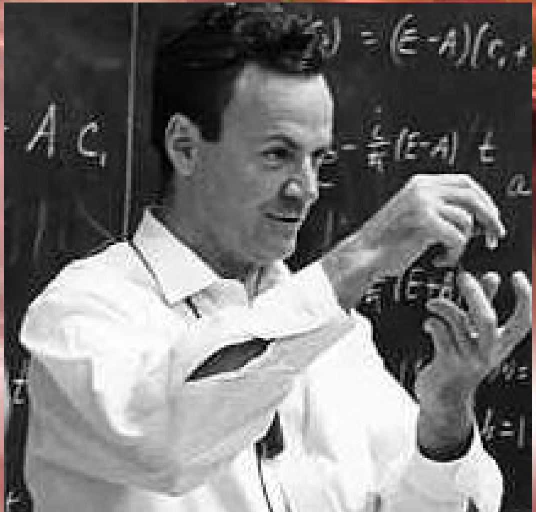
Manipulating Quantum Information with Semiconductor Spintronics

"Aim to create a new class of electronics based on the spin degree of freedom of the electron in addition to, or in place of, the charge."

Richard Feynman challenge:

"computers with wires no wider than 100 atoms, a microscope that could view individual atoms, machines that could manipulate atoms 1 by 1, and circuits involving quantized energy levels or the interactions of quantized spins."

- 1959 March Meeting of the American Physical Society



SCIENCE'S COMPASS

PERSPECTIVES: DEVICE PHYSICS

Pushing the Limits

Paul A. Packan

Science **285**, 2079 (1999).

"Fundamental thermodynamic limits are being reached in critical areas, and unless new, innovative solutions are found, the current rate of improvement cannot be maintained." "There are currently no known solutions to these [fundamental] problems."

The end of the road for silicon?

Max Schulz

Computer chips continue to shrink. But the discovery that a layer of silicon dioxide must be at least four to five atoms thick to function as an insulator suggests that silicon-based microchips will reach the physical limits of miniaturization early next century.

Nature **399**, 729 (1999).

Rationale for Spintronics

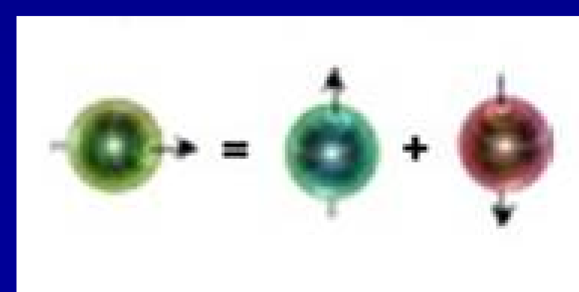
Promises of Spintronics

- little or no moving charge...............spin state variable (vector)
- reduced wiring..............................multifunctional integration
- coherent information processing….quantum logic

…must create, transport, manipulate, store, and detect spin

Spintronics ⟶ *Spin*

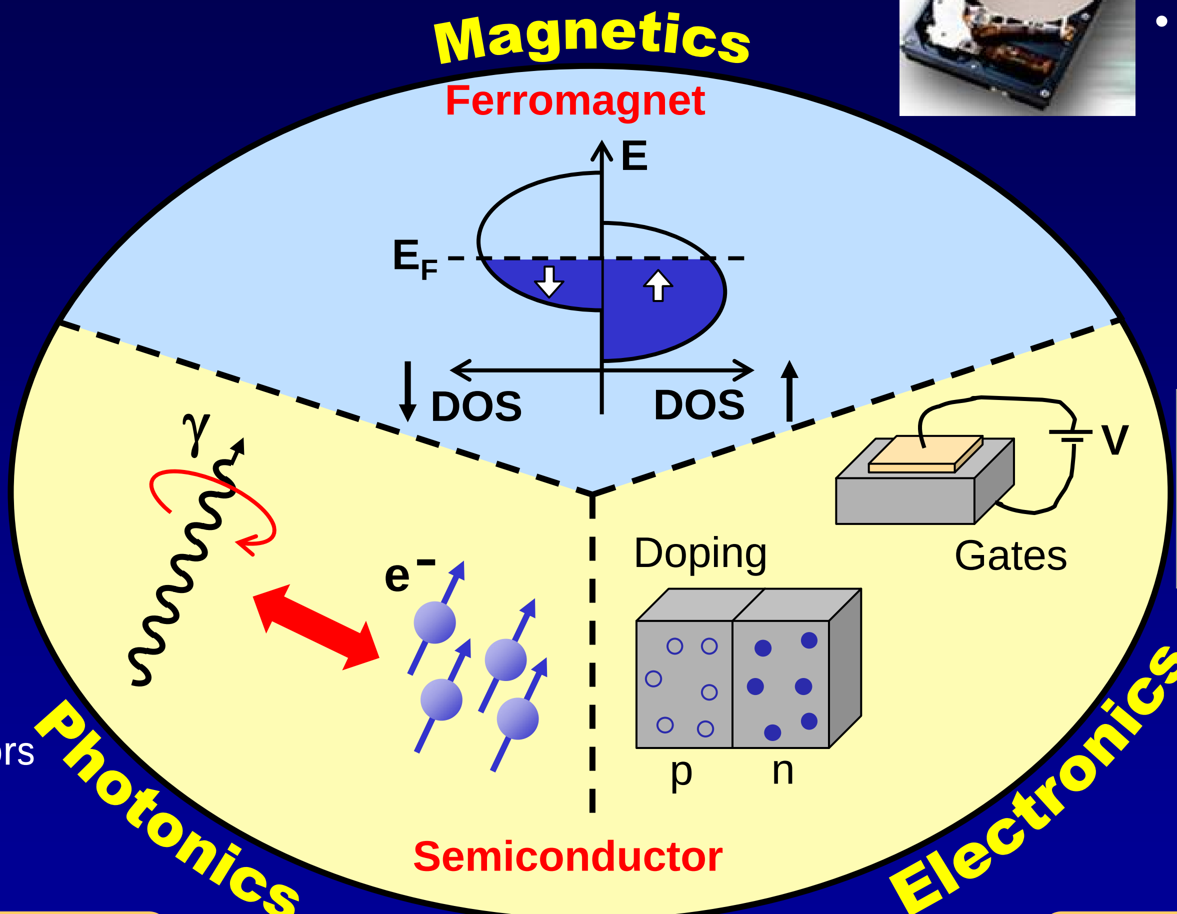
- *Based on direction of spin and spin coupling*
- *Use spin to control the flow of information*
- *Potential path to quantum information processing*

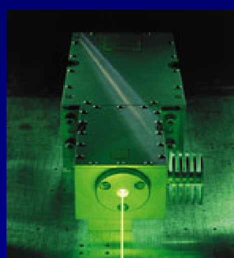


Manipulation and Storage of Information in Semiconductors: Exploiting Spin

Information Storage

- Hard Drives
- Magnetic RAM





- Lasers
- LEDs
- Photodetectors

- Transistors
- Microprocessors

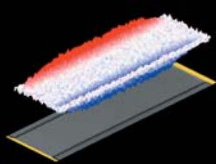
Optical Communications

Computation/Logic

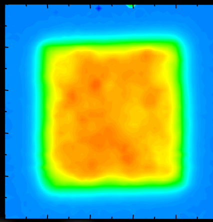
Manipulating quantum information with semiconductor spintronics: New developments

D. D. Awschalom
Center for Spintronics and Quantum Computation & California Nanosystems Institute
University of California, Santa Barbara, California USA

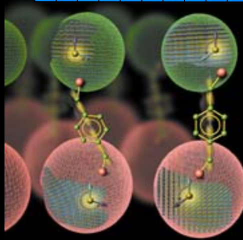
- spintronics with conventional semiconductors
  - all-electrical generation and manipulation of spin



- optoelectronic control of nuclear spins
  - ferromagnetic imprinting in hybrid nanostructures

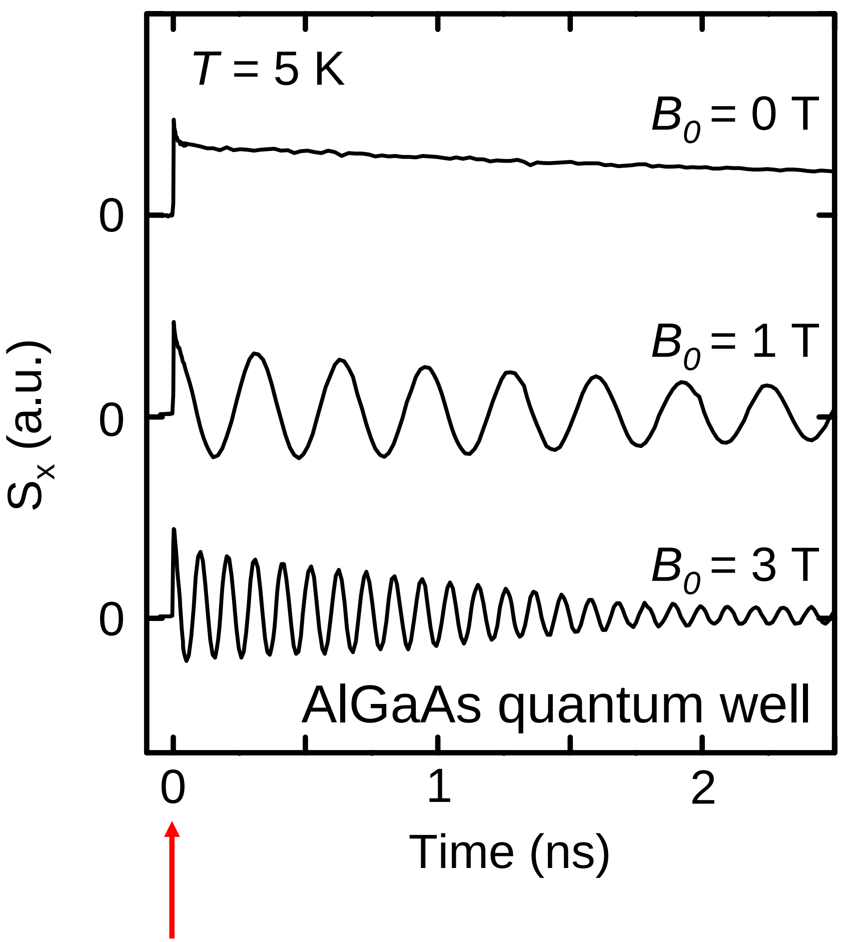


- molecular spintronics for information processing
  - wiring quantum dots for quantum logic



Coherent spin precession in magnetic field

Time-resolved Kerr rotation data

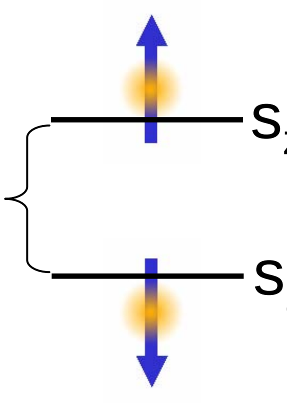


Electron spins are optically injected at t=0

Spin 1/2 in a magnetic field

$$H = g\,\mu_B\, S\cdot B$$

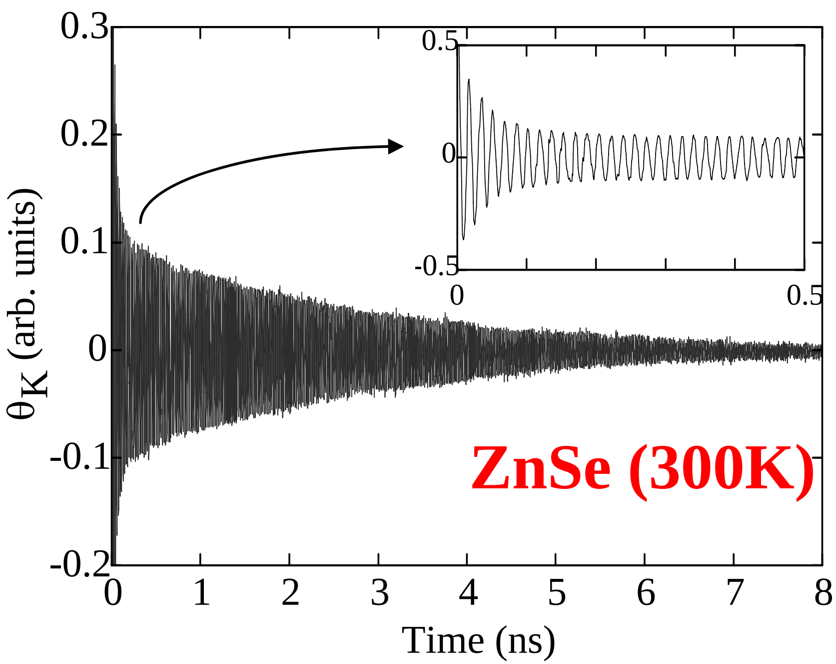
$$\hbar\omega_L = g\mu_B B$$



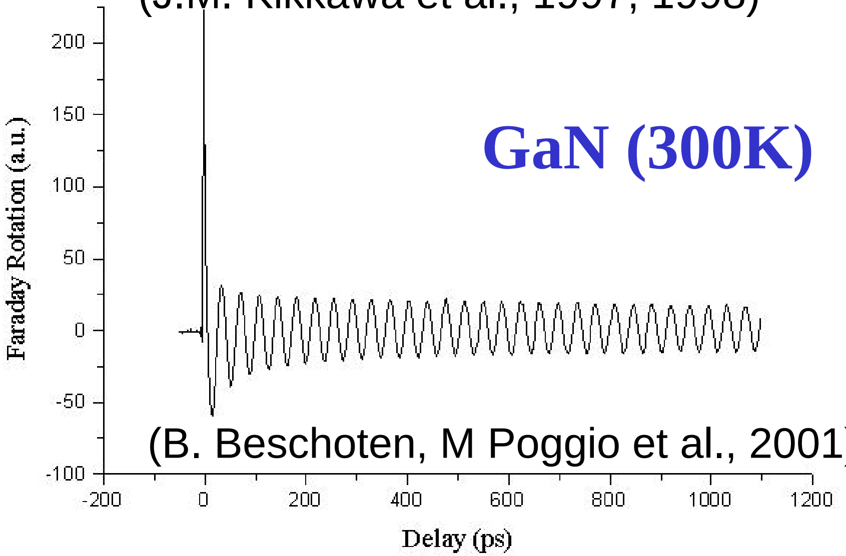
a natural 2 level system:
as a classical bit or a qubit

J. Kikkawa et al., *PRL* **80**, 4313 (1998) – T_2^* ~150ns in bulk GaAs

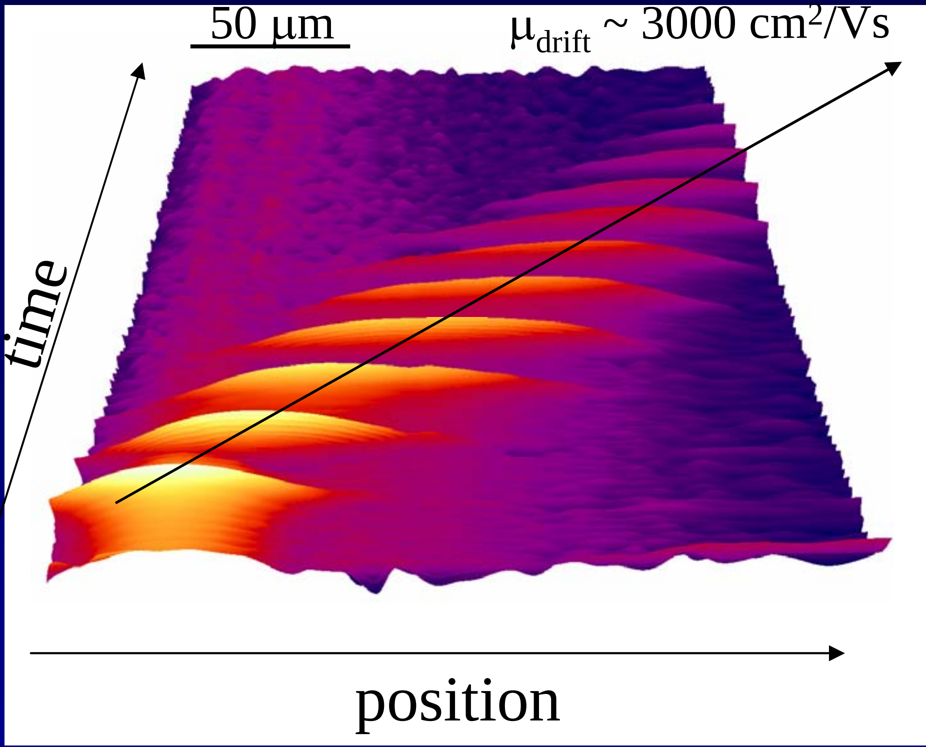
Extended Electron Spin Coherence in n-doped Semiconductors



(J.M. Kikkawa et al., 1997, 1998)



(B. Beschoten, M Poggio et al., 2001)



- drag spins with in-plane E-field over macroscopic distances
- E-field does not introduce substantial additional decoherence

Electrical Control of Spins: Motivation

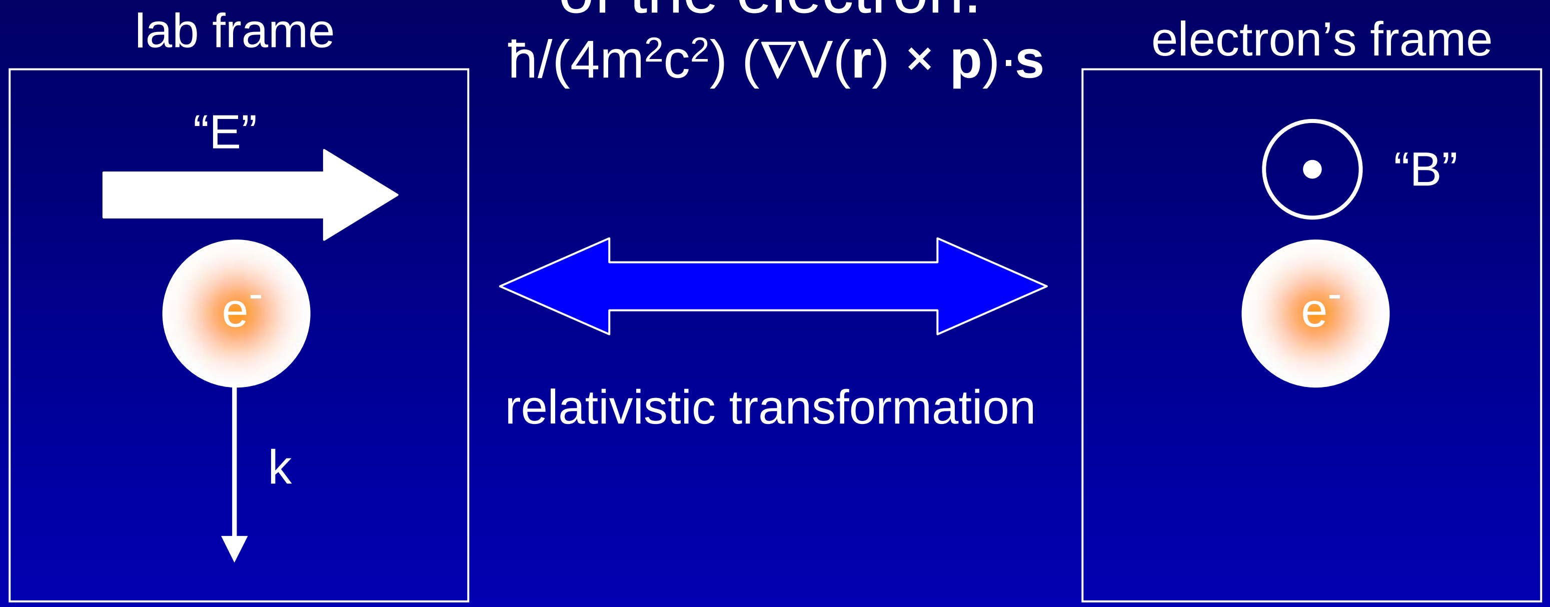
Spin-based quantum information	Spintronics: spin-based electronics
Single qubit operations require a local Hamiltonian which is tunable and controllable within the coherence time	When scaling down devices, precise control of magnetic fields at reduced dimensions is required

Magnetic field	**Electric field**
Difficult to create large fields (~T) in short time (~ns)	Fastest transistors have > 500 GHz bandwidth
Complicated architectures necessary for local fields	Gate sizes <micron are commonly used

Spin control without magnetic fields: strain engineering

Spin-orbit coupling: relativistic interaction between spin and motion of the electron.

$\hbar/(4m^2c^2)\ (\nabla V(\mathbf{r}) \times \mathbf{p})\cdot\mathbf{s}$



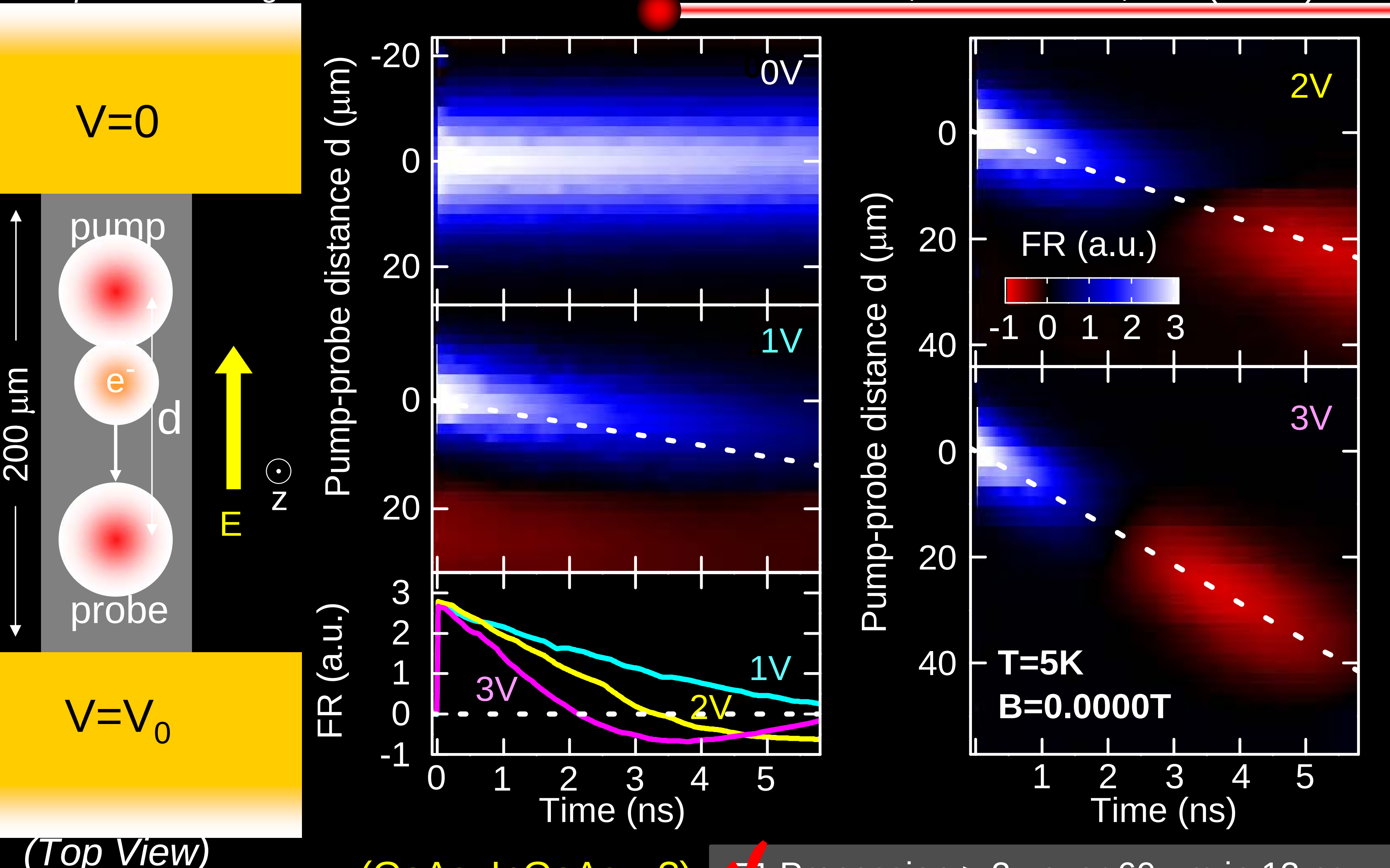
• "E" need not be real electric field, but can be "quasi electric field" occurring from asymmetries in crystal field, band gap, spin-orbit splitting, etc…

Allows zero-magnetic field spin manipulation with *electric fields* without magnetic fields or magnetic materials

Spin precession in *zero* magnetic field: "relativity on a chip"

"Manipulation through motion"

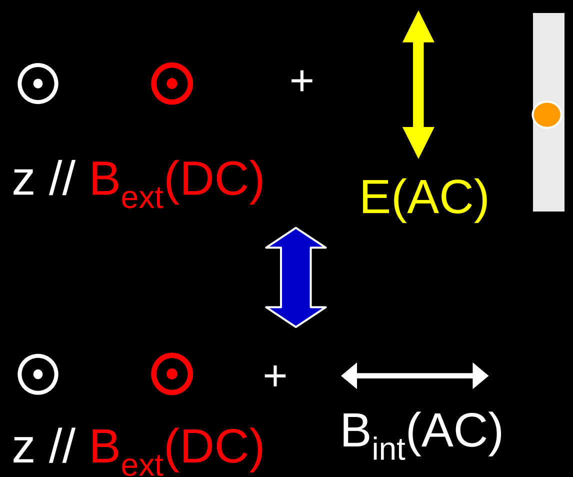
Y. Kato *et al.*, *Nature* **427**, 50 (2004)



(GaAs, InGaAs…?)

☑ Precession > 3π over 60 μm in 13 ns

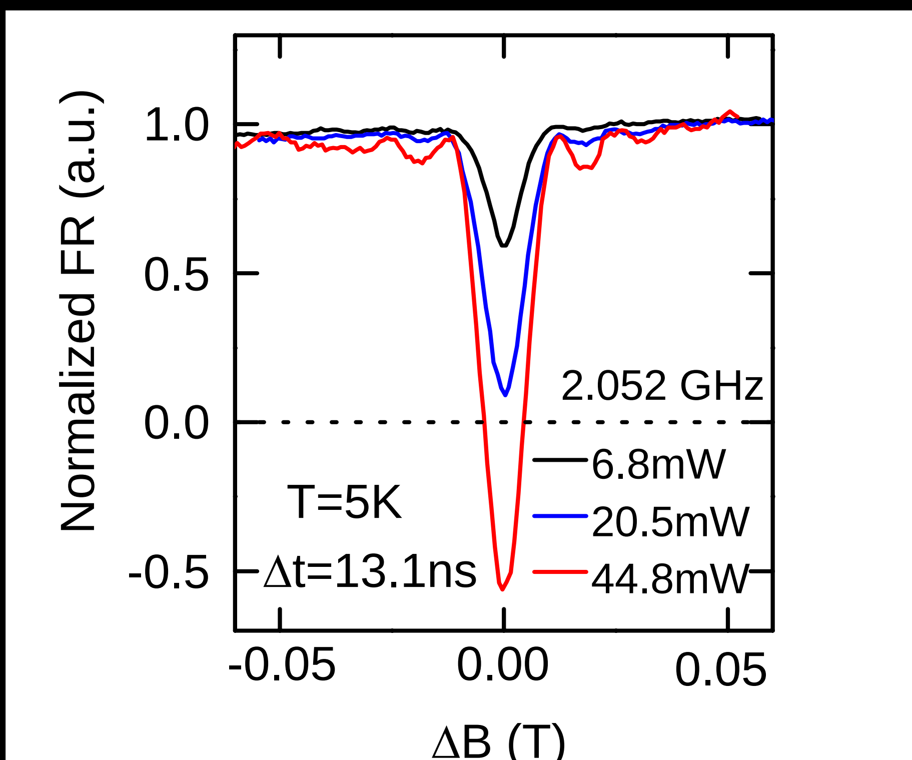
Using fictitious magnetic fields for on-chip spin resonance

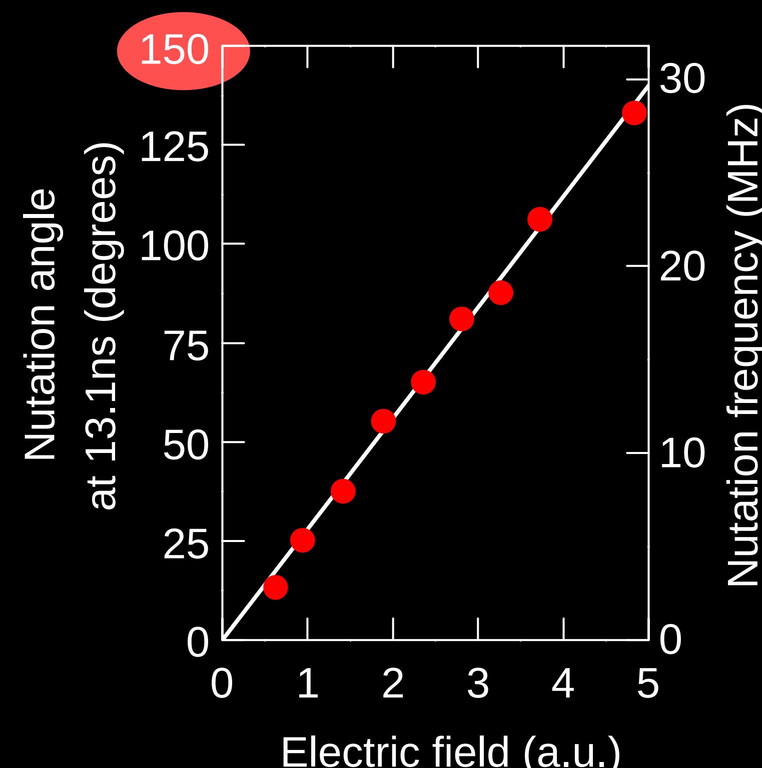


AC electric fields can create fictitious AC magnetic fields

With the application of DC magnetic field, electron spin resonance can be electrically induced

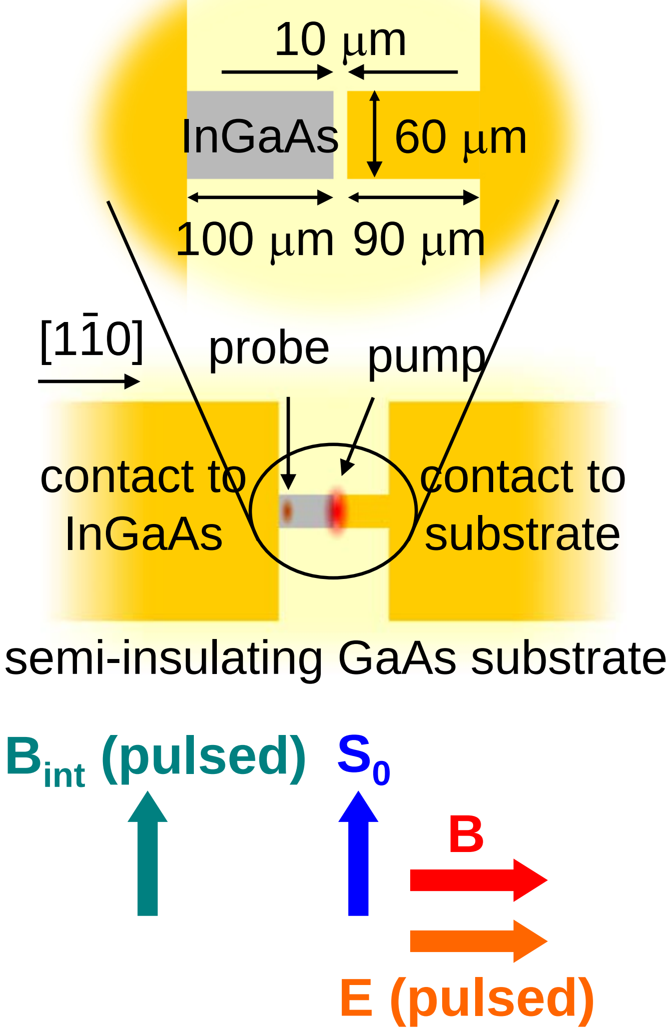
Coherent spin manipulation

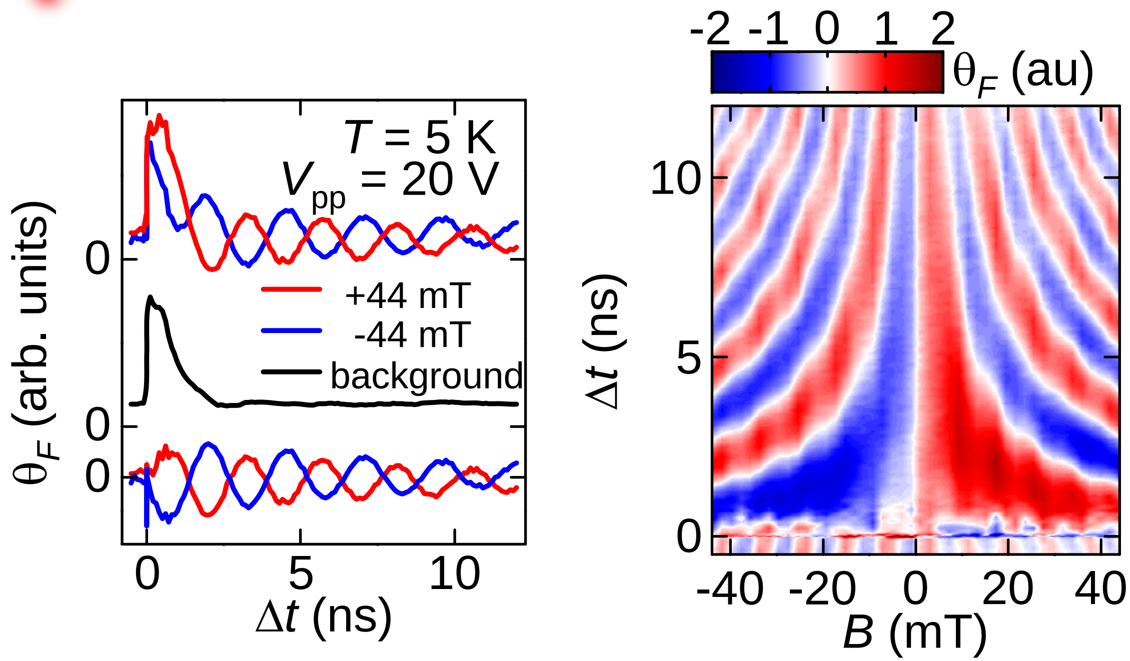




Electrically-generated spin coherence in semiconductors

Y. K. Kato *et al.*, *Phys. Rev. Lett.* **93**, 176601 (2004)





Precession at electron Larmor frequency of InGaAs

→ Faraday rotation signal due to electrons

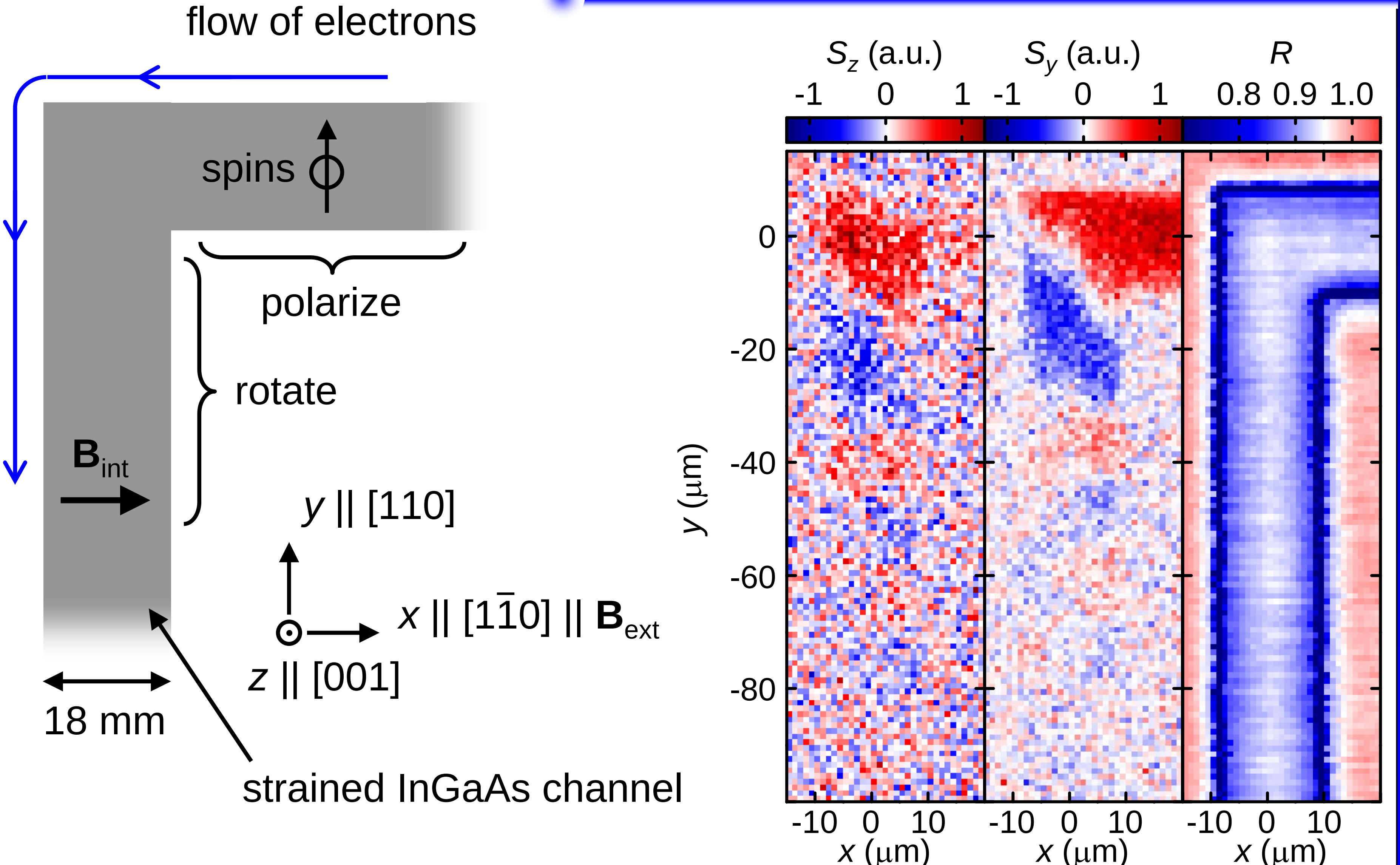
The signal shows sign change with magnetic field

→ spins excited in the plane of the sample (along the effective magnetic field)

☑ Electron spin coherence generated using picosecond electrical pulses

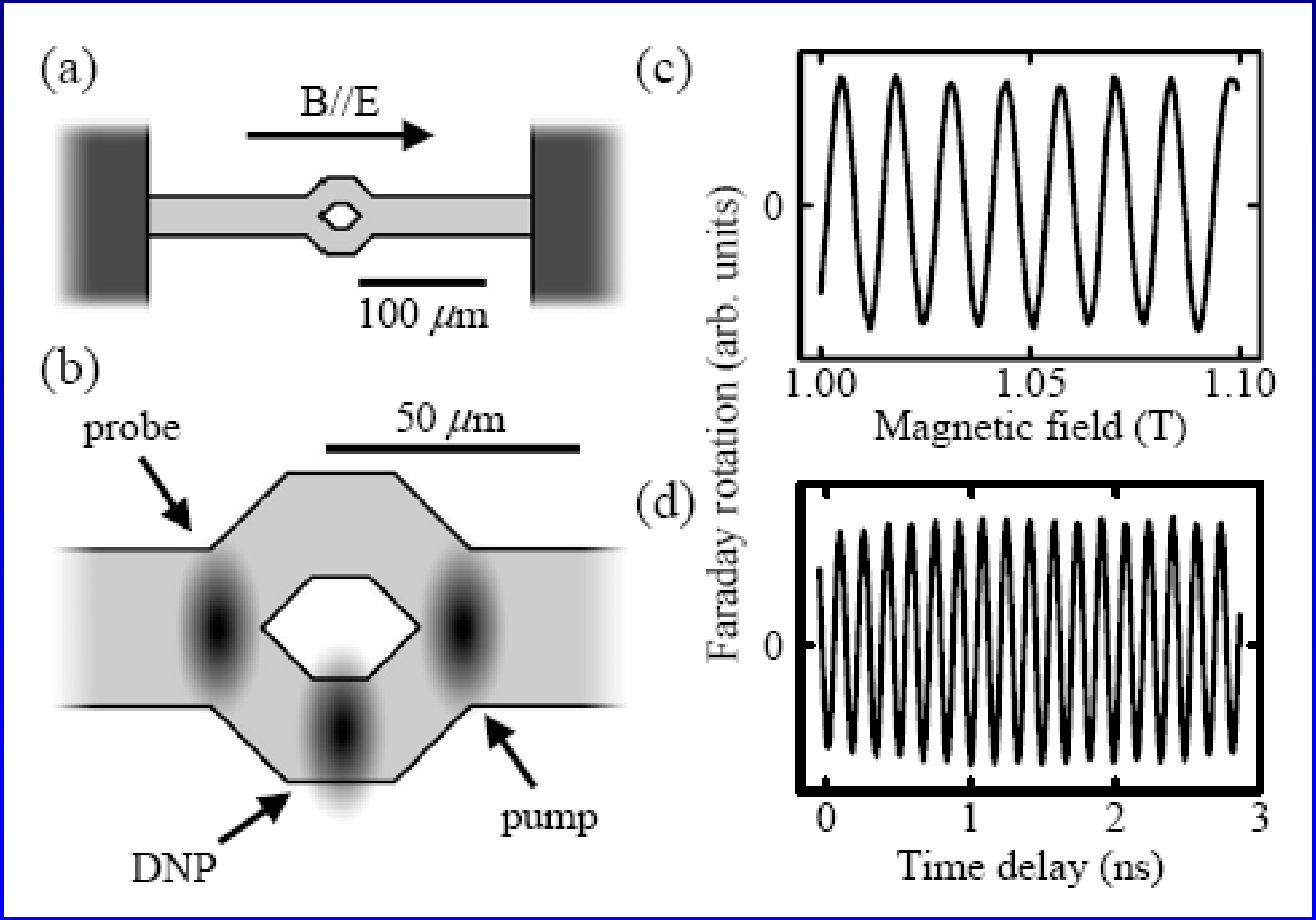
All-electrical spin initialization and manipulation

Y. Kato *et al.*, *Appl. Phys. Lett.* 87, 022507 (2005)



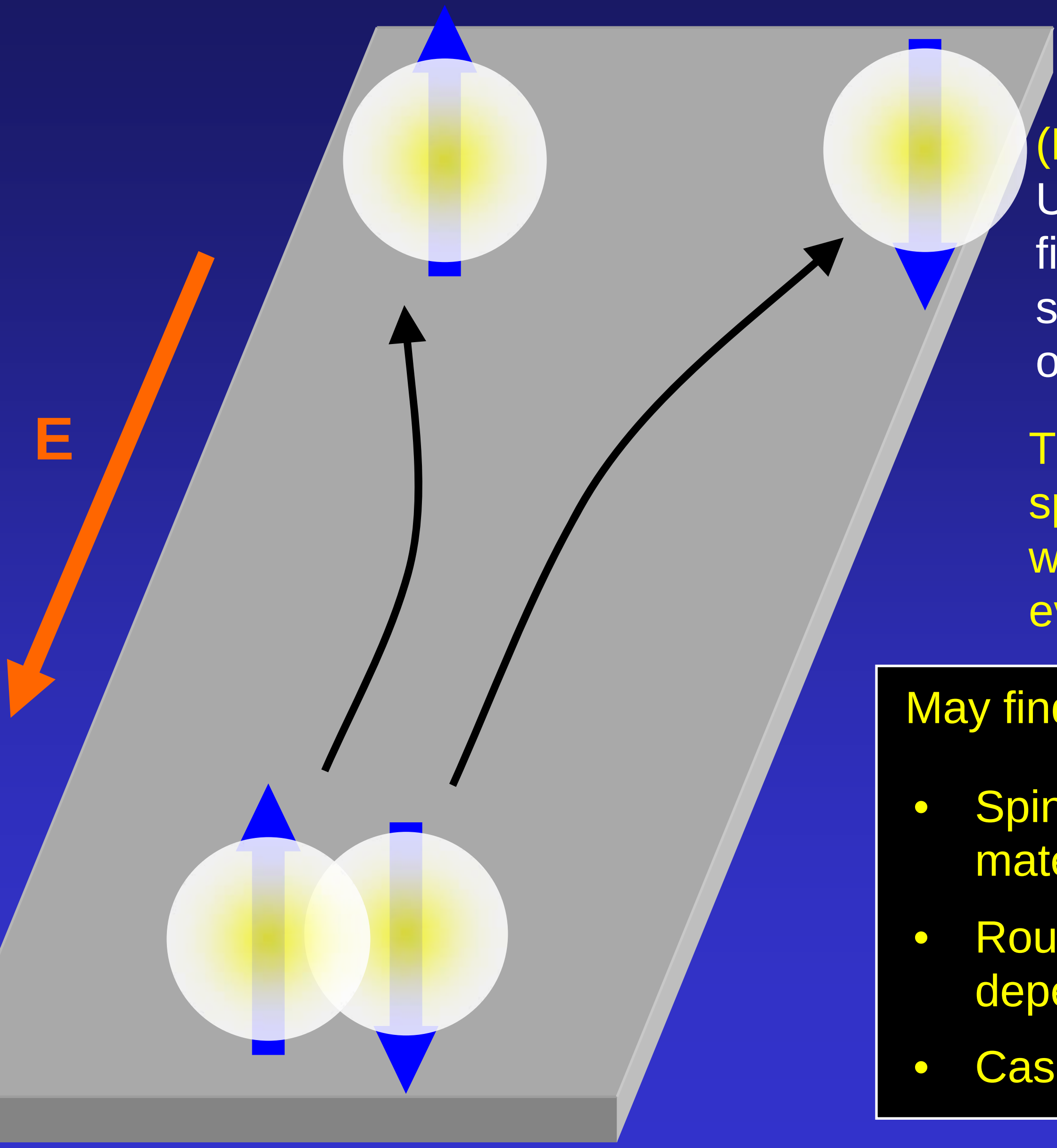
New spin-based quantum device opportunities

- electron spin interferometry using semiconductor ring structures



(Y. Kato *et al*., *Appl. Phys. Lett*. **86**, 162107 (2005))

The spin Hall effect



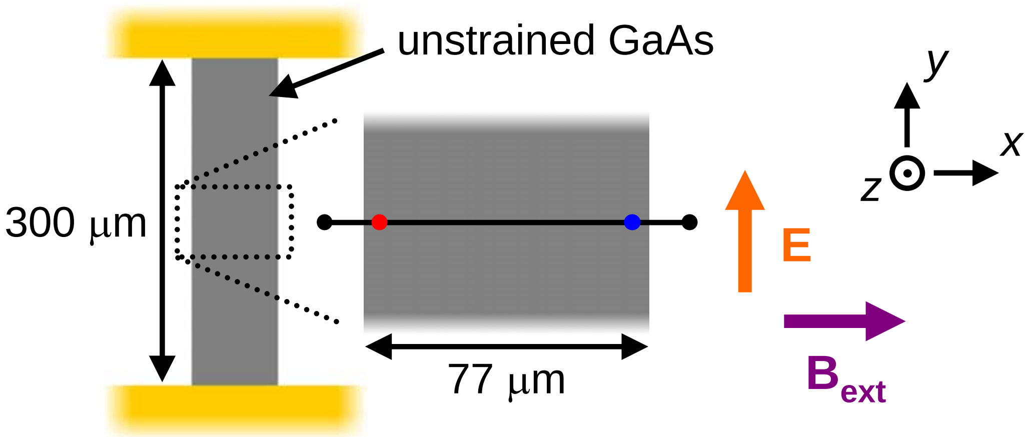
(M.I. Dyakanov, V.I. Perel (1971))
Under an application of electric field spin-up electrons move to one side and spin-down electrons to the other side.

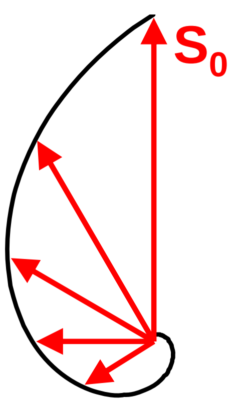
This results in the accumulation of spins at the edges of the sample with opposing spin polarization, even without magnetic fields.

May find applications in

- Spin source in nonmagnetic materials
- Route the path of electrons depending on spin
- Cascade & amplify polarizations

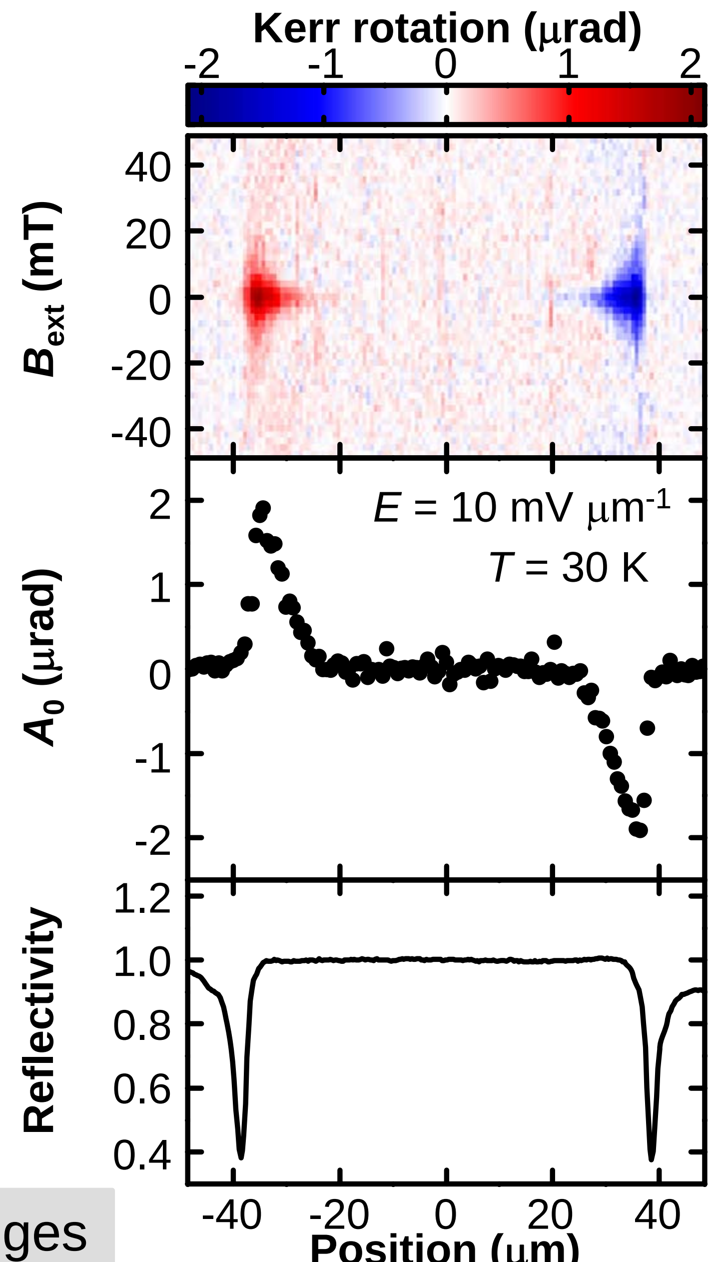
Discovery of the spin Hall effect in semiconductors





$$\int_0^\infty dt\left[\gamma \exp(-t/\tau)\cos(\omega_L t)\right]$$

$$= \frac{\rho_{el}}{(\omega_L \tau)^2 + 1}$$

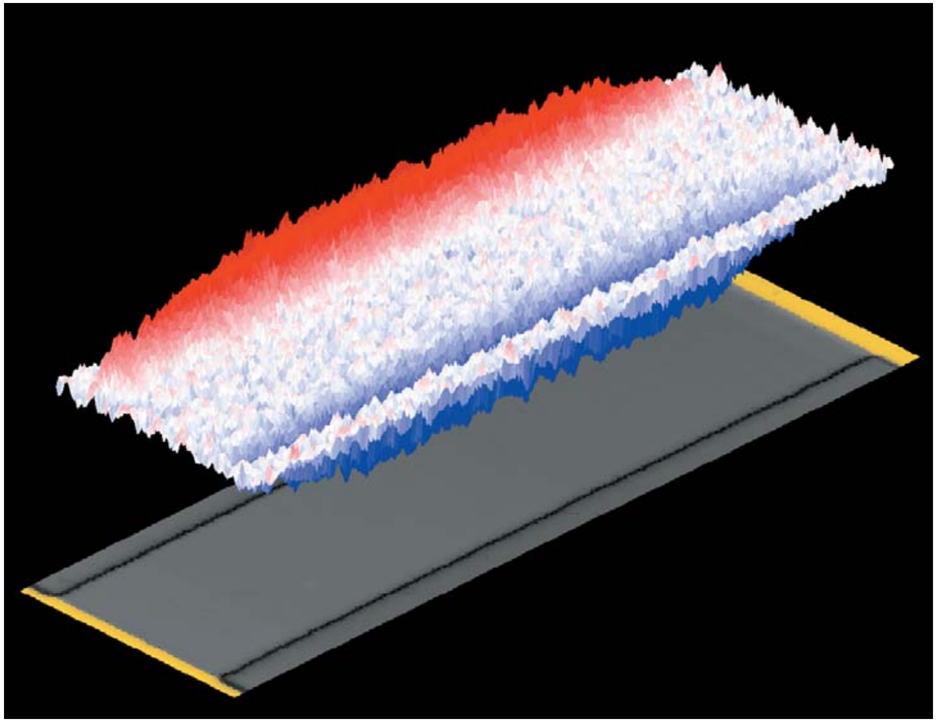


(Science **306**, 1910 (2004))

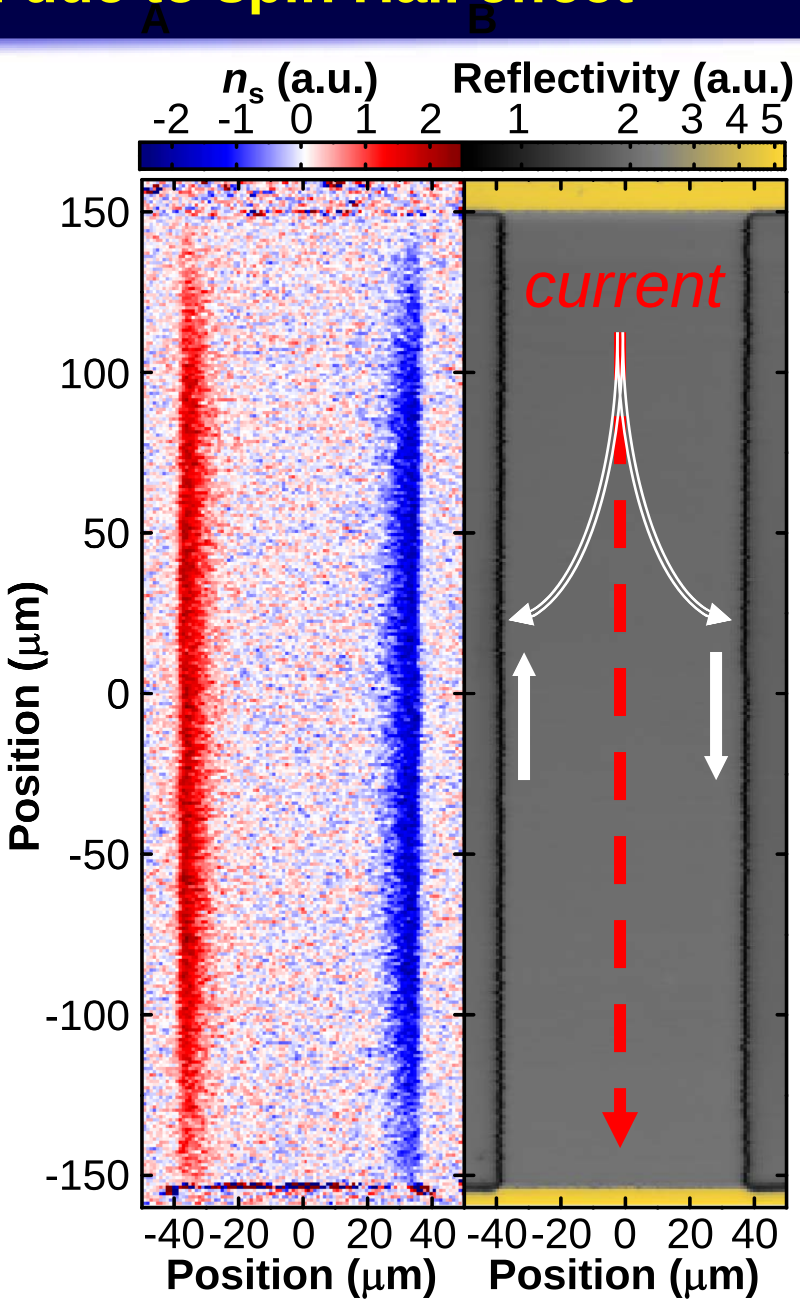
☑ Polarization changes sign for opposite edges

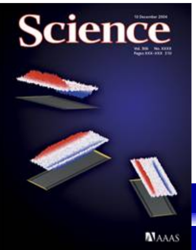
Imaging the spin accumulation due to spin Hall effect

- *Transverse spin current with no net charge flow*



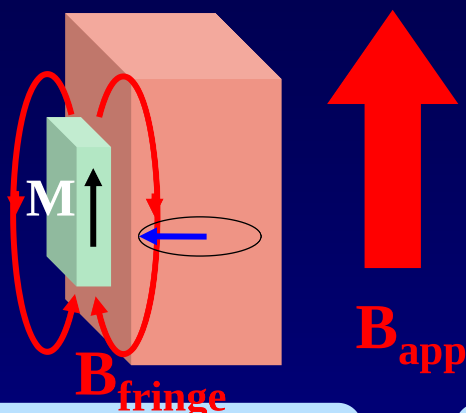
(Kato *et al.*, *Science* (2004))



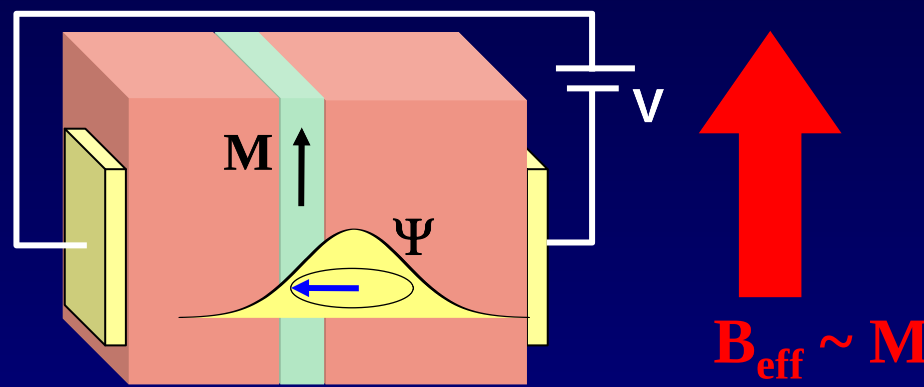


Can spin coherence be controlled with ferromagnets?

- Possibilities for spatially localized control of spin
- Control spins without external magnetic fields

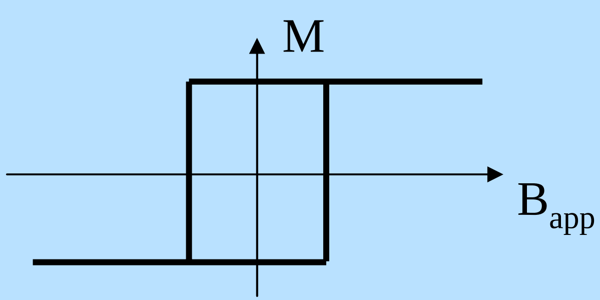


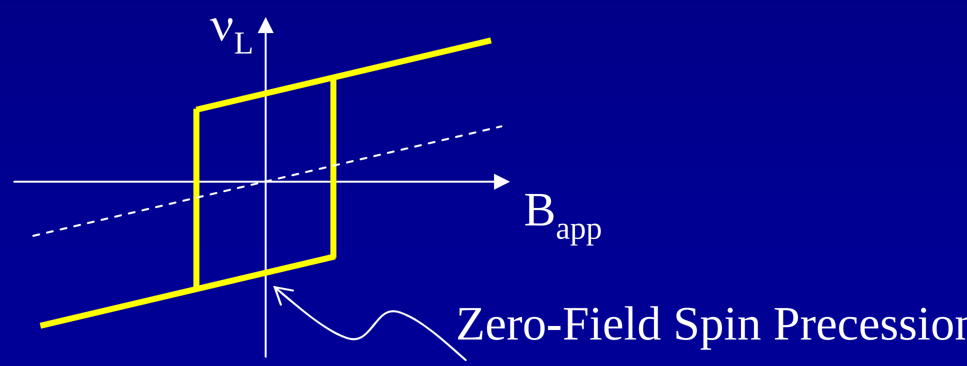
Magnetic fringe fields from ferromagnet



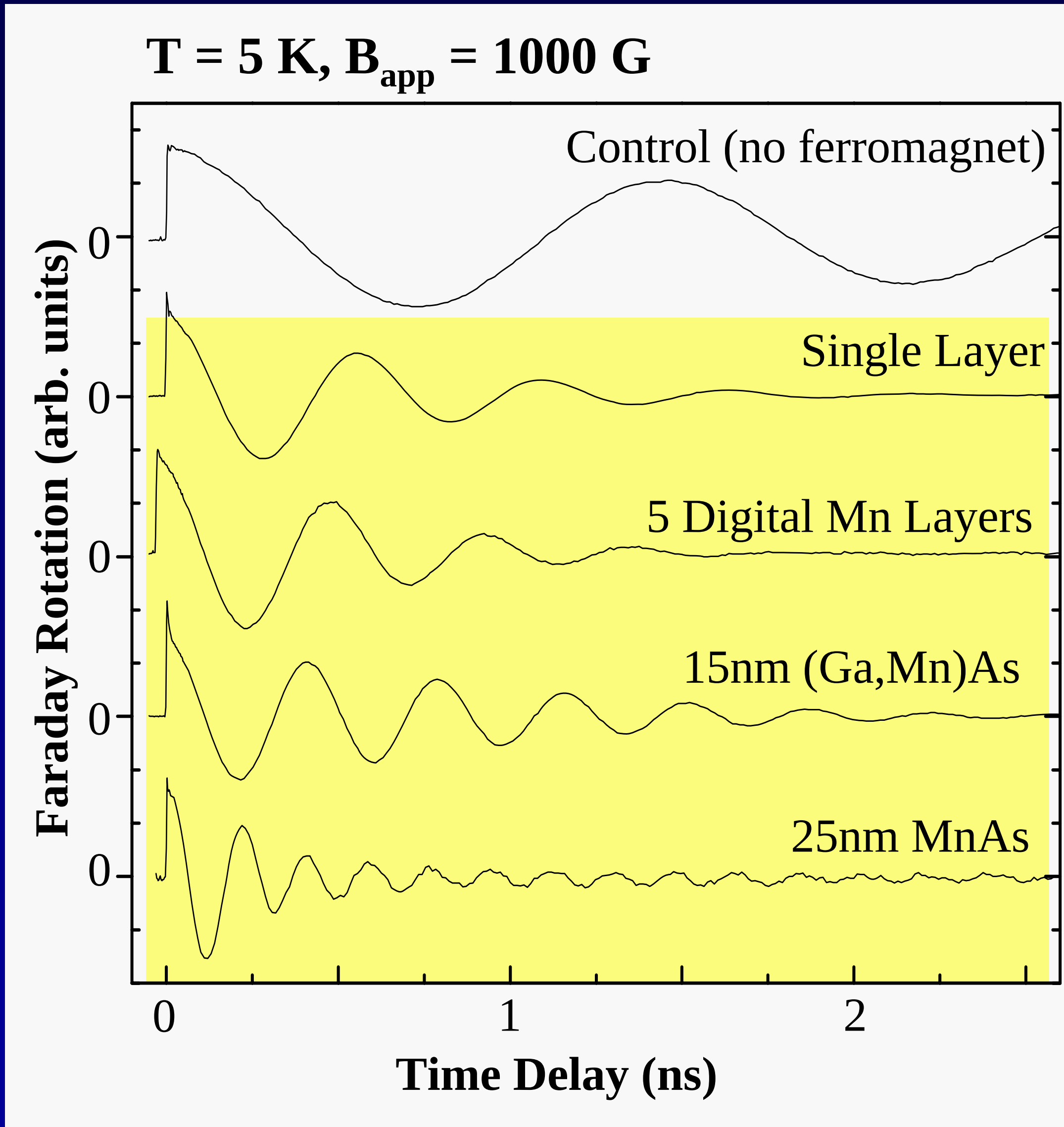
Exchange interactions (**S·M**) could produce effective magnetic fields

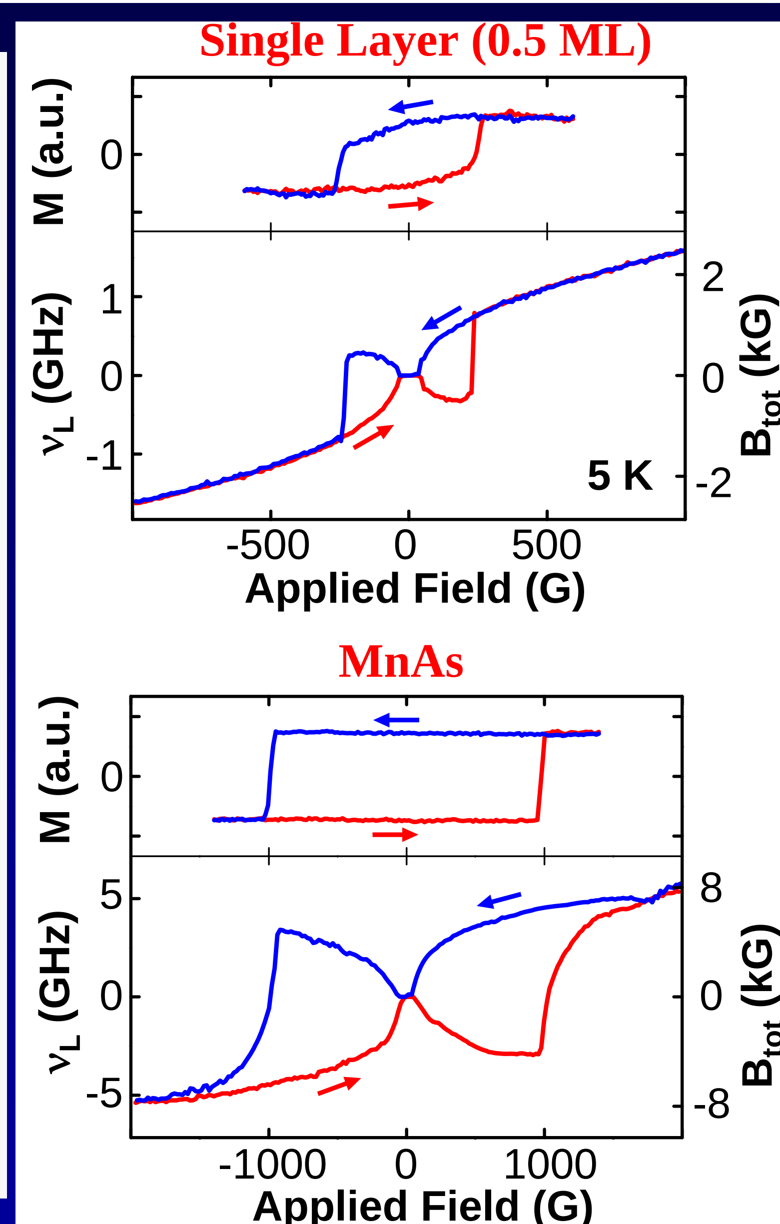
Typical Hysteresis of Ferromagnet





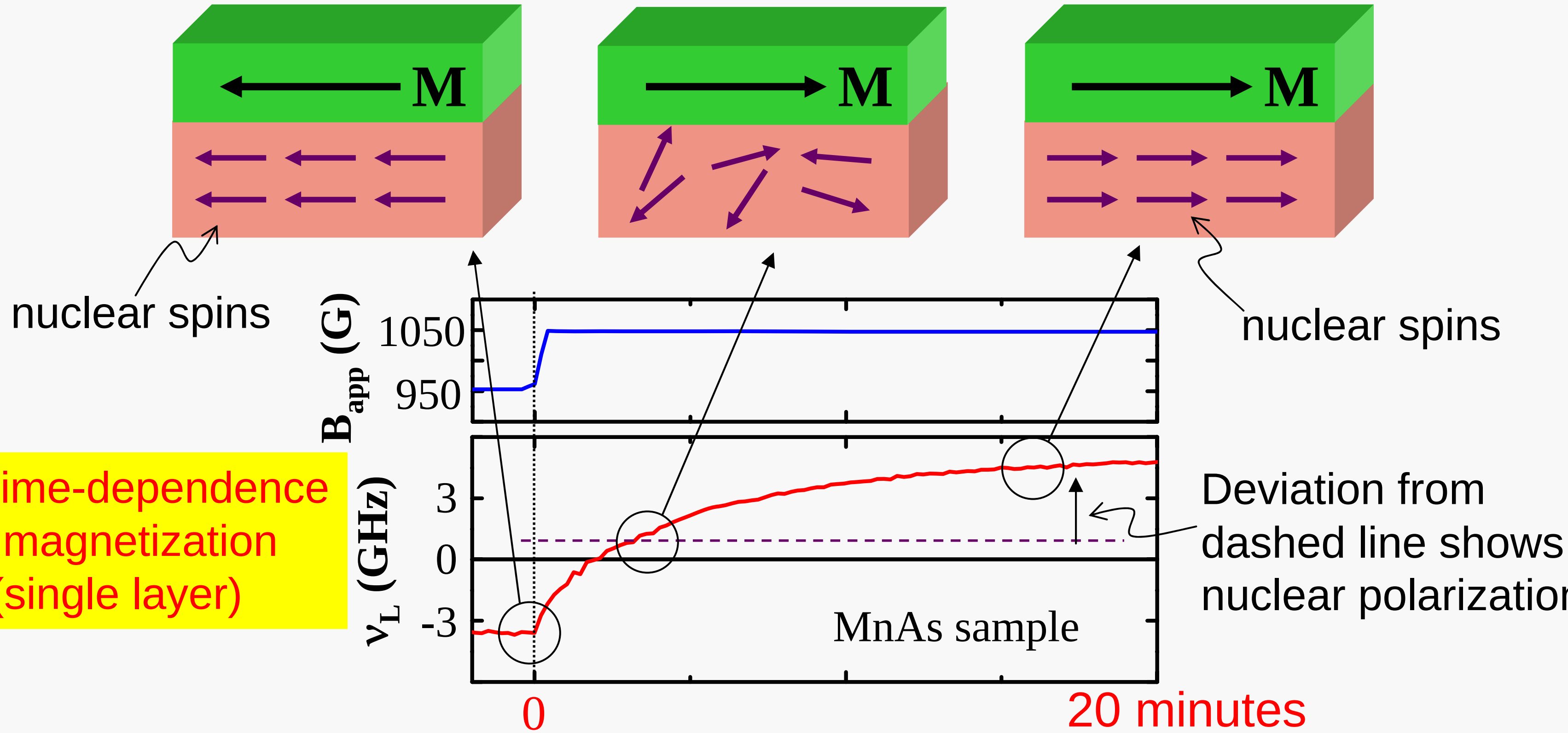
Electron spin precession in hybrid ferromagnetic/semiconductor structures





Ferromagnetic Imprinting of *Nuclear* Spins in Semiconductors

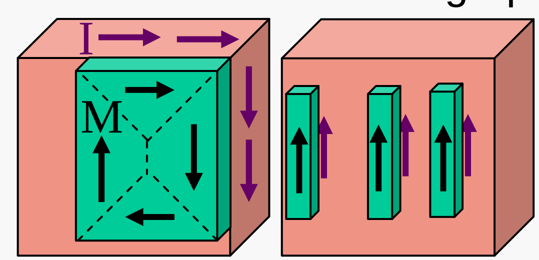
(R.K. Kawakami *et al.*, *Science* (2001))



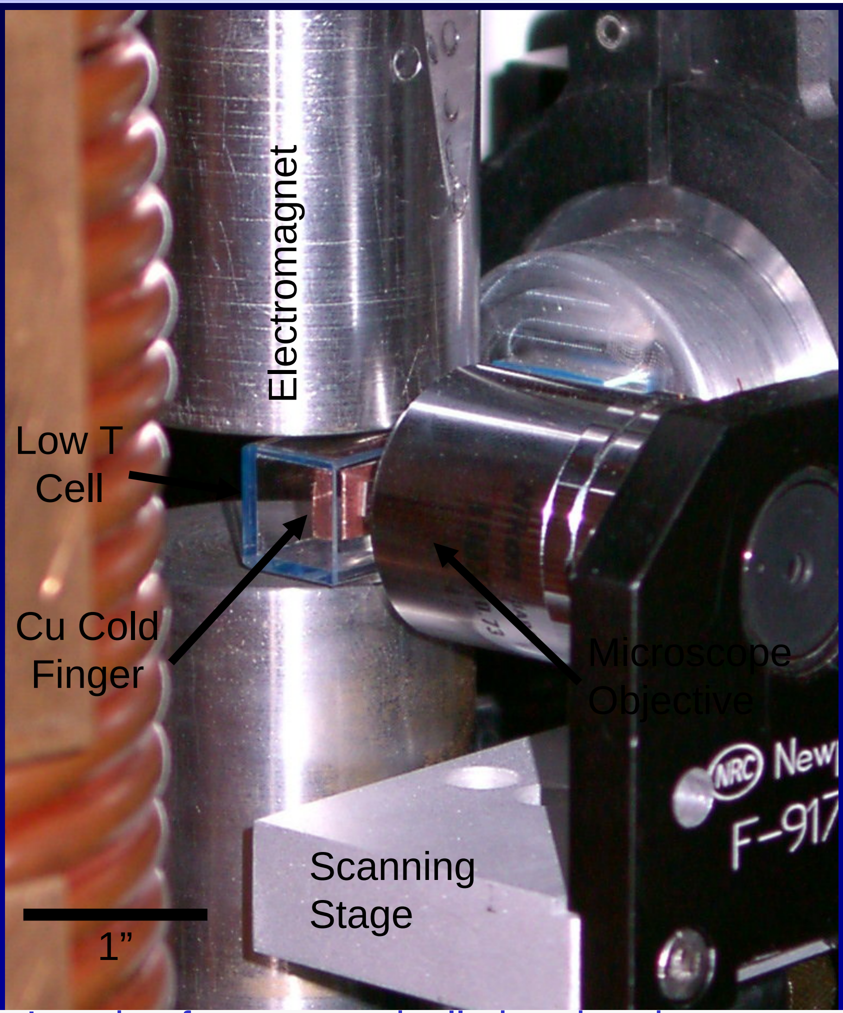
Lab time-dependence of magnetization (single layer)

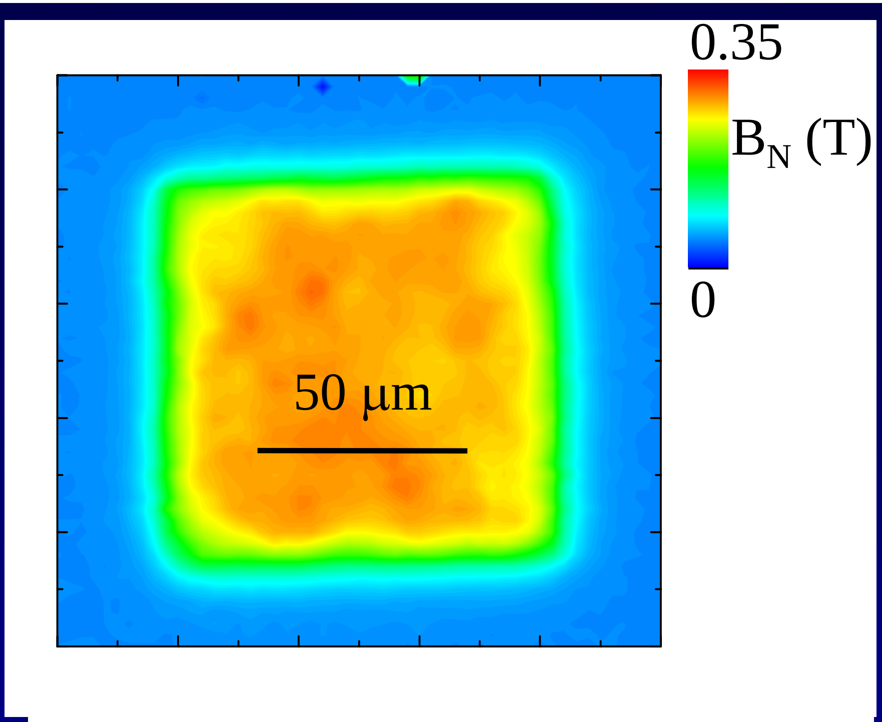
- The ferromagnet’s magnetization is “imprinted” onto the nuclear spins of GaAs
- Nuclear polarization ~ 25%
- Equivalent to >1000T in equilibrium

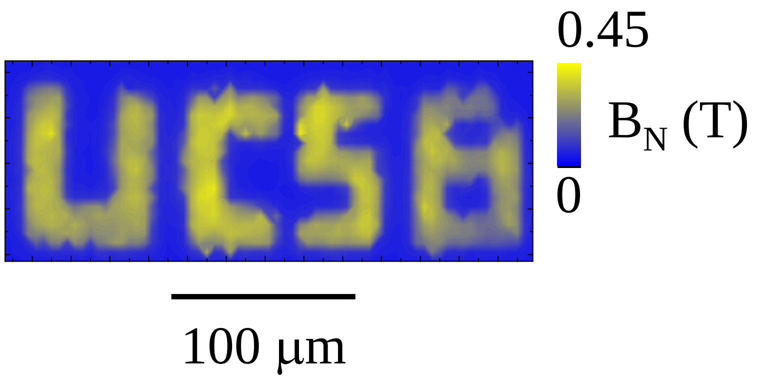
Nuclear spin patterning with magnetic domains or traditional lithography:



Ferromagnetic Imprinting of Nuclear Spins: Gating and Imaging





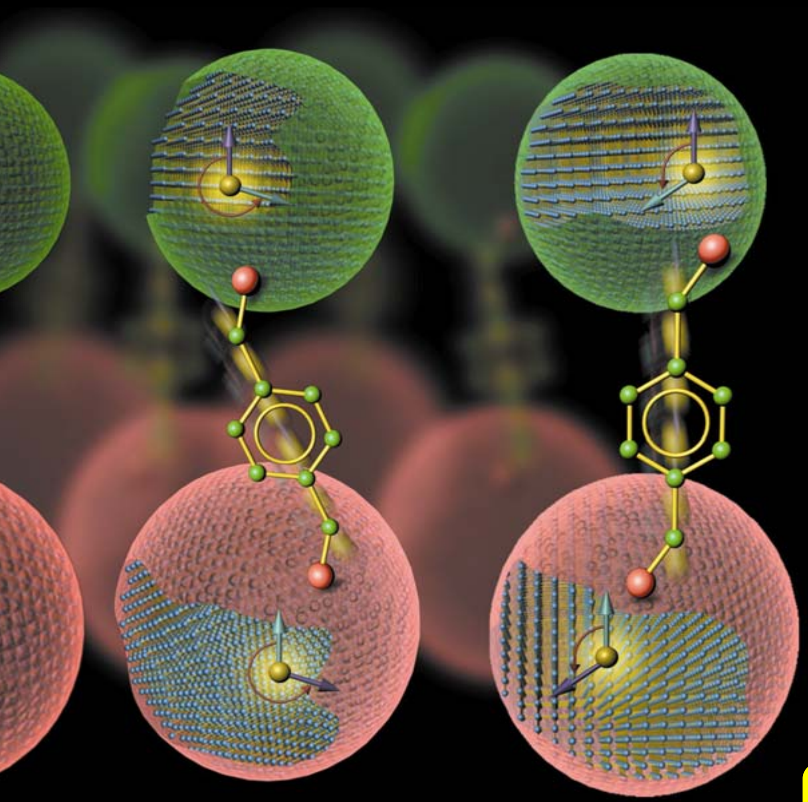


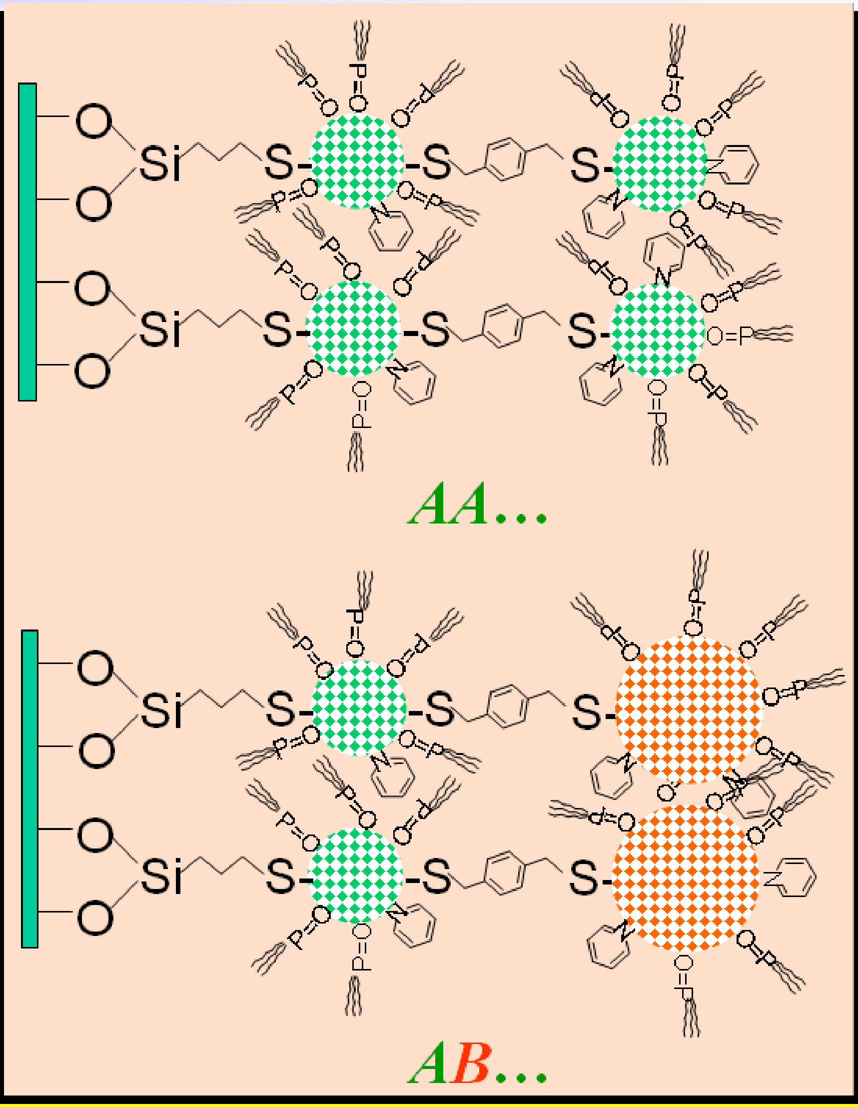
- Imaging ferromagnetically-imprinted nuclear domains
- Spatially-resolved studies of spin transport
- Spin coherence in small structures

(J.M. Stephens et al, PRB Rapid (2003))

Molecularly Wired Quantum Dots for Processing Spintronics

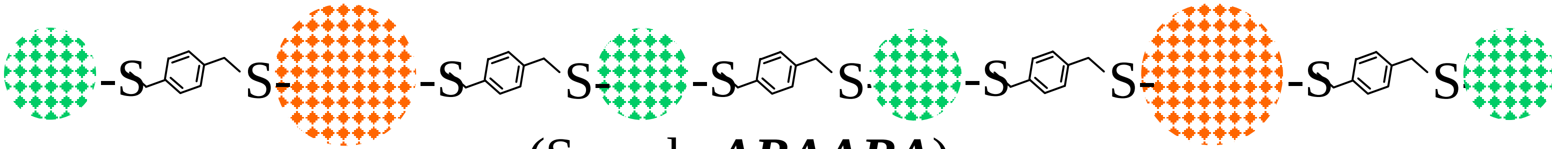
‘Wiring’ Quantum Dots with Molecules
- wires as dynamic logic elements
- electrical/chemical control information





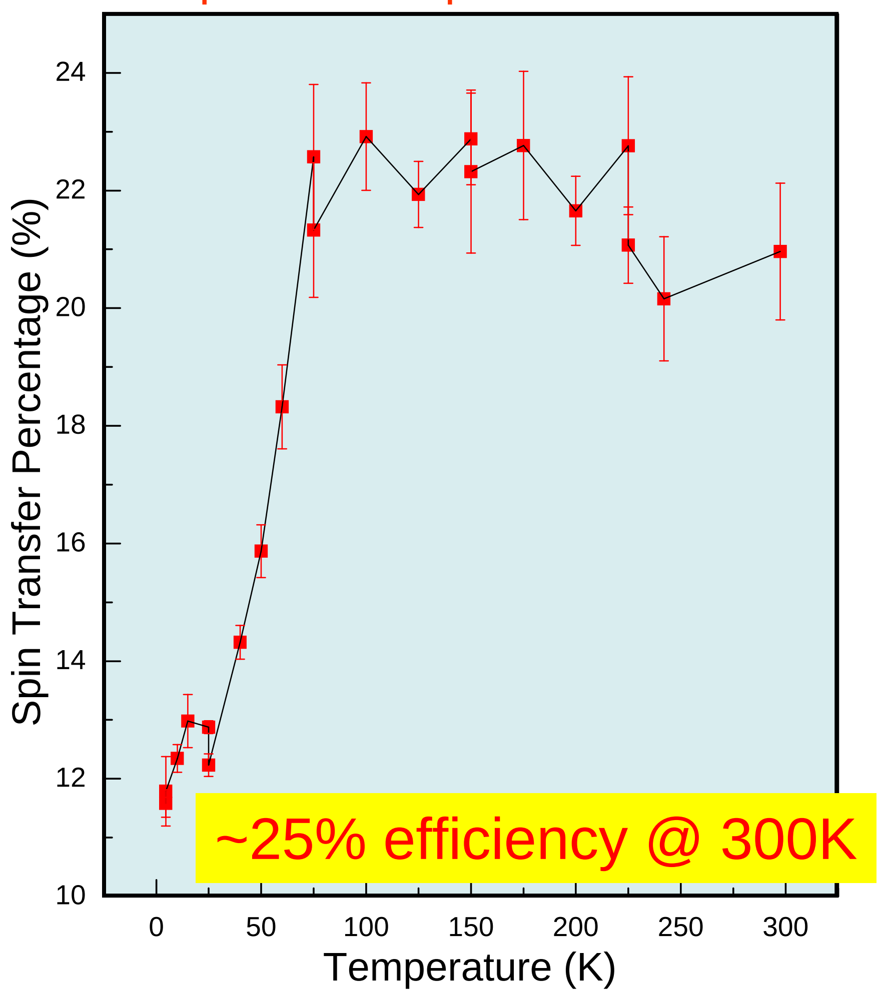
- A wet-chemistry layer-by-layer assembly method
- Different sized QDs can be spectrally resolved

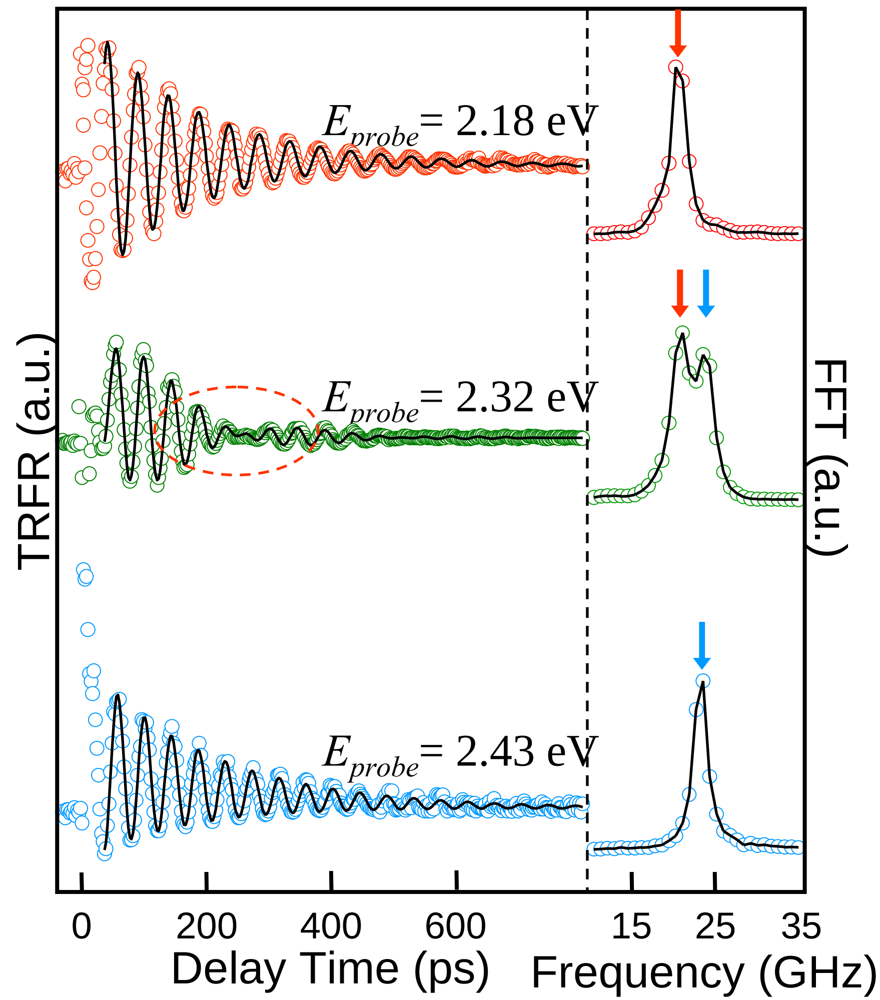
Transfer of spin coherence across molecular bridges



(Sample ***ABAABA***) (M. Ouyang *et al.*, *Science* (2003))

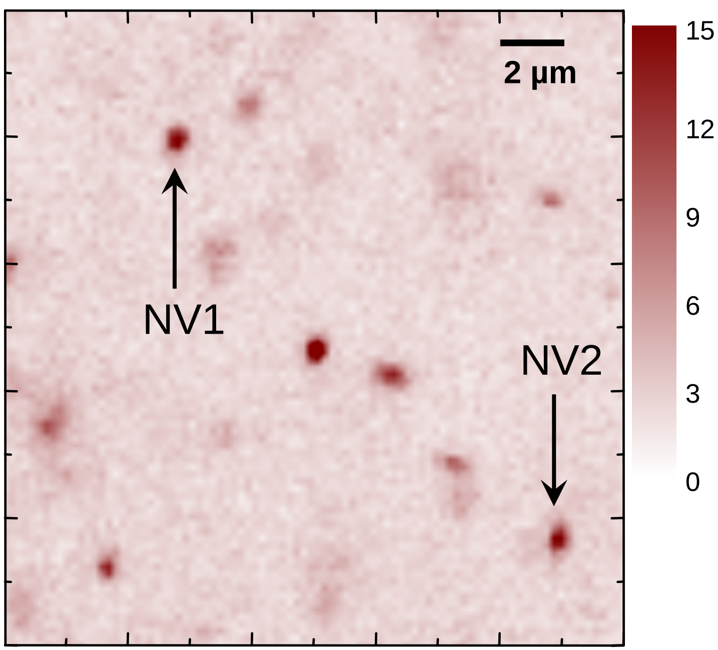
Temperature dependence of *STP*



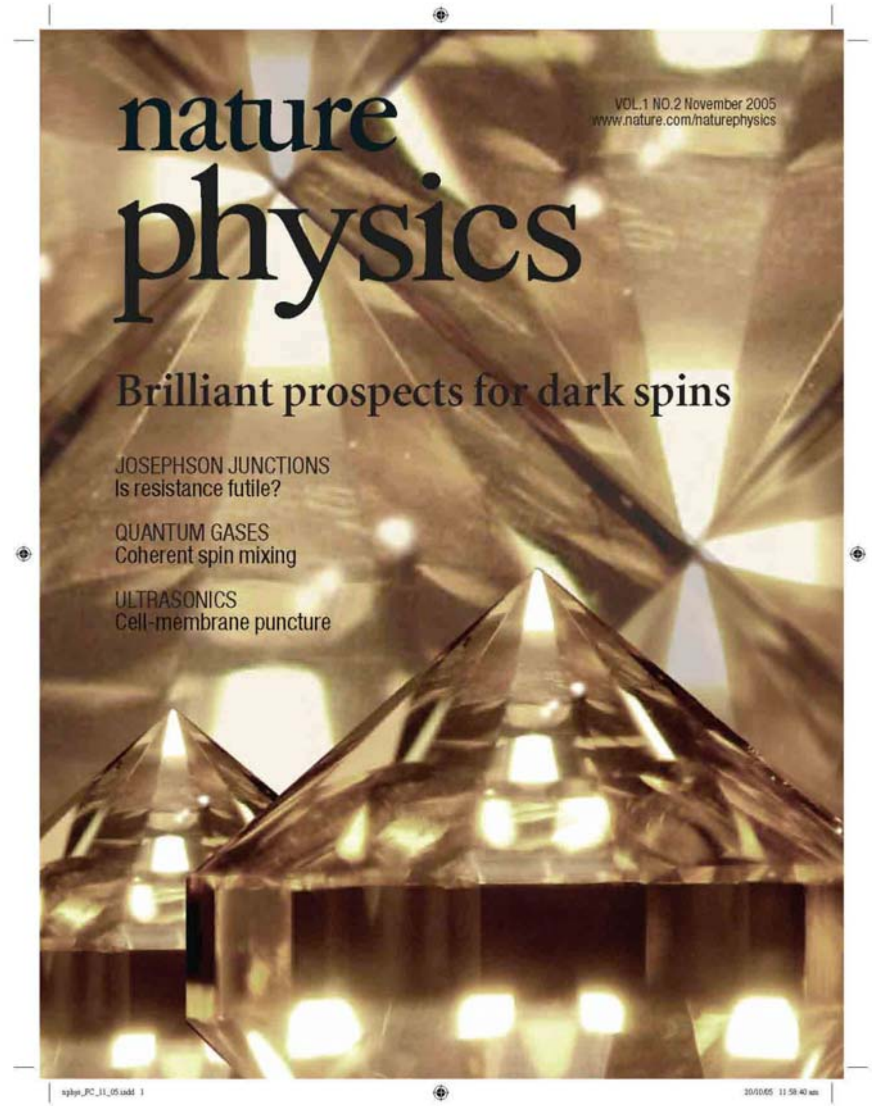


Imaging single spins in diamond at room temperature

Fluorescence Image

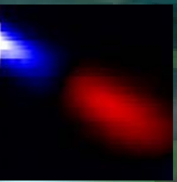


Single spins detected at room temperature

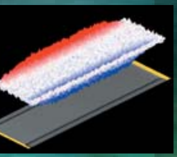


Nature Physics **1**, 94 (2005)

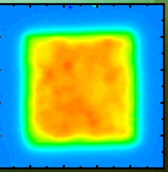
Summary



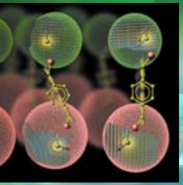
➢ New pathways for all-electrical generation and manipulation of spin-based information using conventional semiconductors and strain engineering: current-induced spin polarization.



➢ Observation of the spin Hall effect provides new opportunities for sensing and logic by enabling spin separation and on-chip routing.



➢ Ferromagnetic imprinting of nuclear spins produces substantial polarization, enabling the patterning and gating of nuclei in nanostructures.



➢ Molecules act as both physical links tethering quantum dots *and* as efficient spin channels for shuttling quantum information at room temperature with ~25% efficiency.

www.physics.ucsb.edu/~awschalom
www.spintronics.ucsb.edu

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