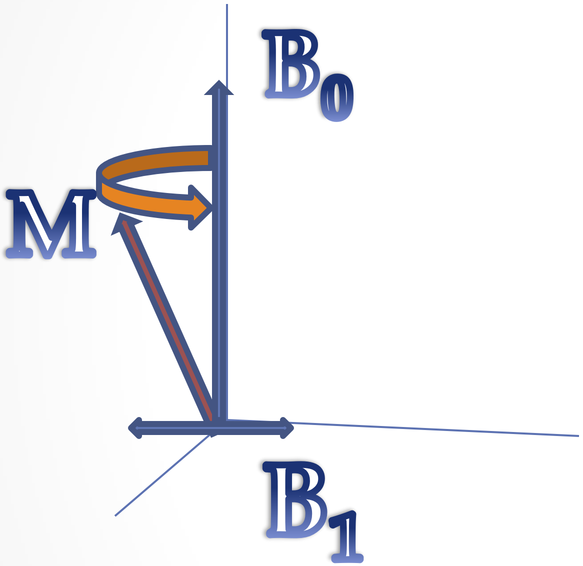
Nuclear Zeeman

Dipolar



Change the reference frame

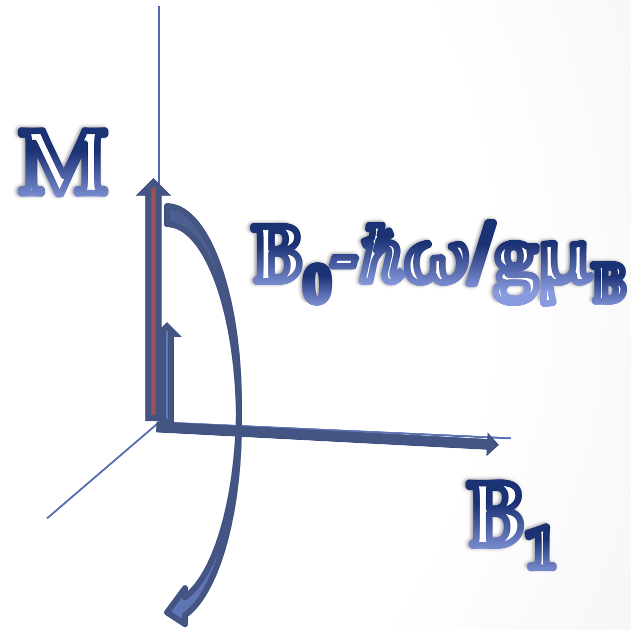
- In the lab frame



$$\frac{d\mathbf{M}(t)}{dt} = \gamma \mathbf{M}(t) \times \mathbf{B}(t)$$

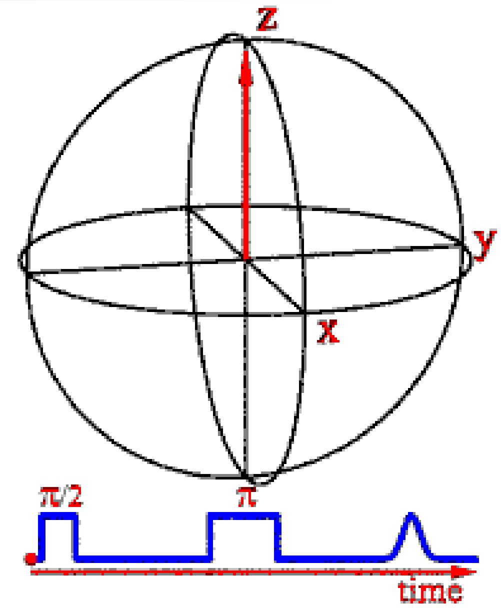
Procession around B_0

- In the rotating frame (ω)



Procession around B_1

What is pulse EPR/NMR ?



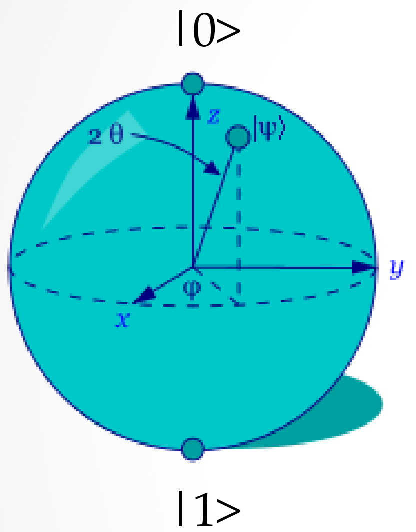
A spin echo seen in the rotating frame

Relaxation parameters

T_1 Spin-lattice relaxation time

T_2 Spin-memory time, spin-spin relaxation time

Relaxation



$\Psi = \cos(\theta)|0\rangle + \exp^{-i\varphi}\sin(\theta)|1\rangle$

Loss of θ: T_1 (Energy)

Spin Lattice Relaxation

Longitudinal Relaxation

Loss of φ: T_2 (Phase)

Spin-Spin relaxation

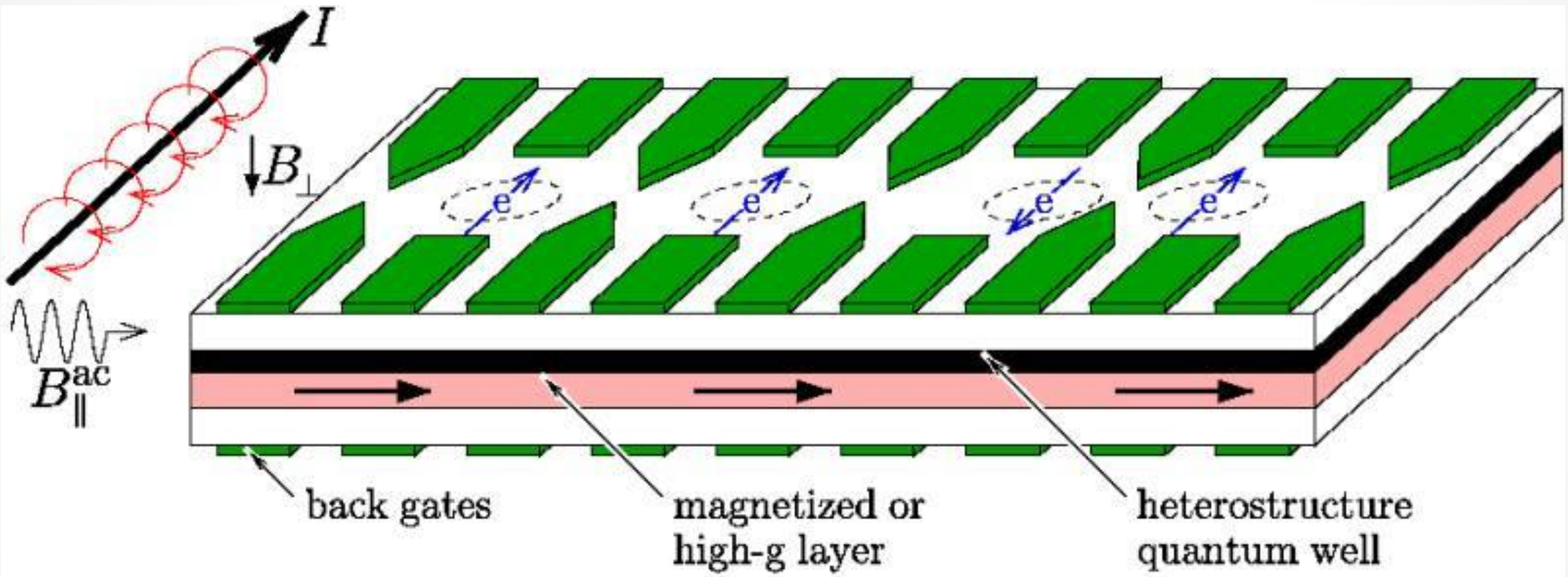
Phase relaxation

Spin memory time

Coherence time

Quantum Dot QC

Loss and DiVincenzo, PRB '98

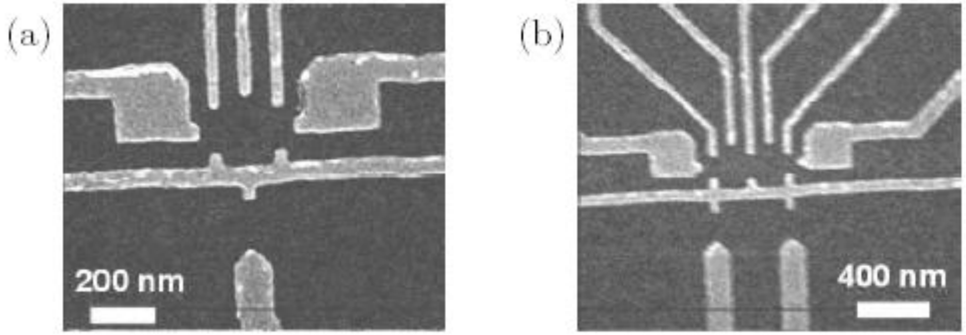


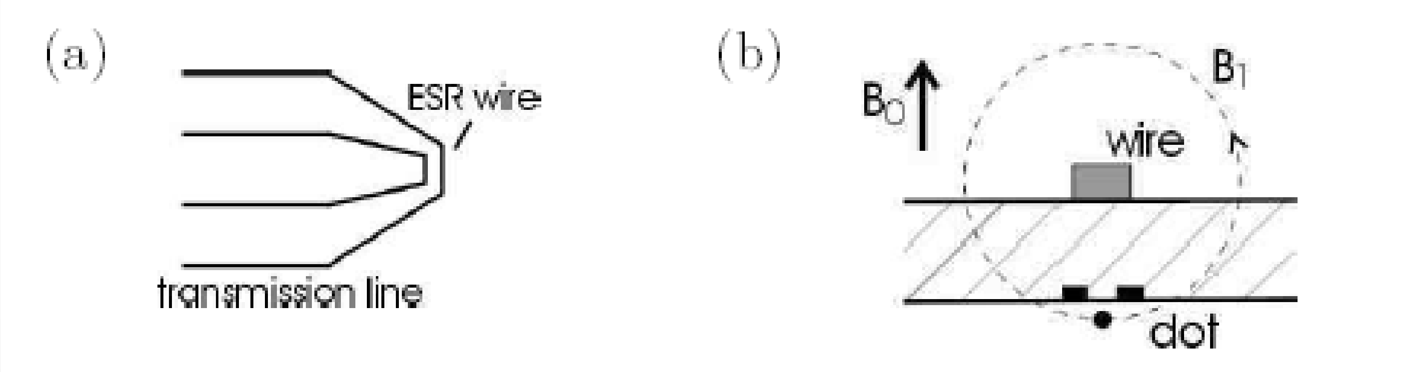
Elzerman, Kouwenhoven et al. (Delft University of Technology)

" Single-shot read-out of a Spin Qubit"

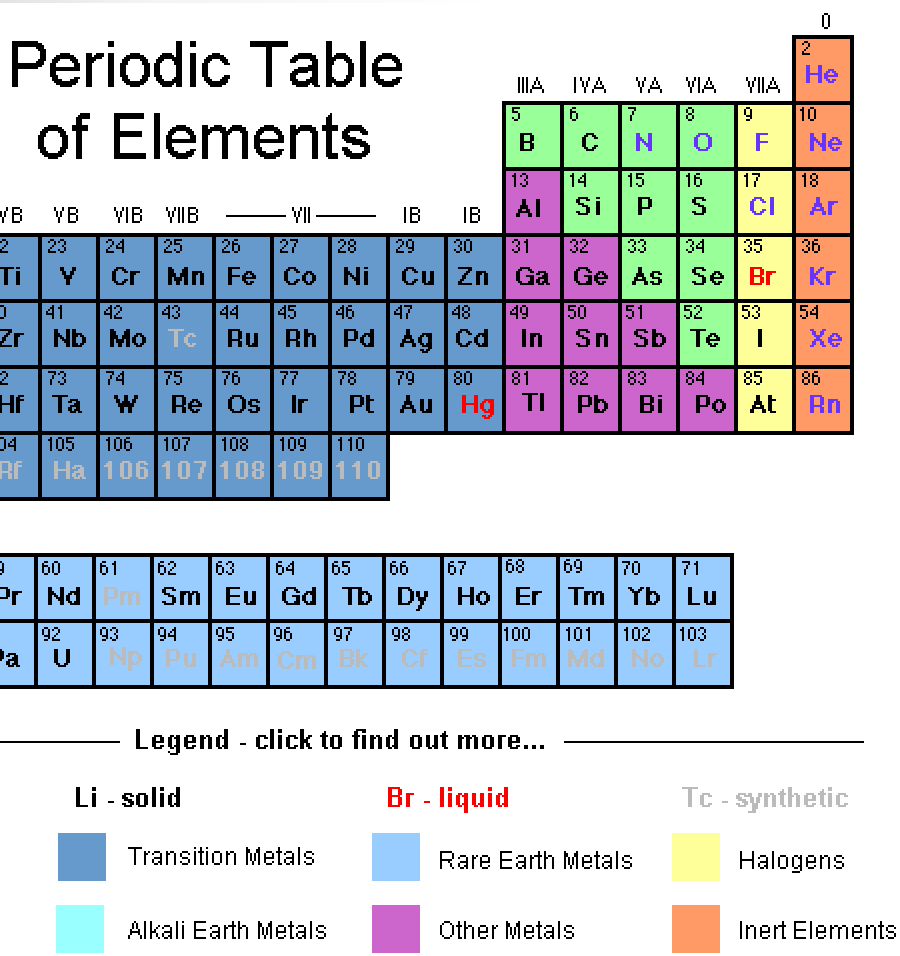
Electron Spin Resonance in quantum dots

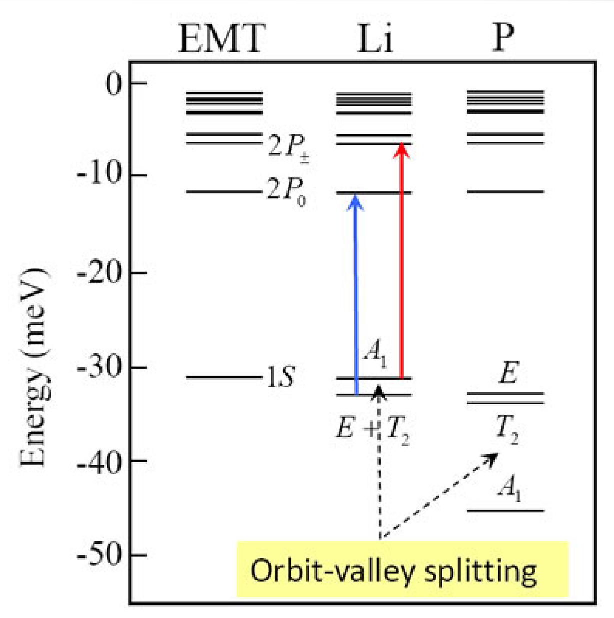
Vandersypen et al. "Quantum Computing and Quantum Bits in Mesoscopic Systems", Kluwer





Shallow donors





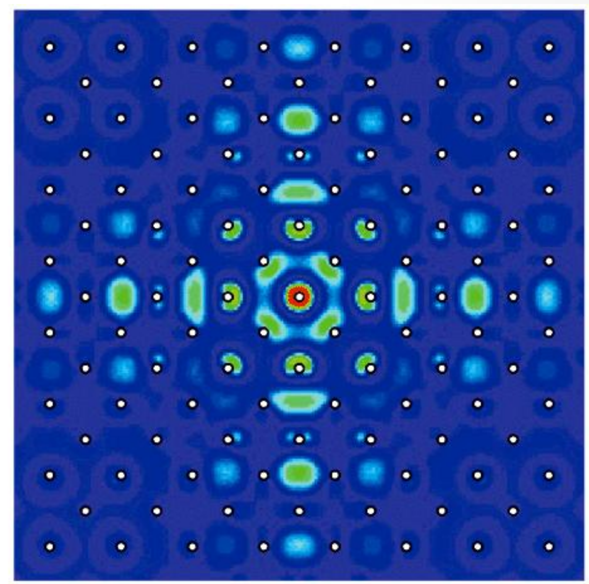
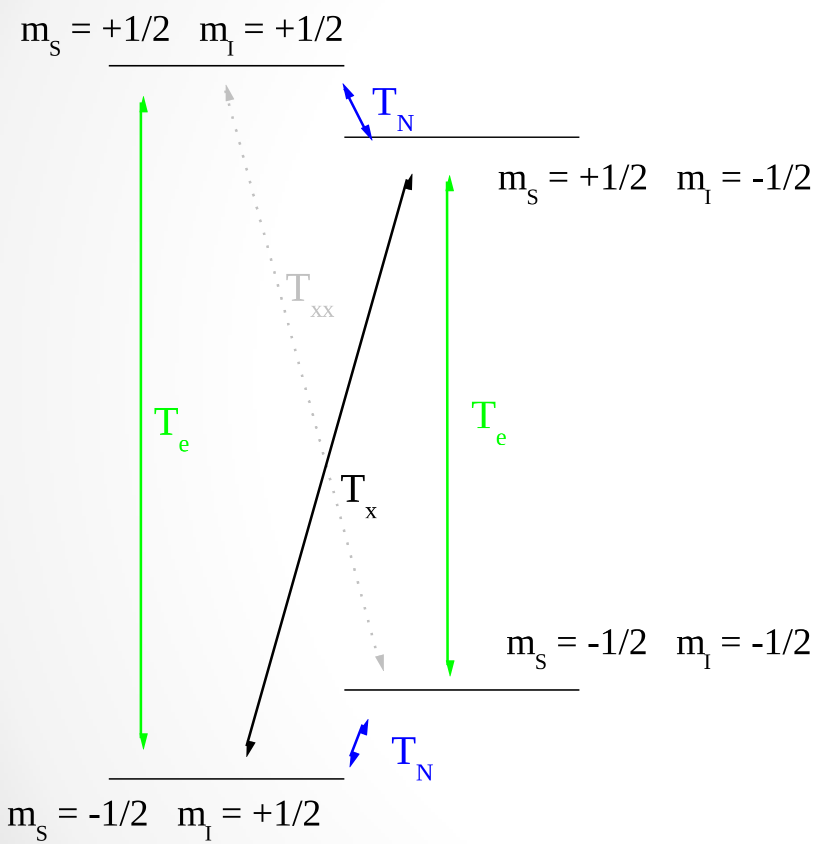


Fig. 1 – (Color) Electron probability density on the (001) plane of bulk Si for the ground state of a donor in Si within the Kohn-Lutttinger effective mass theory. The white dots give the in-plane atomic sites.

Si:P

- Spin system



$$H = gu_B \vec{S}\cdot\vec{B} - \gamma_n \vec{B}\cdot\vec{I} + a\vec{S}\cdot\vec{I}$$

$$S_z I_z + \tfrac{1}{2}(S^+ I^- + S^- I^+)$$

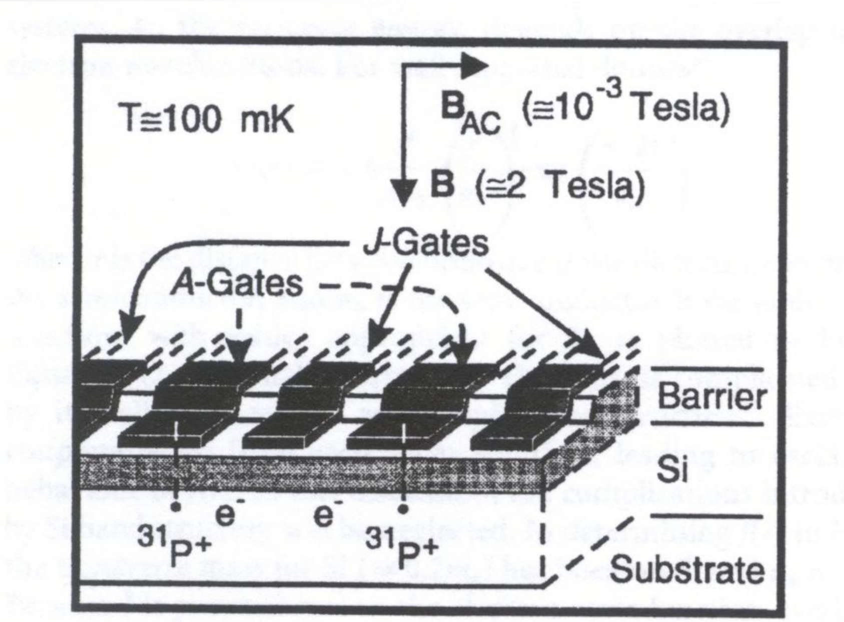
+ ^{29}Si…

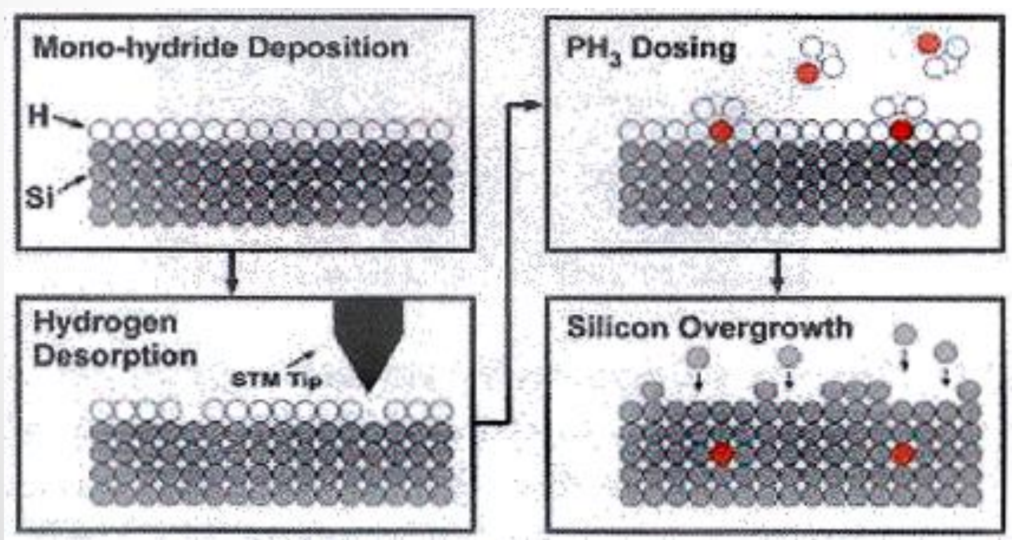
4 CNOT gates

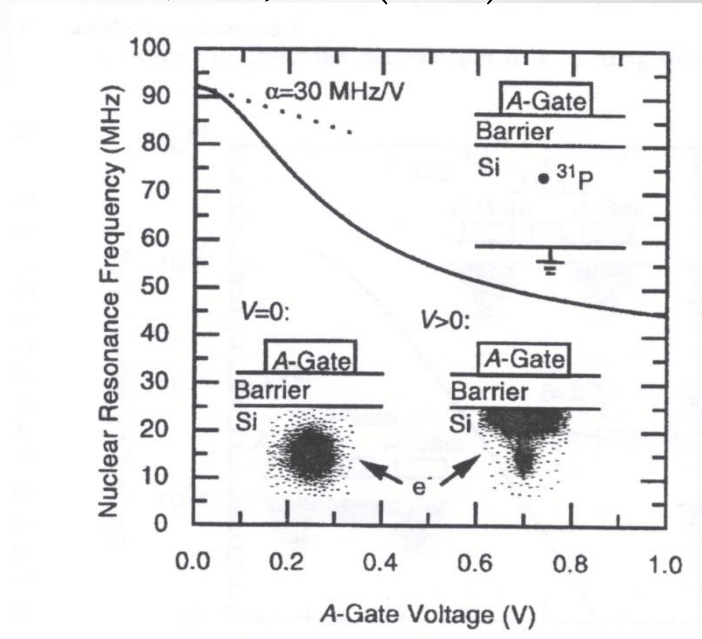
Universal set of quantum gates

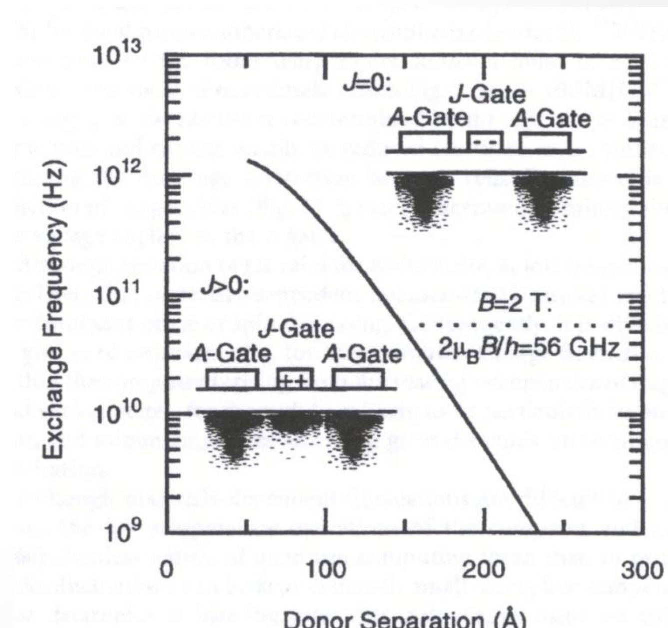
Kane's model

Nature, **393,** 133 (1998).



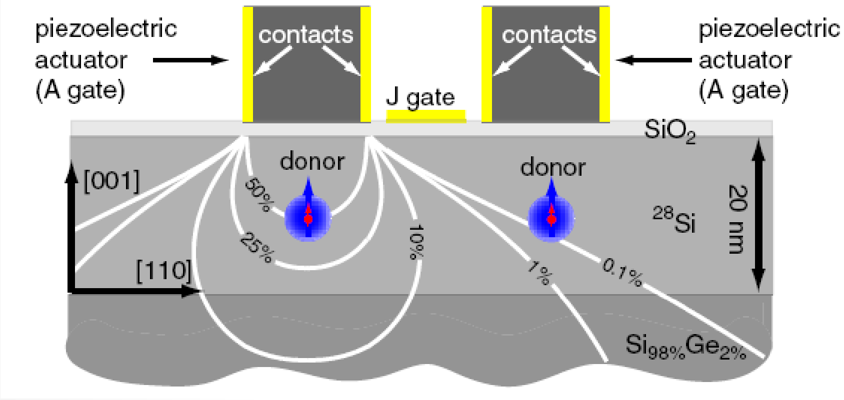


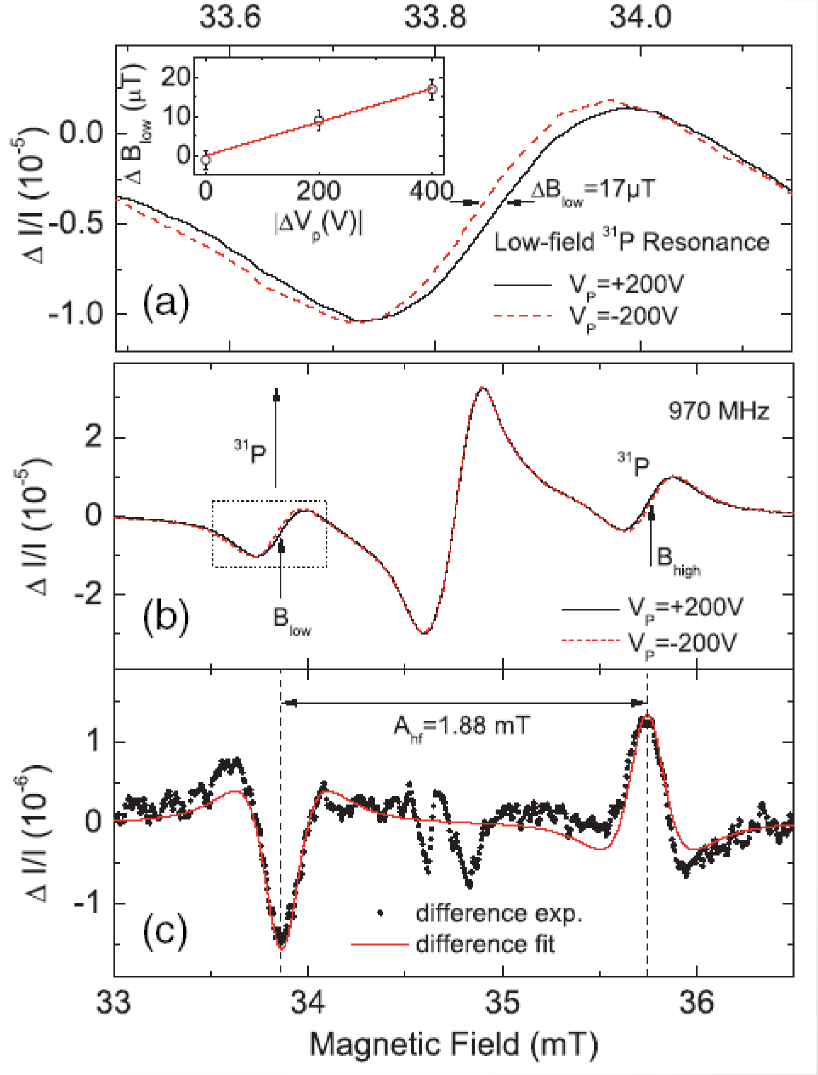




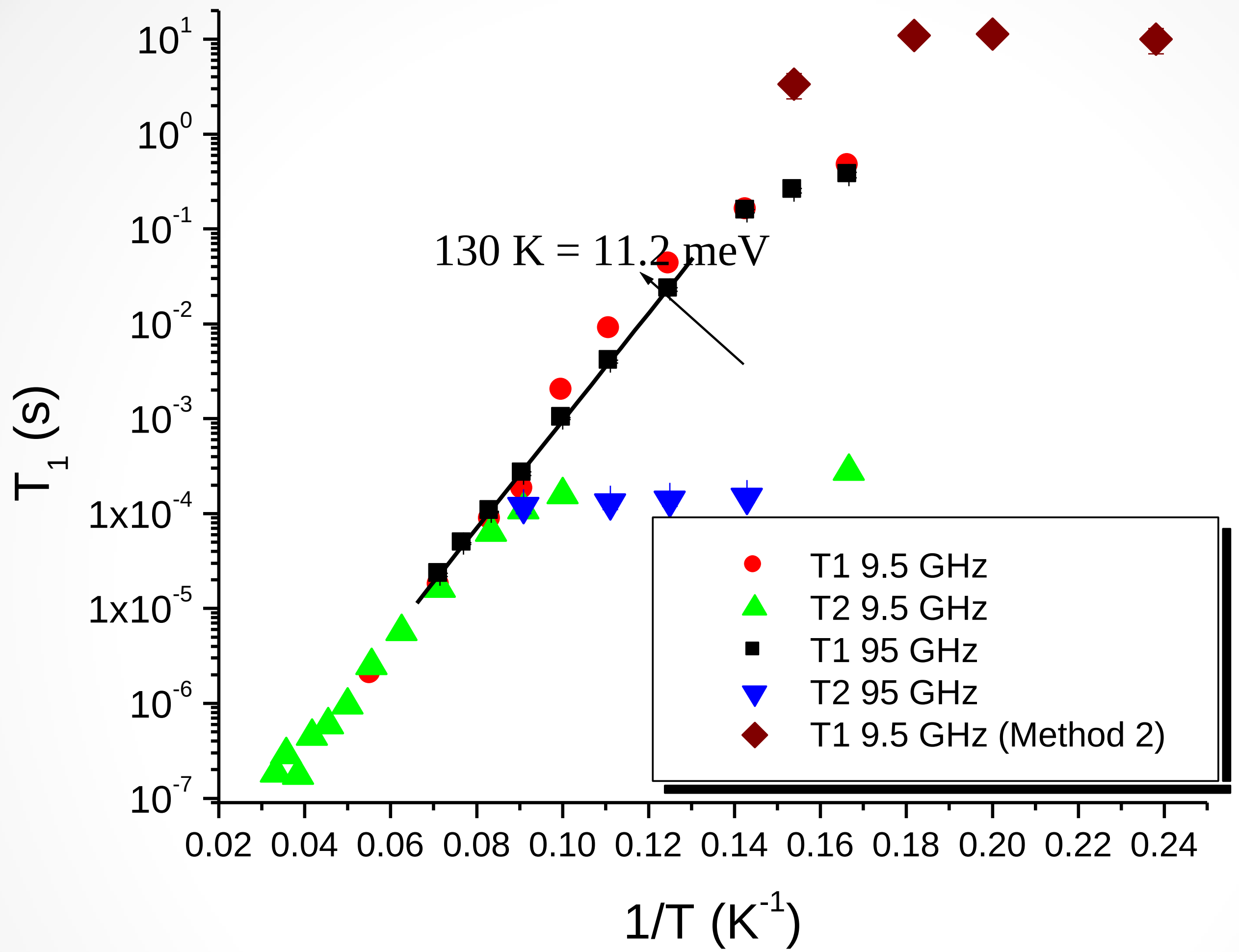
Tuning the hyperfine

- Dreher et al. PRL 106, 037601 (2011)



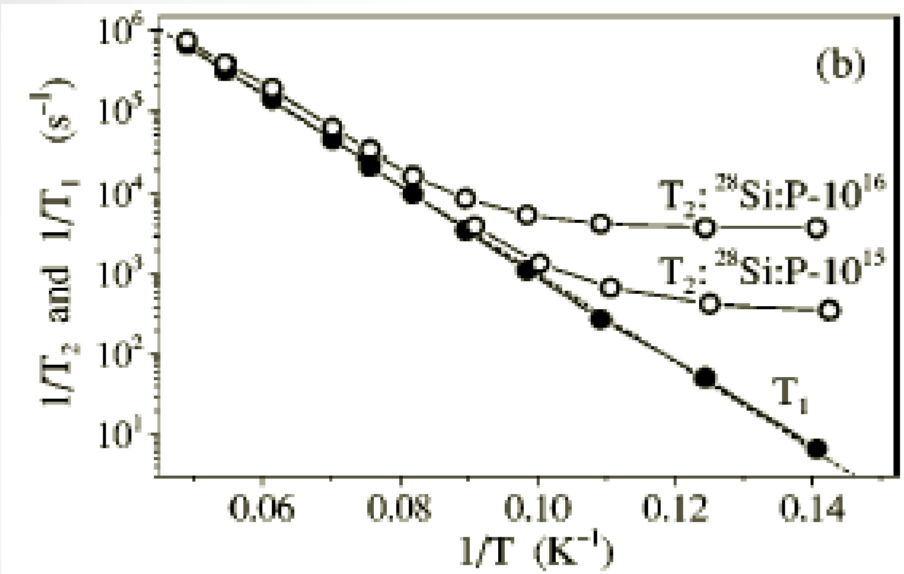


Electron Spin relaxation

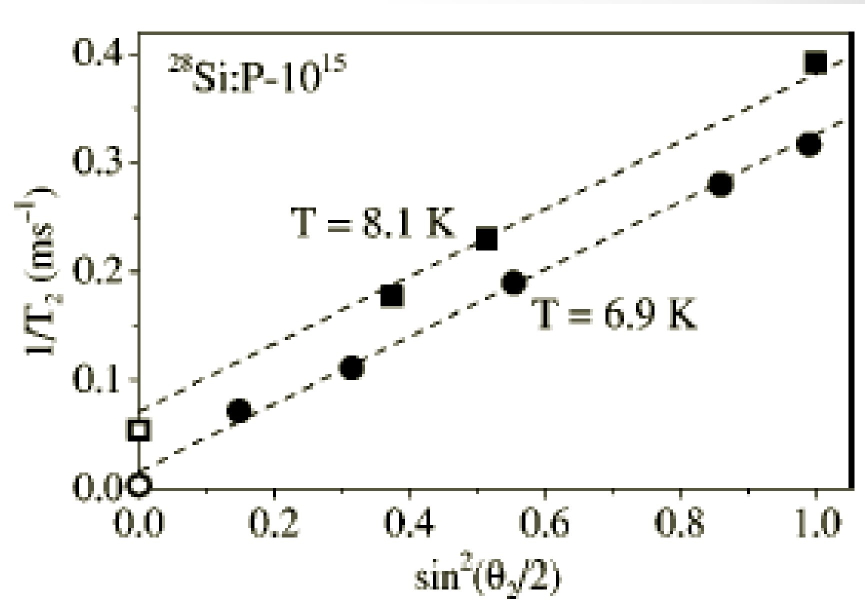


- T_1 exponential temp. dependence: shallow donor excited state
- T_2 is constant ~ 200-300 μs due to ^{29}Si
- No field/frequency dependence up to 95 GHz down to 7 K

From: Tyryshkin AM, **Lyon SA**, Astashkin AV, Raitsimring AM , PRB 68, 193207

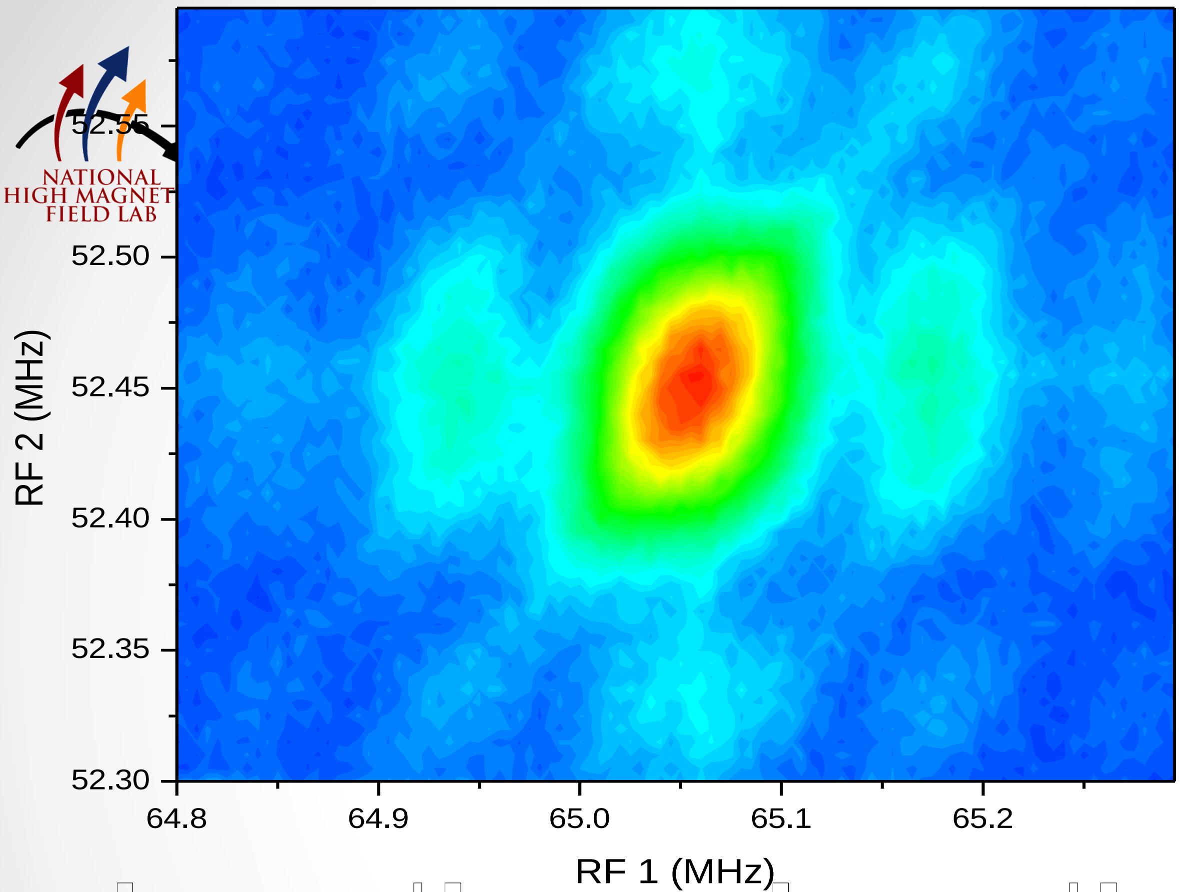


Temperature dependence T_1, T_2



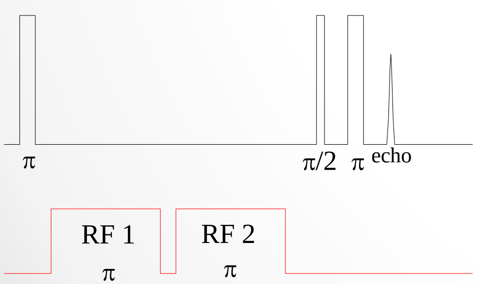
Instanteneous diffusion contribution

- In ^{28}Si samples T_{2e} is limited by dipolar interactions

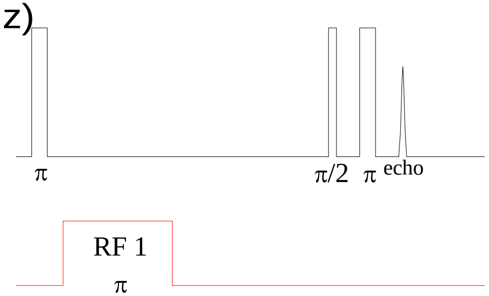


Strong TRIPLE enhancement

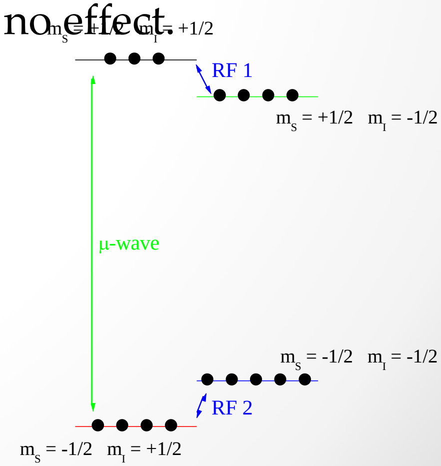
The pulsed ^{31}P TRIPLE spectrum in both Davies and Mims ENDOR is much stronger than the pulsed ENDOR itself, due to the slow relaxation of the nuclear spins. After a typical Davies-ENDOR sequence, followed by electron-spin T_1 decay, the populations of the levels end up as shown below – after the electron spin inversion pulse, the RF pulse has no effect.



"Davies TRIPLE" ENDOR"

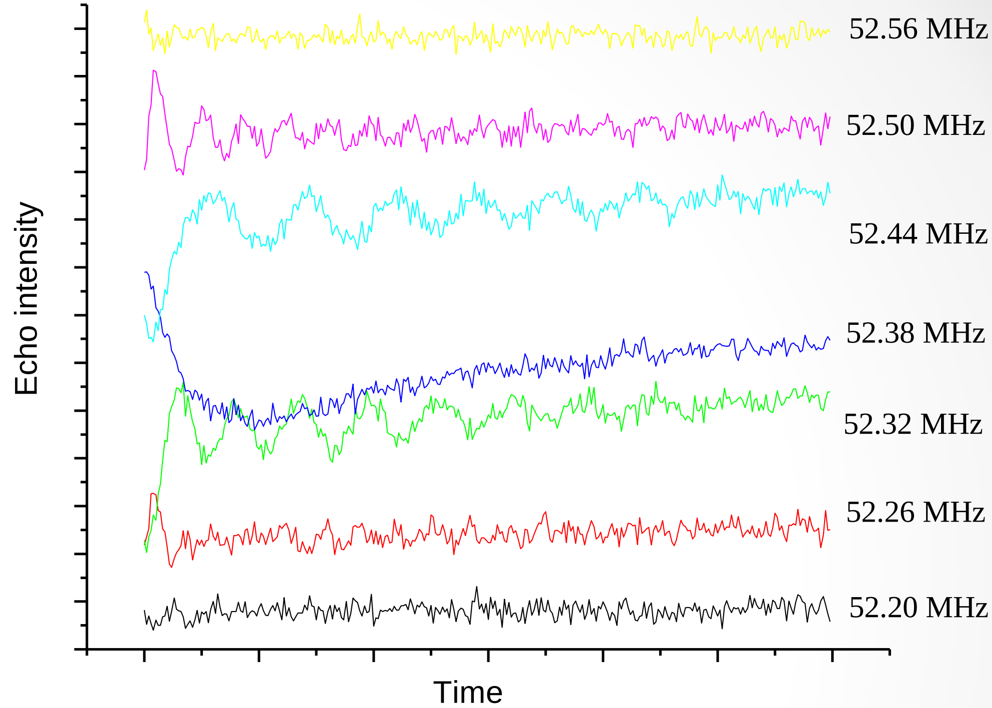


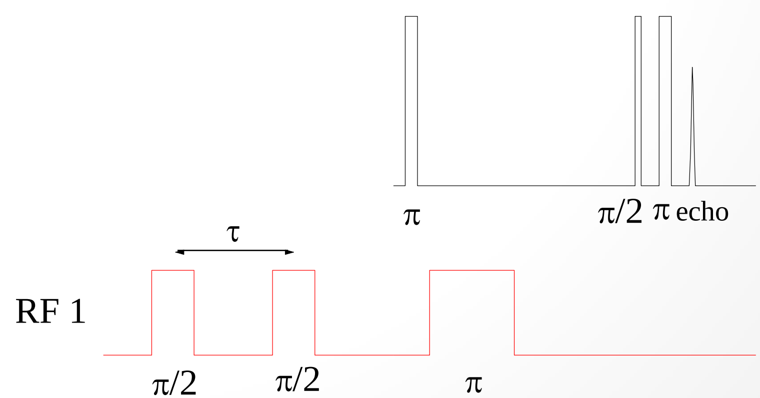
"Davies-



^{31}P free induction decay, measured by "ENDOR"

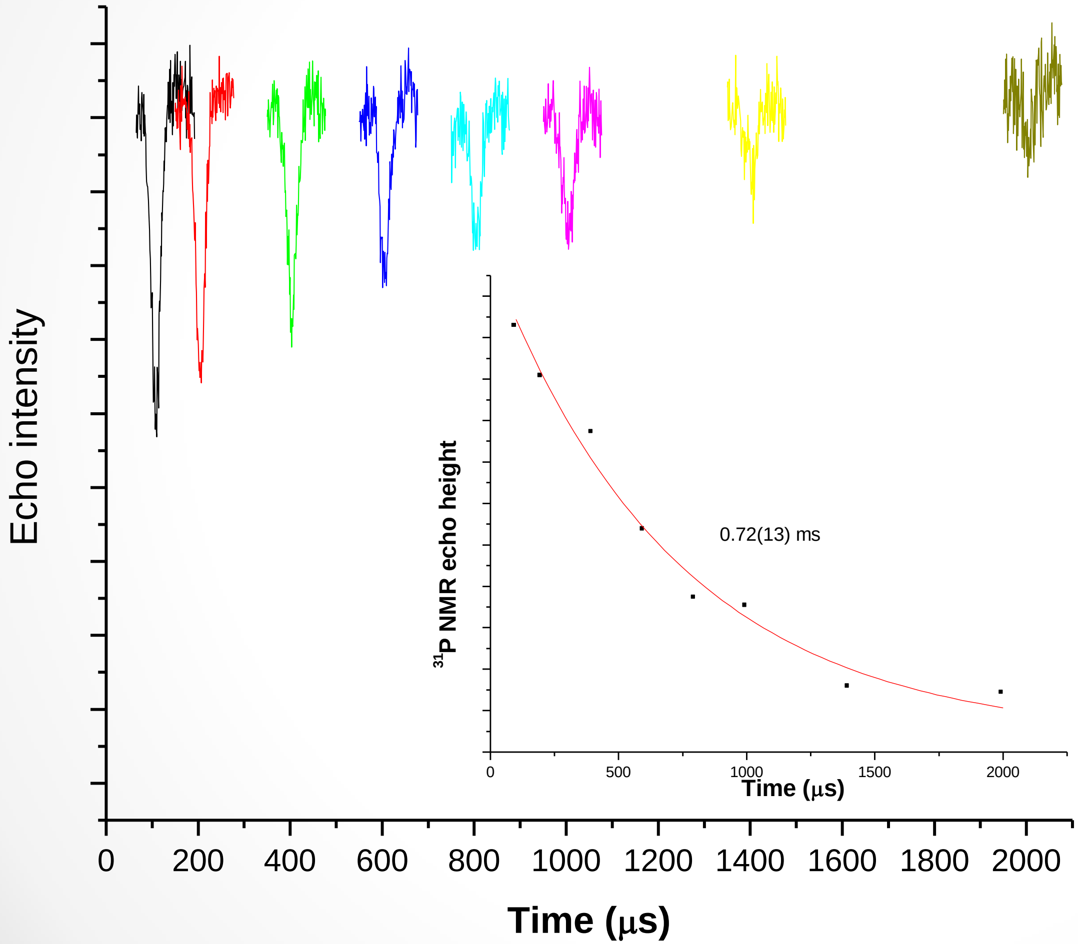
The pulsed-ENDOR sequence can be used to both induce the nuclear polarization and to detect the NMR signal of the ^{31}P nuclei. The repetition rate is slow with respect to the electron spin T_1, but fast with respect to the nuclear T_1. The first RF pulse induces the free-induction decay, the second translates the nuclear coherence to a population difference, and is detected with the pulsed ENDOR sequence

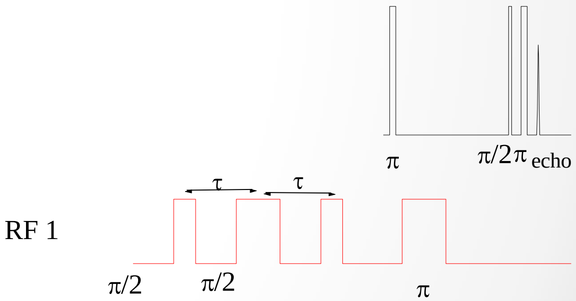




“NMR” echo, detected on EPR/ENDOR signal (10 K)

→ Nuclear coherence time T_{2N} seems to be close to T_{1e}





Si:P ([P] ~10^{15}-10^{16}) Below 20 K no conduction electrons: Nicely isolated from surroundings

Long relaxation times

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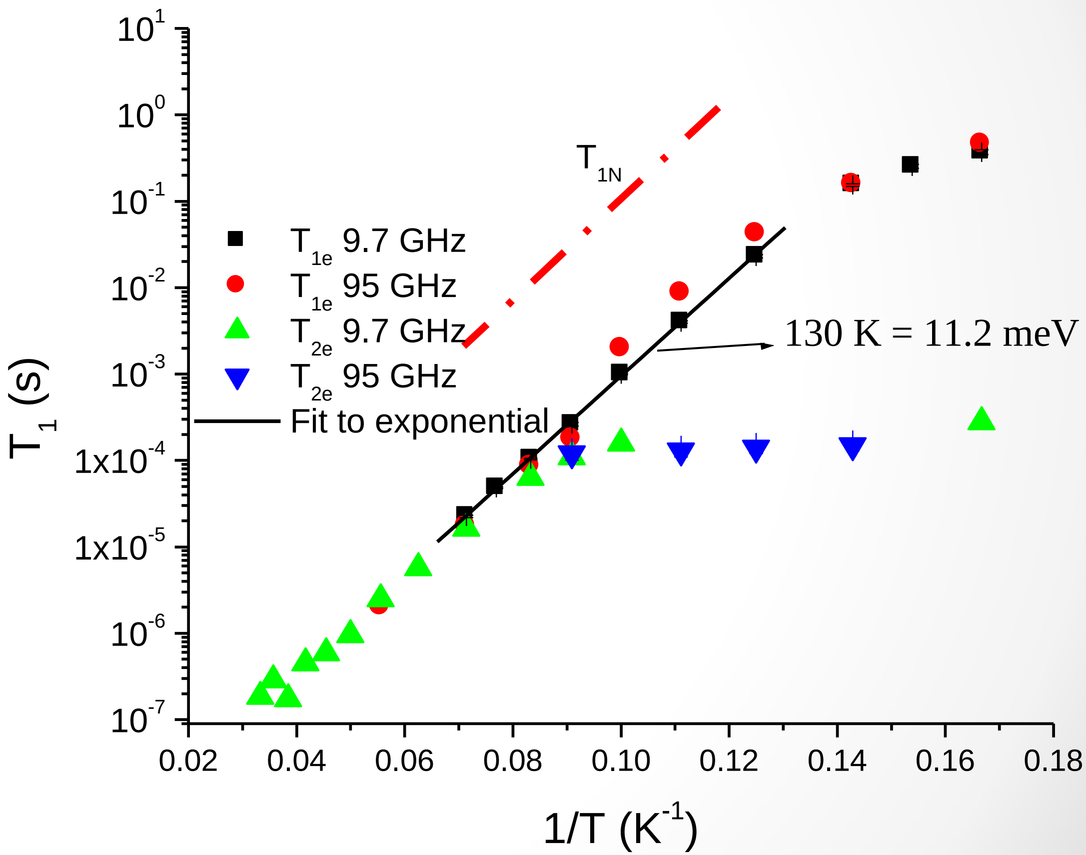
- T_{1e} exponential temp. dependence: shallow donor excited state
- T_{2e} is constant ~ 200-300 μs due to ^{29}Si
- No field/frequency dependence up to 95 GHz

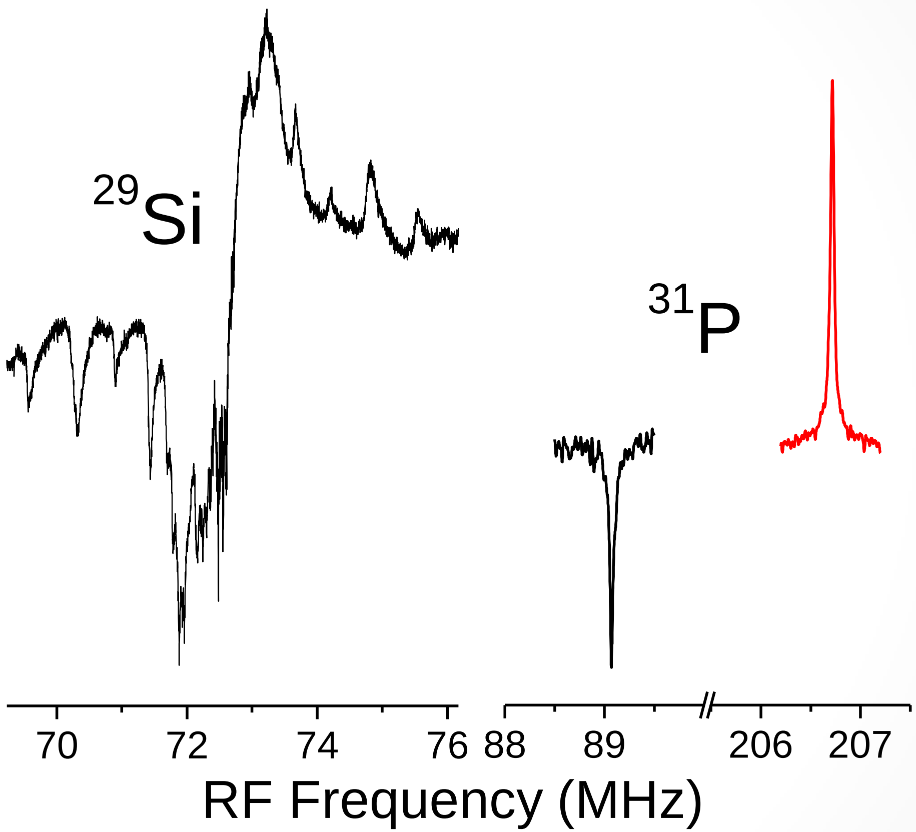
- The ^{31}P nuclear T_{1N} relaxation rate at these temperatures and at 0.35 T is about 2 orders of magnitude slower than T_{1e}, while the nuclear T_{2N} of the phosphorus spins is limited by the spin-lattice relaxation rate of the electron spins (T_{2N}~T_{1e})



240 GHz ENDOR

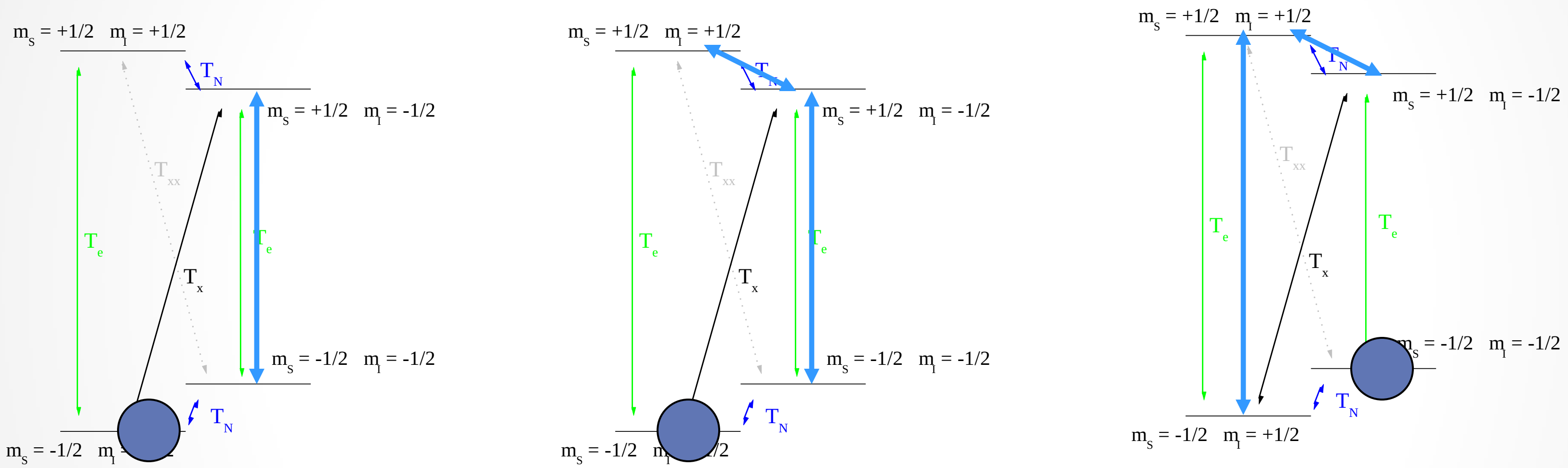
^{29}Si ENDOR from different shells. Strongly coupled Si relax much slower than the weakly coupled Si.

In principle they could add another qubit to the system.

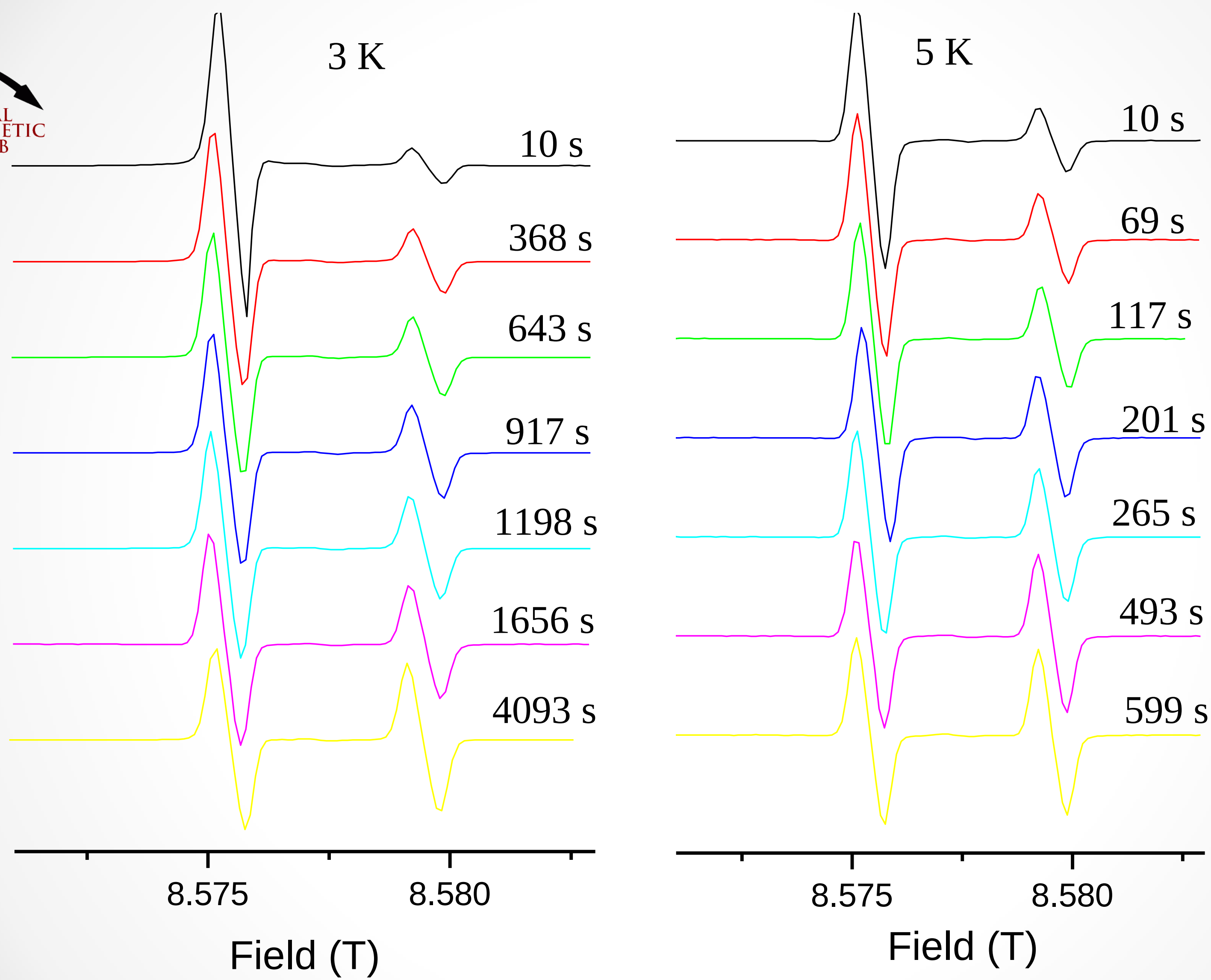


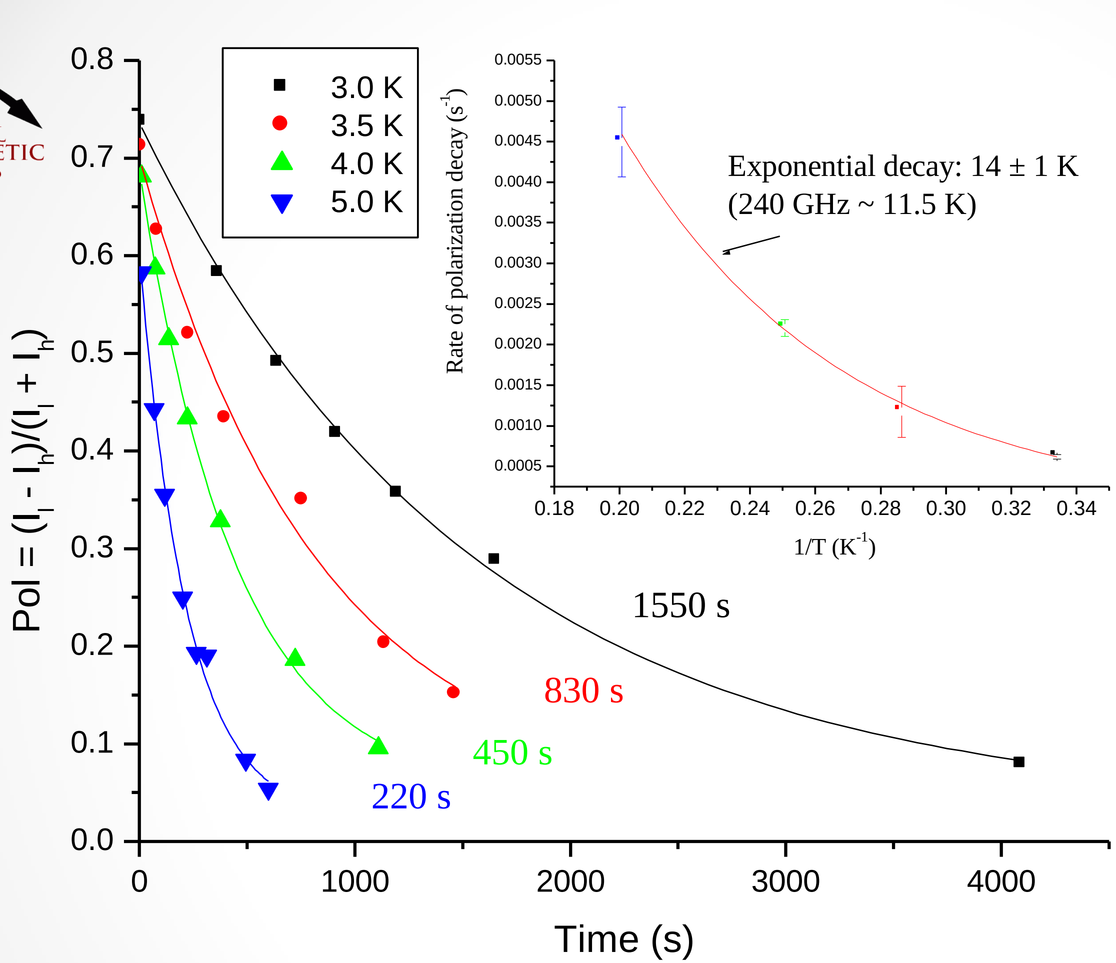
High-field dynamic nuclear polarization at hν >> kT

Creation of close to 100% polarized initial state



Initialization/Relaxation of nuclear spin polarization



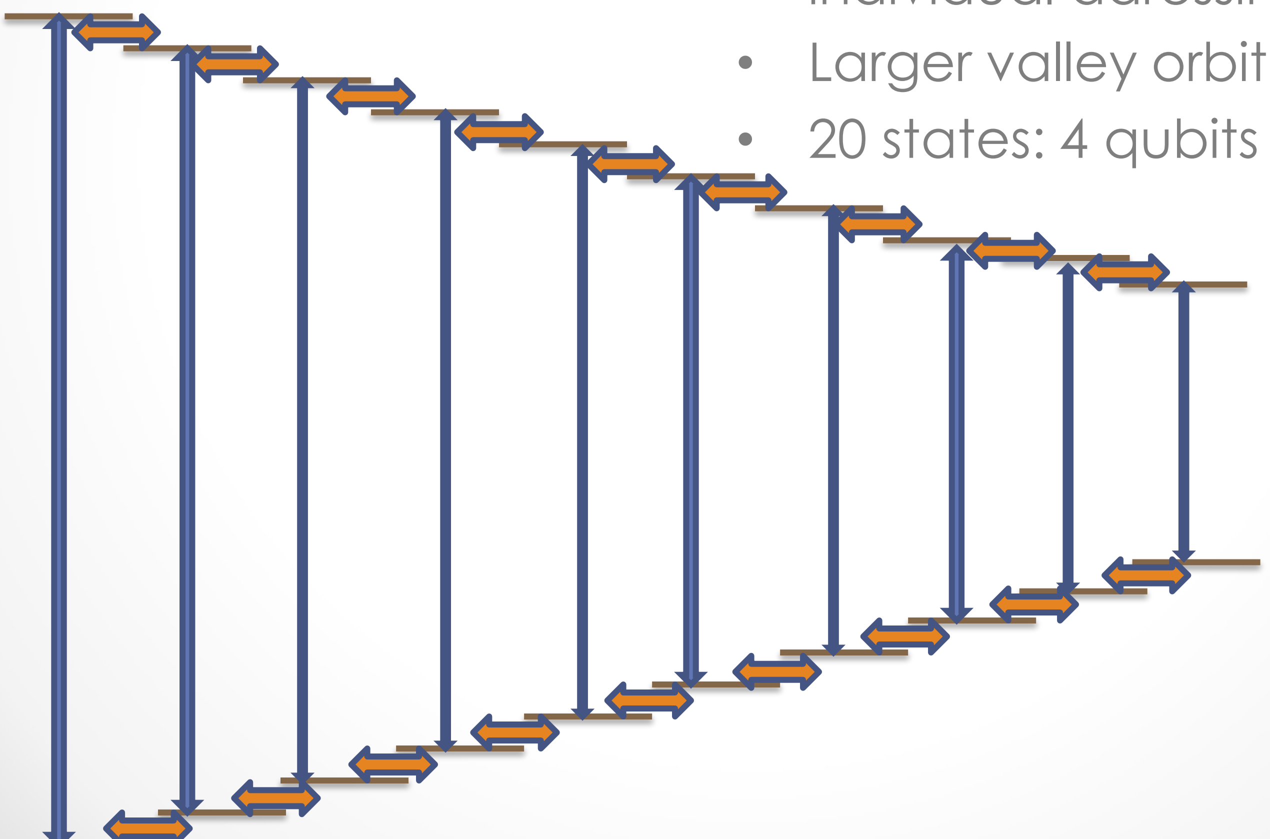


The relaxation to equilibrium spin polarization is well described with a single exponential. The temperature dependence indicates a thermally excited process with an energy close to the electron spin Zeeman splitting at these fields.

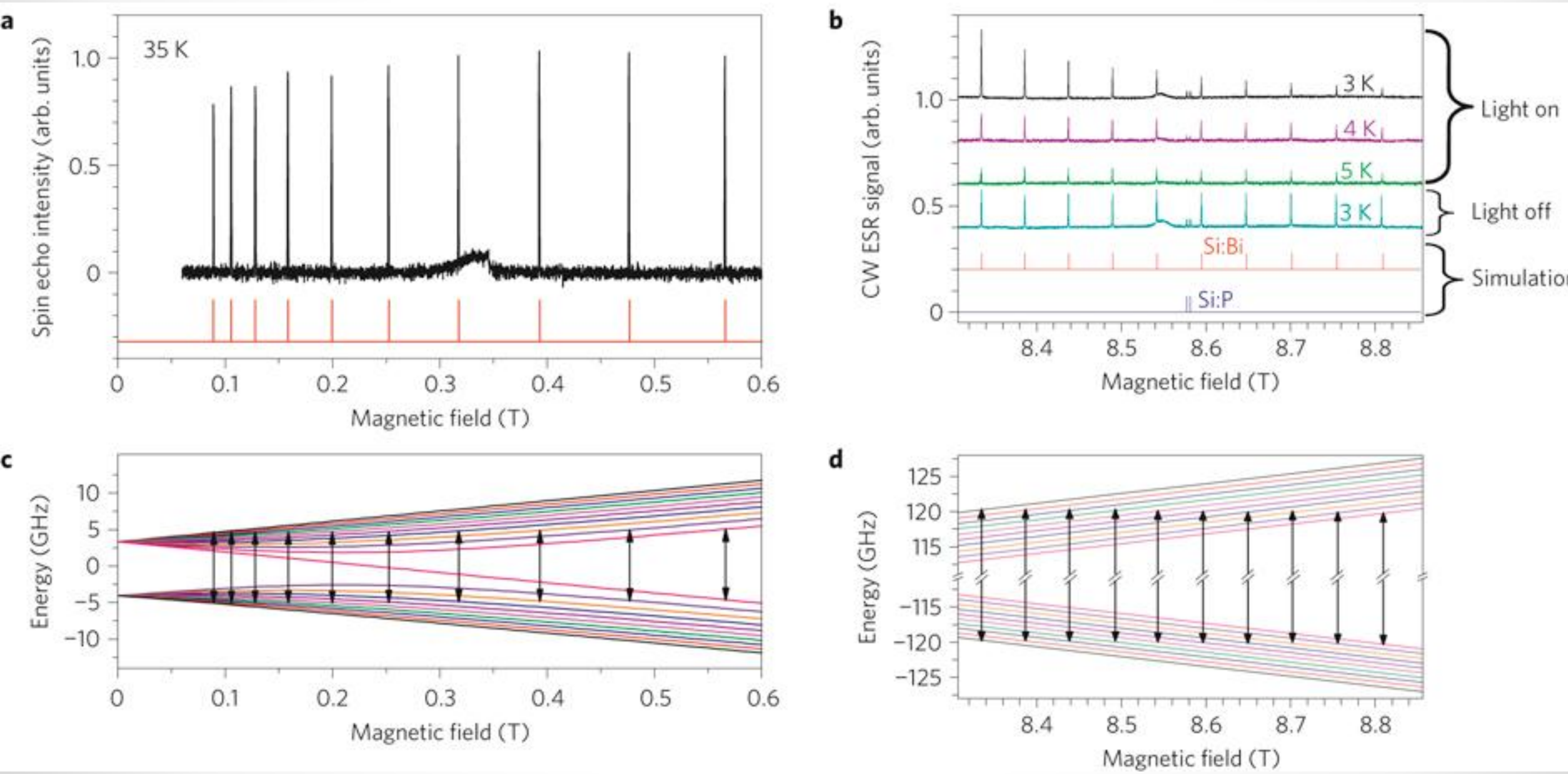
No polarization is achieved by saturation of the low-field hyperfine component.

Bismuth in Silicon

- I=9/2
- Relaxation times similar to phosphorus
- Much larger hyperfine splitting -> individual adressing
- Larger valley orbit splitting
- 20 states: 4 qubits at once ?

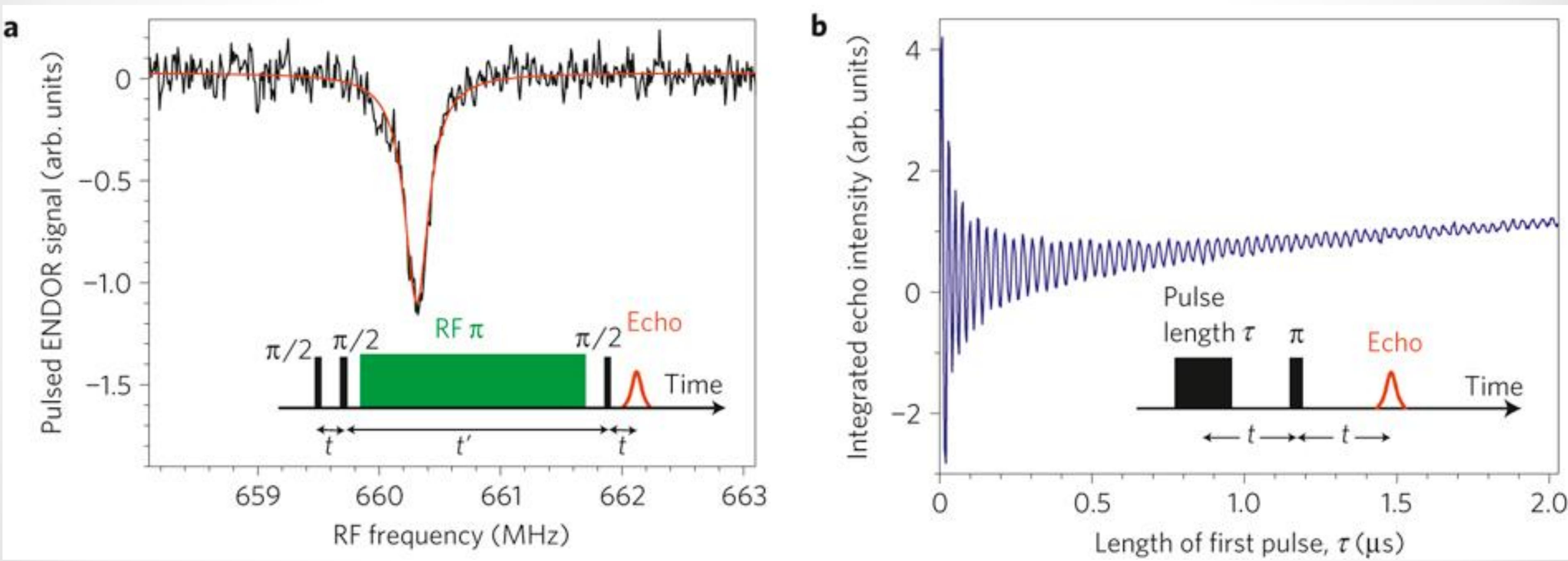


Another candidate: Bi in Si



Morley et al. Nature Materials 9, 725 (2010)

Electron Nuclear Double Resonance and coherent manipulation



Bismuth is the heaviest stable element.
It has a large nuclear spin 9/2 -> More information can be stored
Nature Materials 9, 725 (2010)

What about Read-out ?

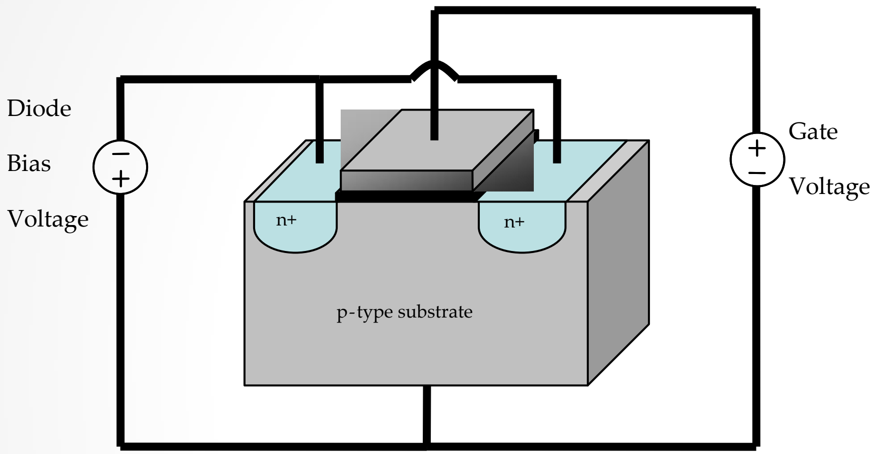
- Long relaxation times
- Initialization
- Manipulation
- Readout ??
  - Read-out is usually destructive
  - Magnetic resonance is not very sensitive 10^9 spins

Detection

Electrical detection of the spin resonance of a single electron in a silicon field-effect transistor

M. Xiao[1], I. Martin[2], E. Yablonovitch[3] & H. W. Jiang[1]

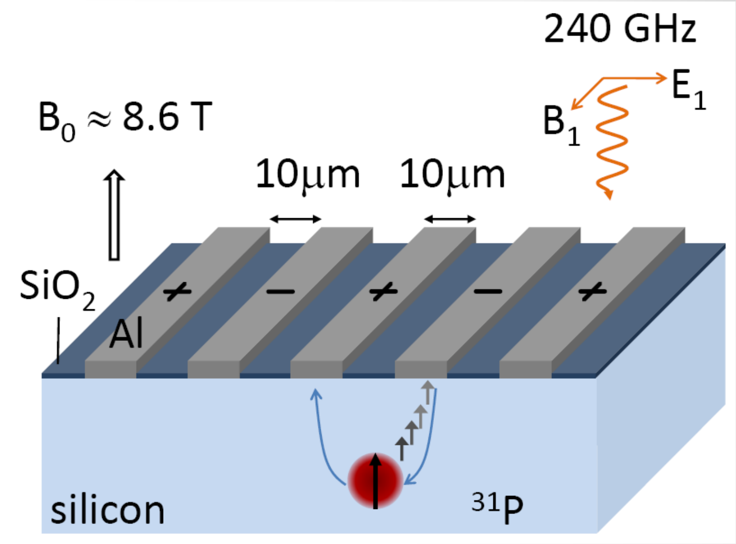
[1]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*
[2]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[3]*Department of Electrical Engineering, University of California, Los Angeles, California 90095-1594, USA*



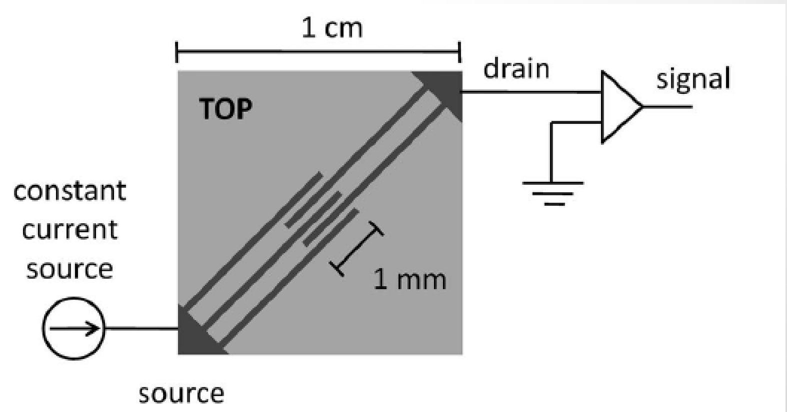
MOSFET : spin-dependent recombination
High frequency advantage : Boltzmann populations

Electrical detection of Magnetic Resonance (Read out)

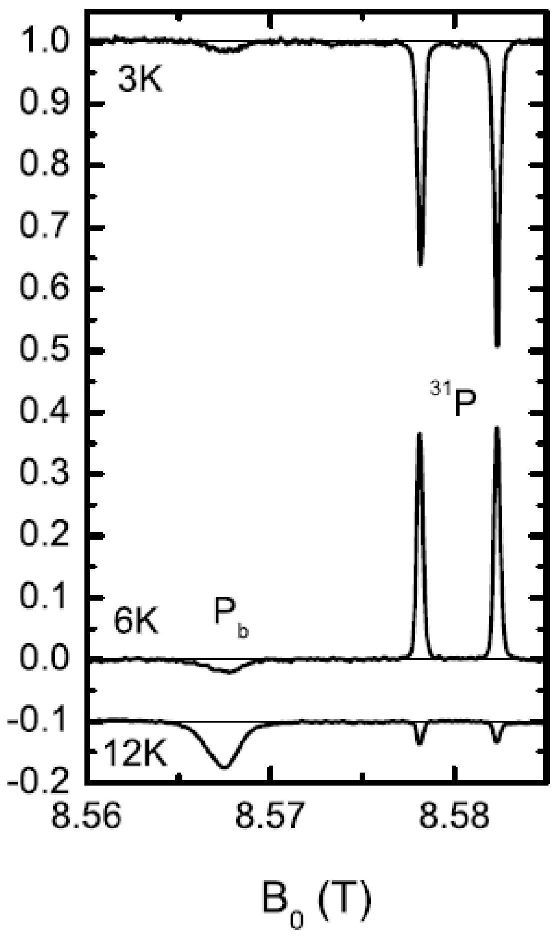
- Electrical detection can be very sensitive
- At low frequencies a P_b (surface) center is involved

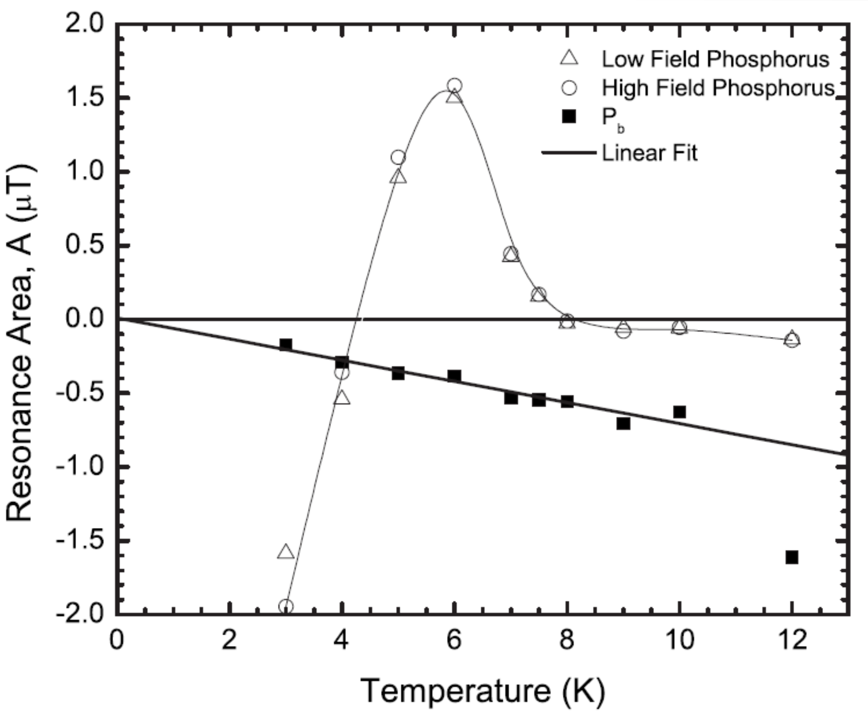


  - In order to measure a current we use light excitation to create carriers
    - T_1 is shortened, T_2 more or les unchanged



EDMR spectra



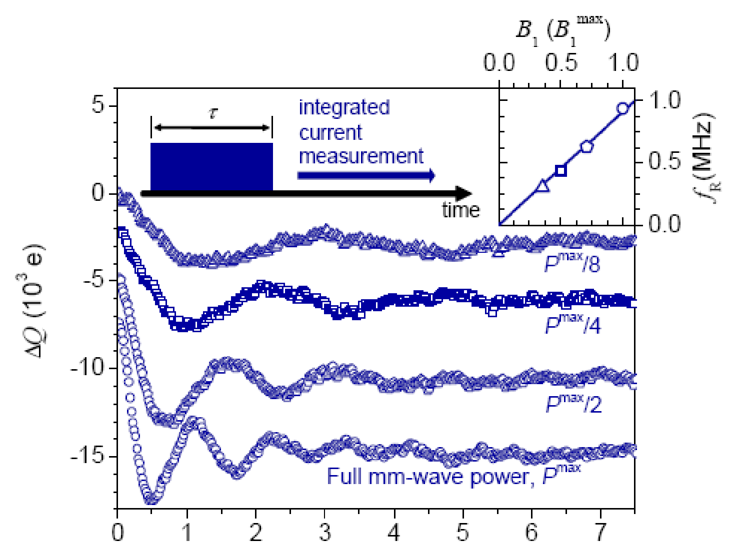


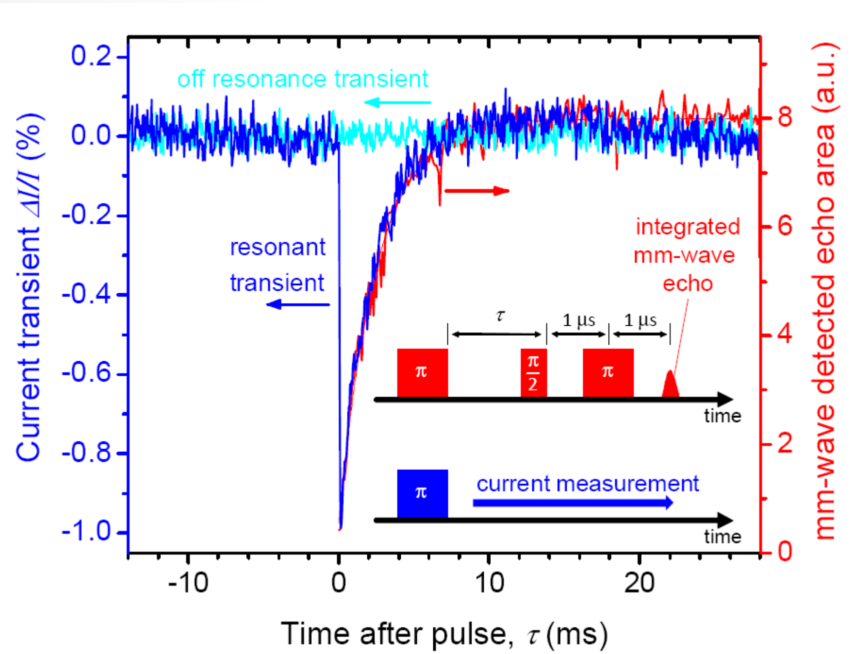
Up to 10% current changes on phosphorus resonance

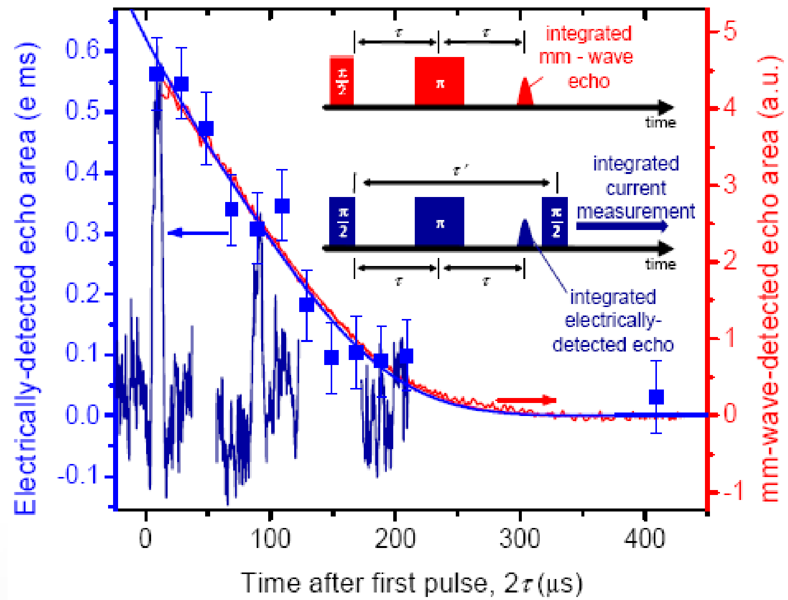
McCamey et al., PRB 2008

Coherence ?

- At low frequency the electrically detected spin coherence laster for ~ 2 μs due to fast recombination of electron-hole pairs.
- At high frequency the main mechanism is dominated by spin traps -> longer coherence times ?

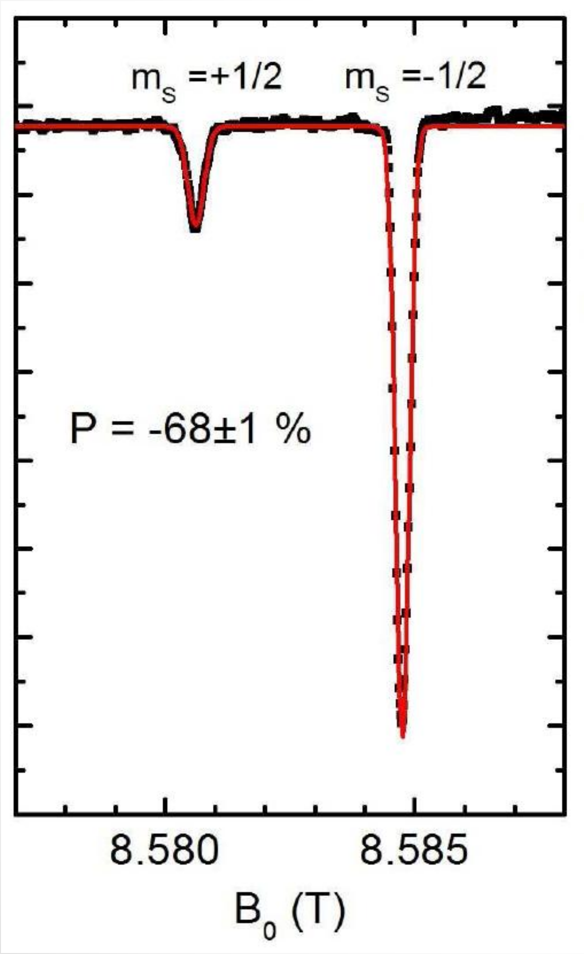


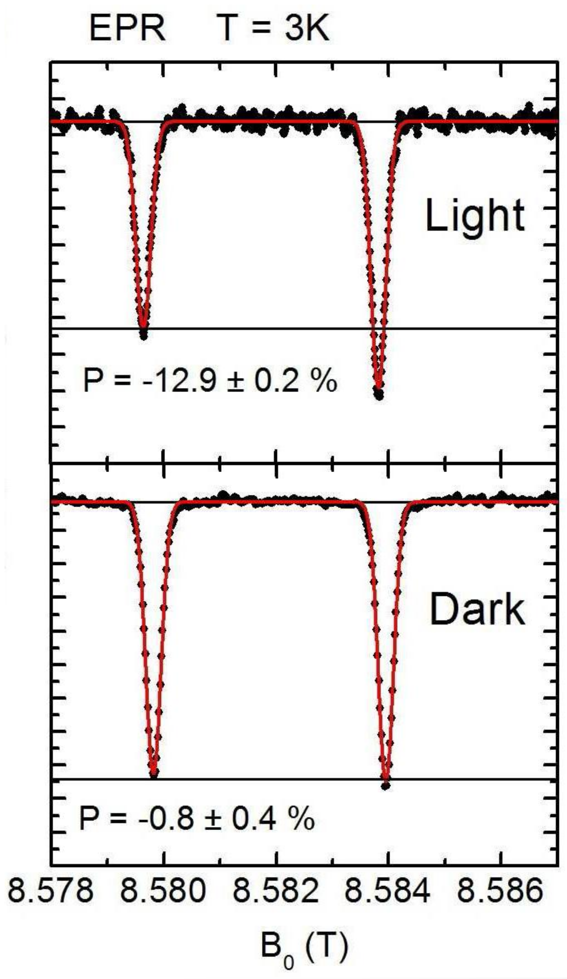




Morley et al, PRL 101 (2008)

Light Induced Nuclear Polarization

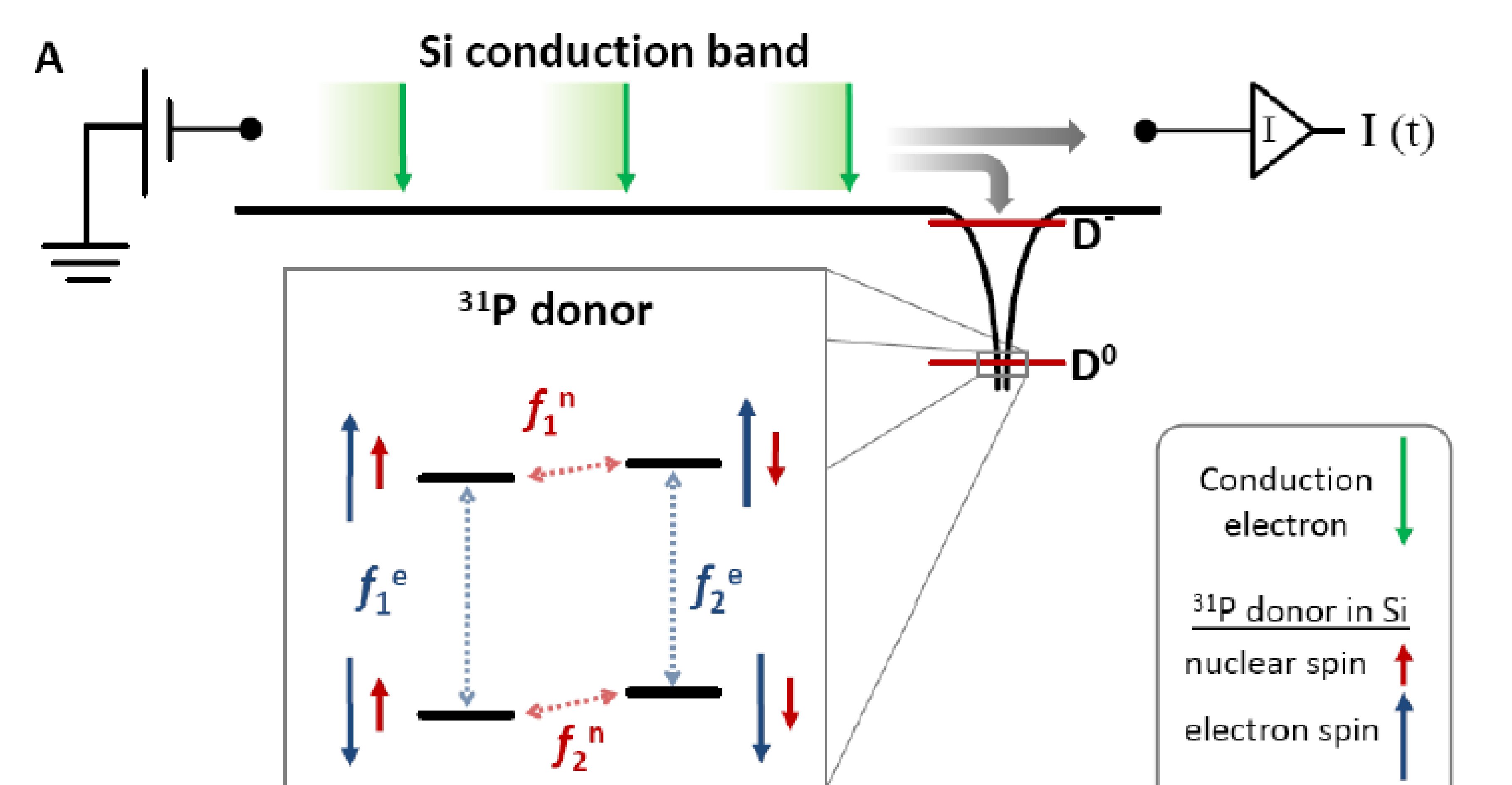




McCamey et al. PRL 102 (2009)

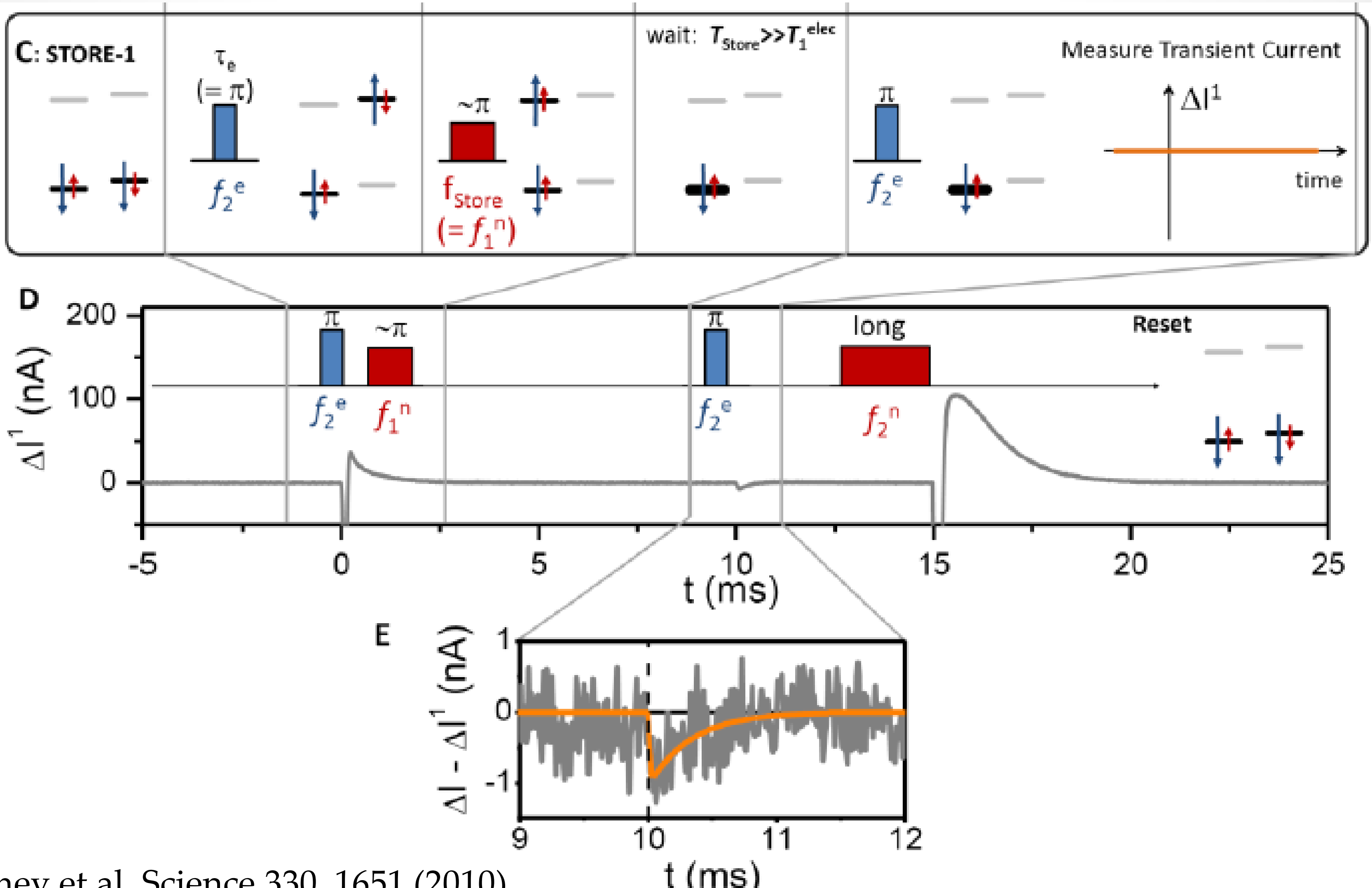
Storage of information

- Use the nuclear spin to store electron spin



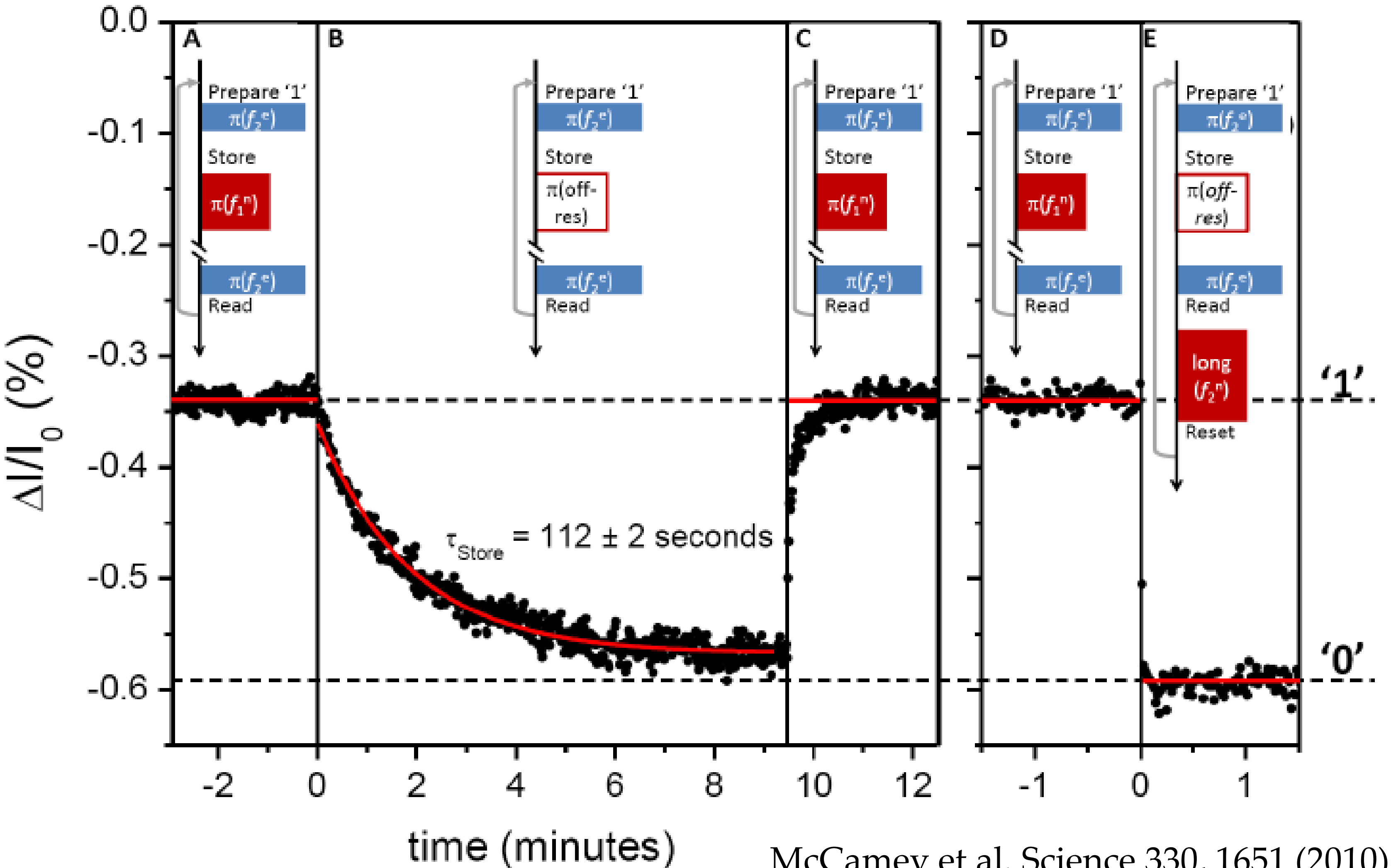
McCamey et al. Science 330, 1651 (2010)

Electrical storage and readout of spin information



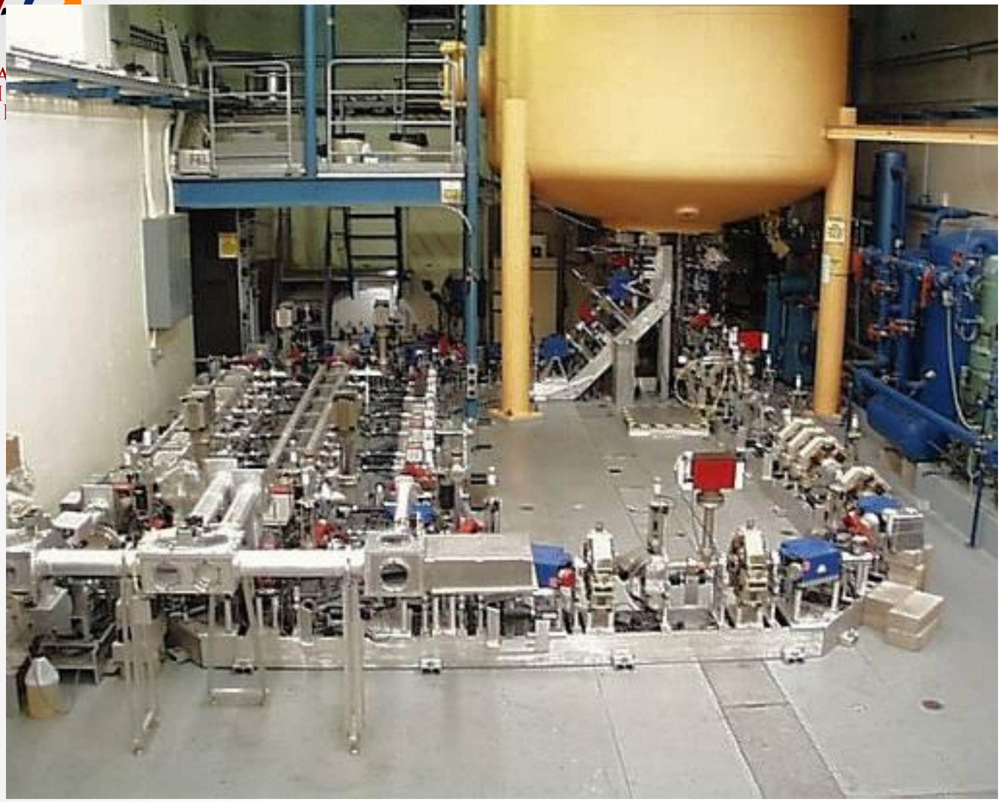
McCamey et al. Science 330, 1651 (2010)

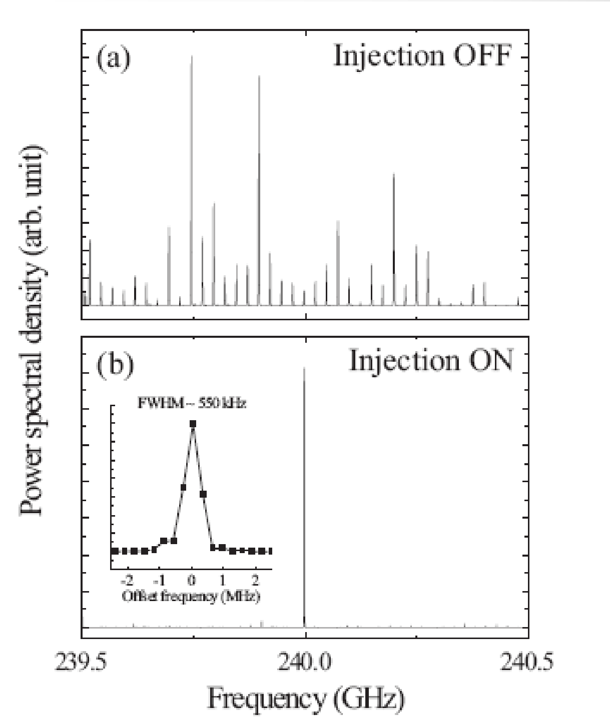
A minute or so…



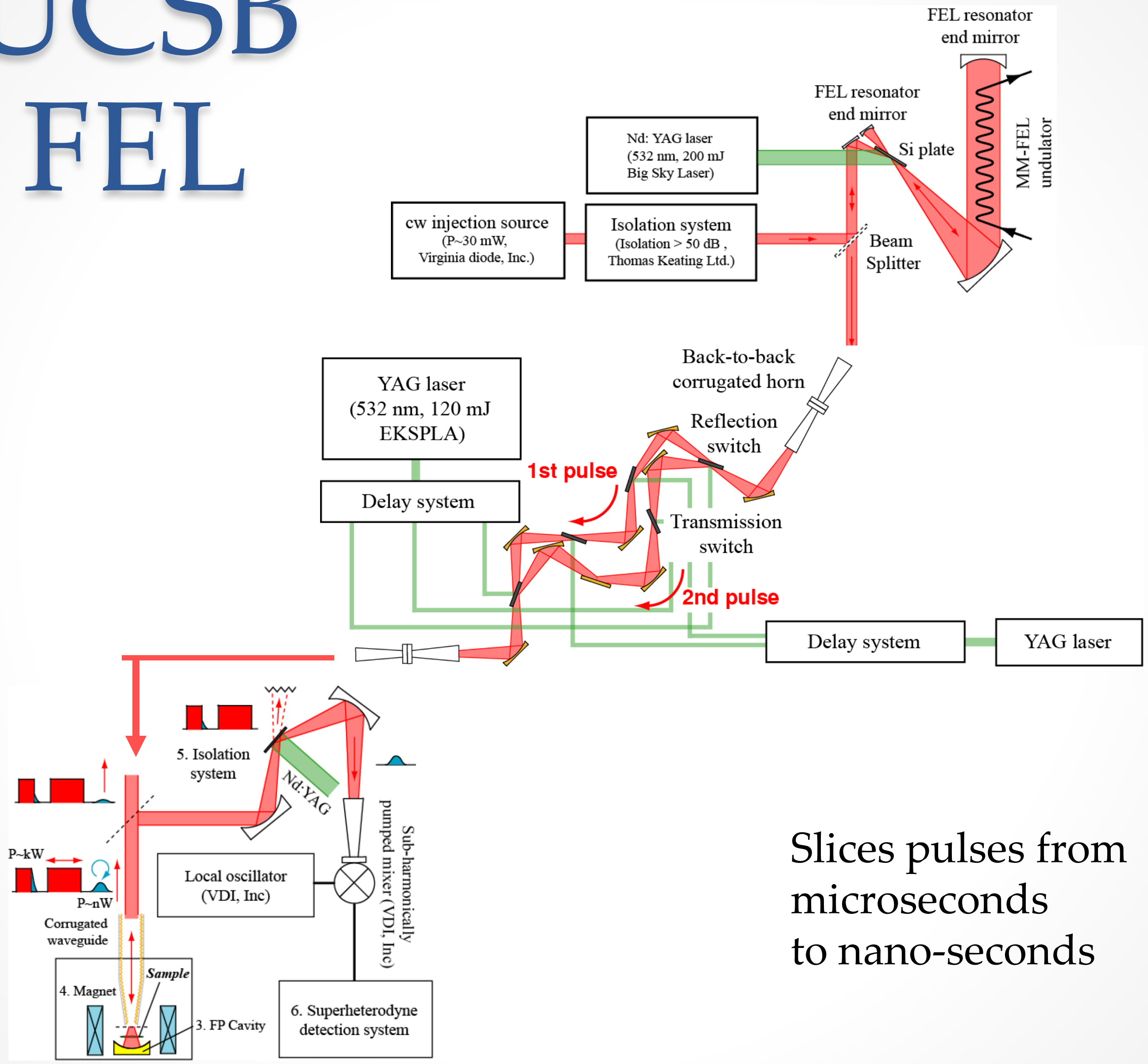
McCamey et al. Science 330, 1651 (2010)

How strong is the spin dependent current





UCSB FEL



Slices pulses from microseconds to nano-seconds

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