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Title: Multiferroics and Spintronics

Author(s): Avadh B. Saxena, 113324, T-4 LANL

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EST. 1943

Multiferroics ~~Materials~~ and Spintronics

Avadh Saxena

Los Alamos National Lab.

Abstract: Materials exhibiting ferroic behavior are ubiquitous in nature. Ferroic materials are those which possess two or more orientation states (domains) that can be switched by an external field and show hysteresis. Typical examples include ferromagnets, ferroelectrics and ferroelastics which occur as a result of a phase transition with the onset of spontaneous magnetization (M), polarization (P) and strain (e), respectively. A material that displays two or more ferroic properties simultaneously is called a multiferroic, e.g. magnetoelectrics (simultaneous P and M). The microscopic analog of multiferroics is related to spintronics (an acronym for "spin transport-based electronics"). It refers to the science and engineering of devices in which transport properties can be altered by manipulating electron spin. The ability to control and measure spin degrees of freedom in solids has been proposed as an operating principle for a new generation of novel electrical devices with the potential to overcome power consumption and speed limitations of conventional electronic circuits, and also as a means to physically implement schemes for quantum information processing and computing. The materials of interest include ferromagnetic metals and magnetic semiconductors with properties dictated by interfaces between them and their heterostructures. I will discuss how to inject, maniputate and detect spin polarized electrons (and currents) into a material by both electrical and optical means. The spin-orbit interaction plays a major role in this context. Next, I will describe the basics of spin-based optoelectronic devices such as spin valves, spin transistors, magnetic tunnel junctions and memory elements. Finally, I will briefly mention the connection of spintronic concepts with organic electronics and the emerging field of multiferroics.

Jinan abstract

LA-UR-11 --- (needed)

MULTIFERROICS and SPINTRONICS

Avadh Saxena (Los Alamos National Lab)

1. What are multiferroics; what is spintronics?

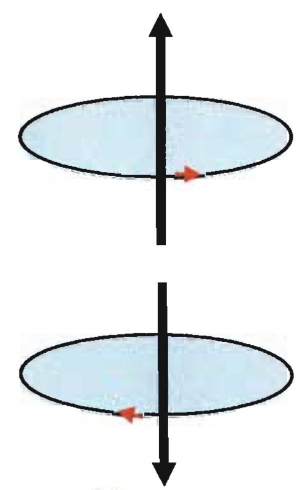
3. Recent developments and new materials/devices.

4. Optical spin injection and detection.

5. Electrical spin injection and detection.

6. Dilute magnetic semiconductors.

7. Organic semiconductors and spintronics.



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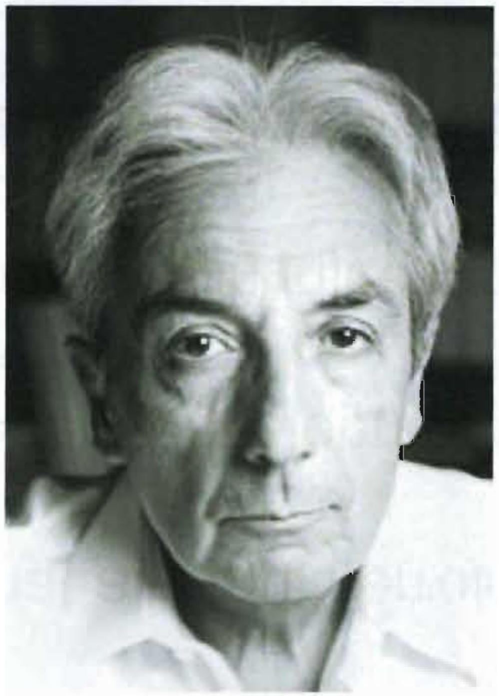
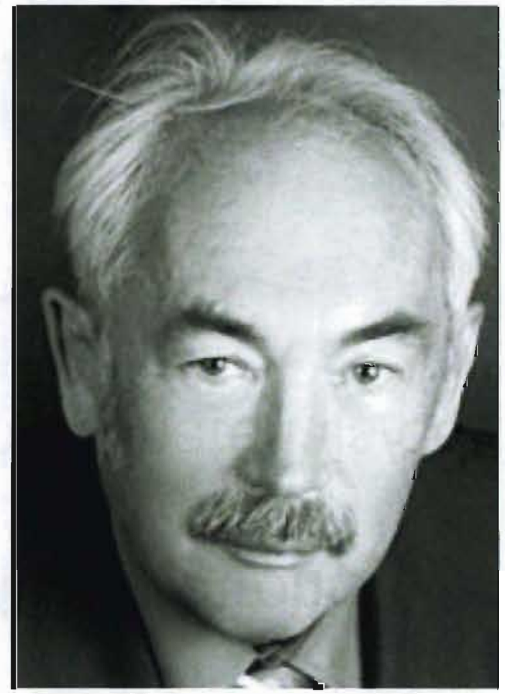
The Nobel Prize in Physics 2007

"For the discovery of Giant Magnetoresistance (GMR)"





Albert Fert (Orsay, France, b. 1938)

Peter Grunberg (Julich, Germany, b. 1939)

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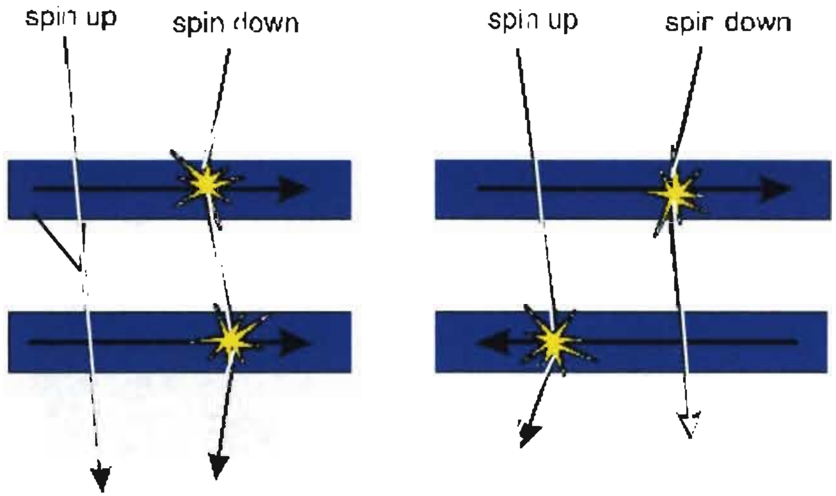
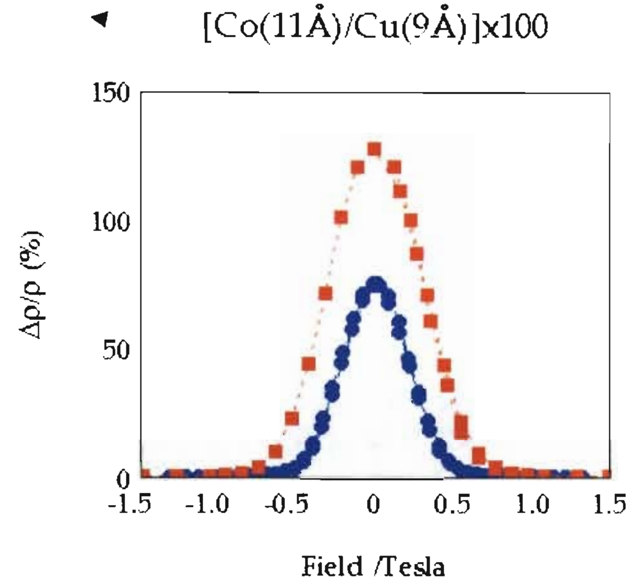
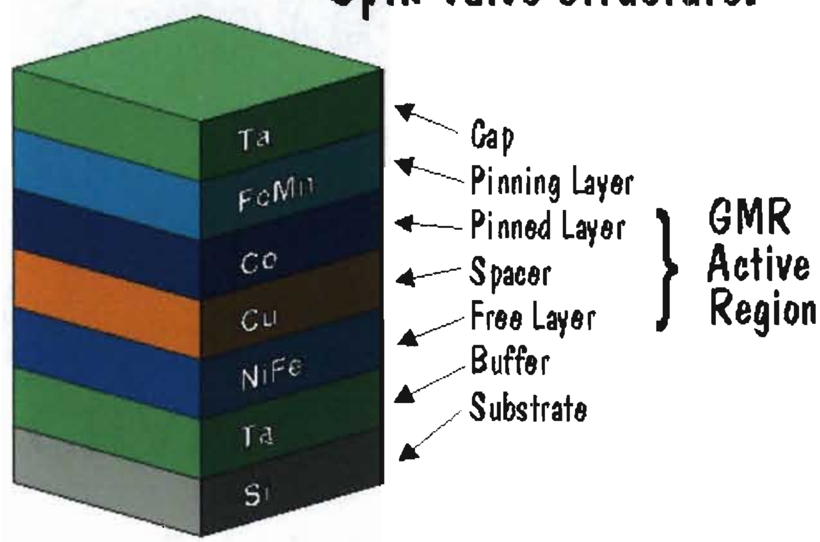
GIANT MAGNETORESISTANCE





Spin-valve structure.



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Three Pillars of Functional Materials/Devices

CHARGE SPIN LATTICE

Tholos Temple at Delphi, Greece, 300 BC

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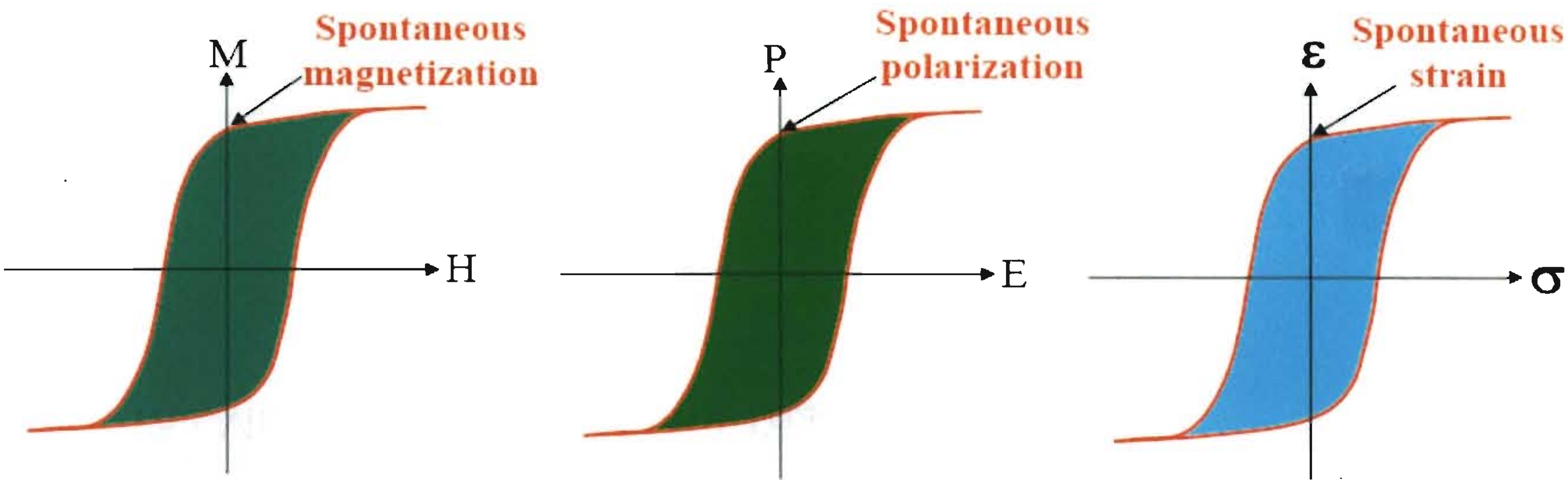
Ferroic phenomena

Ferroics is a family of materials exhibiting one or more multifunctional characteristics such as **ferroelectric, ferromagnetic, or ferroelastic** properties

Ferromagnetic | **Ferroelectric** | **Ferroelastic**



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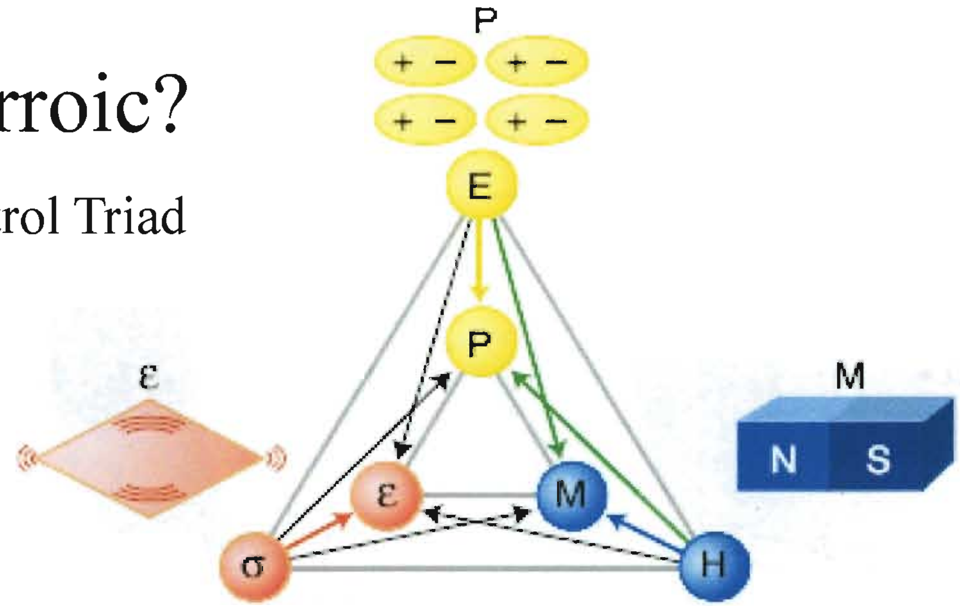
What is a multiferroic?

The Multiferroic phase-control Triad



(Spaldin and Fiebig, Science 2005)

A compound that displays two or more ferroic states

- Ferromagnetic – spontaneous magnetization M
- Ferroelectric – spontaneous polarization P
- Ferroelastic – spontaneous strain ε

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Spintronics

- **Conventional electronics: charge of electron used to achieve functionalities – *e.g.*, diodes, transistors, electro-optic devices (detectors and lasers....)**

- **Spintronics: manipulate electron spin (or resulting magnetism) to achieve new/improved functionalities -- spin transistors, memories, higher speed, lower power, tunable detectors and lasers, bits (Q-bits) for quantum computing....**

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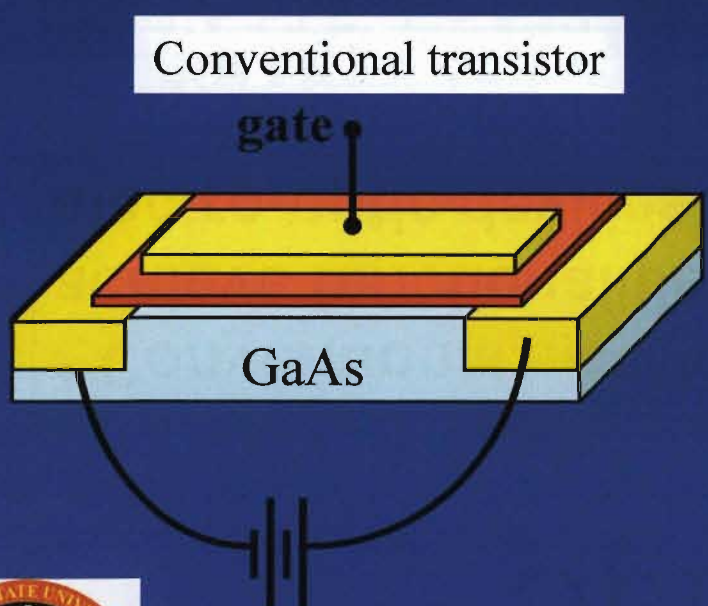
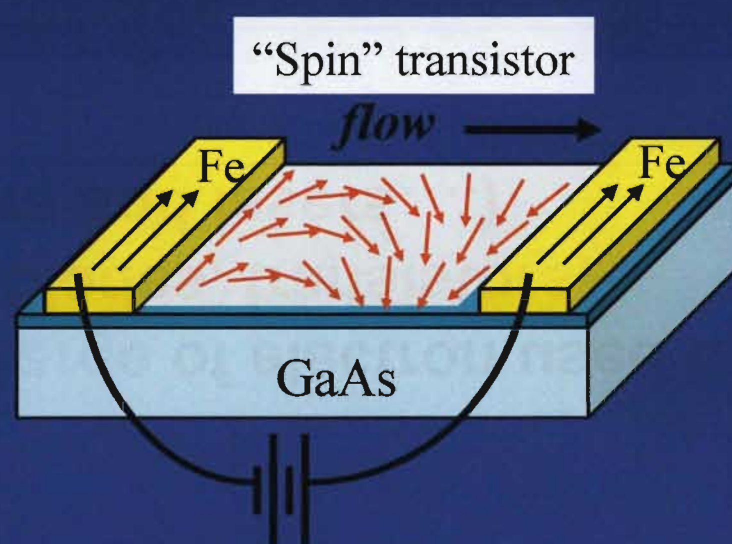
"Semiconductor Spintronics"

- Electrons have *spin* as well as *charge*.

- A (proposed) new generation of "spintronic" devices that derive functionality from electron spin degrees of freedom (not charge)





Semiconductor Spintronics

Objective

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

Richard P. Feynman
(1965 Nobel Prize)

1918 - 1988

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SPINTRONICS CHALLENGE

In March of 1959, Richard Feynman challenged his listeners to build

> "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."

Richard Feynman - "There's Plenty of Room at the Bottom"

1959 Annual Meeting of the American Physical Society

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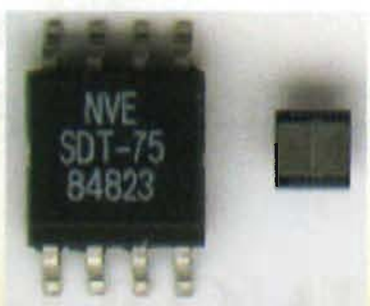
Spintronics

Magnetoresistive thin films and nanostructures are already extremely important scientifically, technologically and economically.

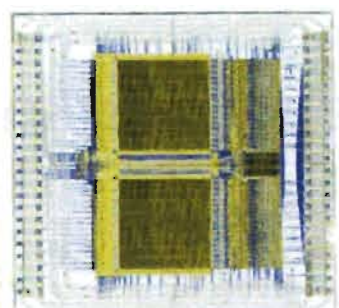
- Economics: -Today
  - Magnetic recording alone is a $100 billion/yr

The IBM Travelstar disk drive
uses magnetoresistive devices to achieve 4.1Gb/in^2

  - Tomorrow – Potential additional $100 billion/year



Sensors-Isolators



Non-Volatile
Radiation Hard
High Density
Very High Speed
Low Cost

Magnetic RAM

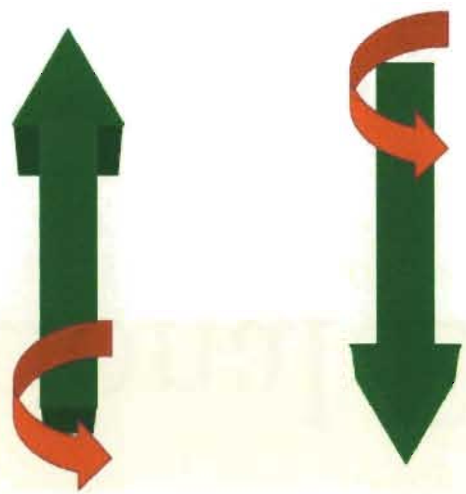
Rationale for Spintronics

Conventional Electronics → Charge

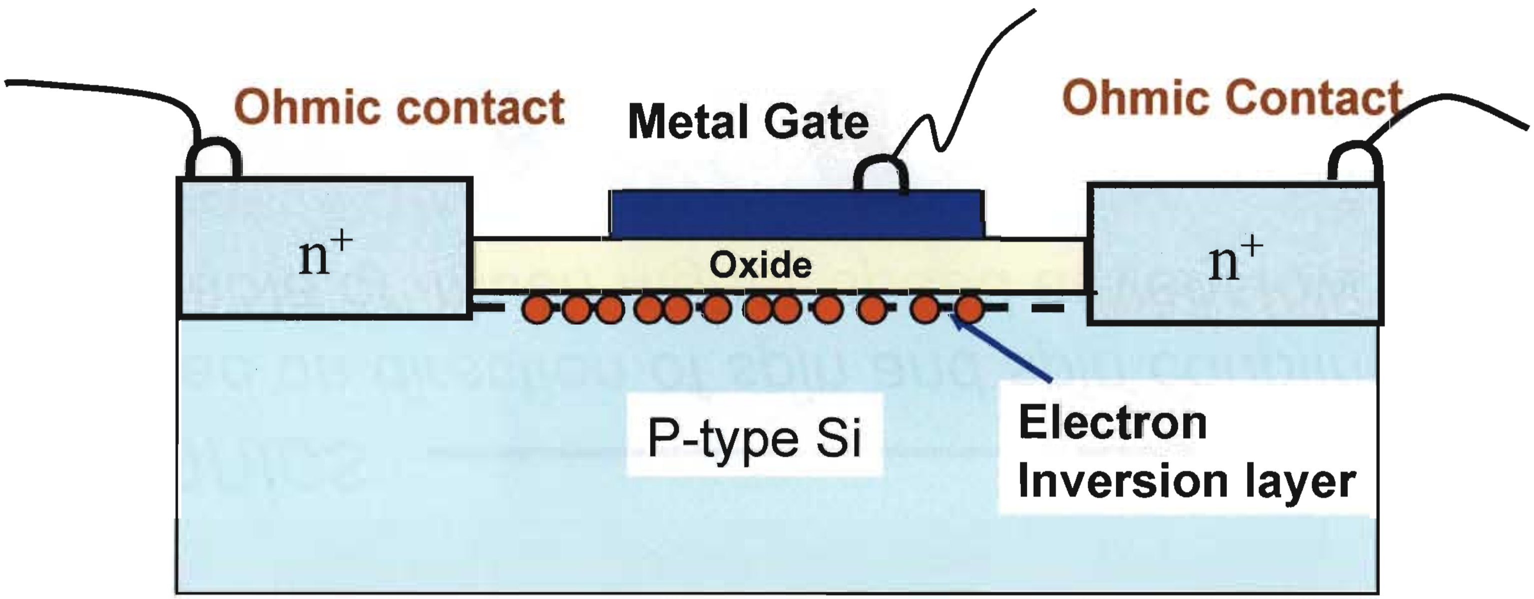
- *Based on number of charges and their energy*
- *Performance limited in speed and dissipation*

Spintronics → Spin

- *Based on direction of spin and spin coupling*
- *Capable of much higher speed at very low power*



Conventional Electronics



Metal Oxide Semiconductor Field Effect Transistor
MOSFET

Gate Voltage changes electron density
⟹ changes conductivity

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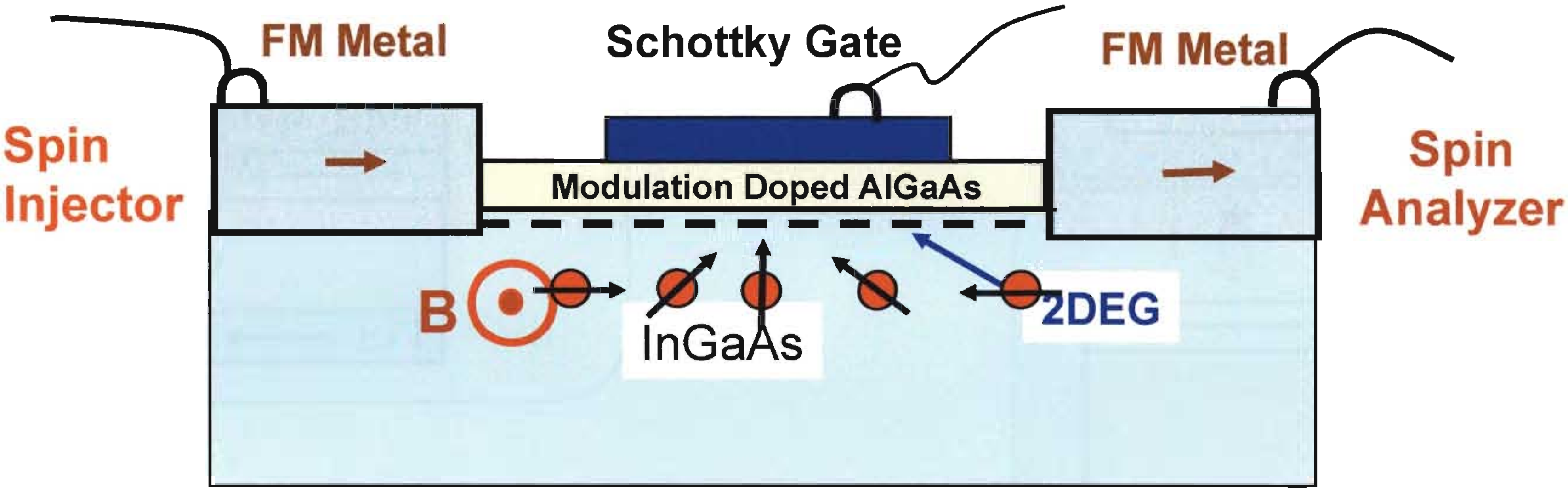
Spintronic
s

Spin Valves, Spin transistors, Switches, Modulators, MRAM,....



Spin Transistor

Inject polarized spin from one FM contact -- modulate current by modifying spin precession via Rashba effect (Asymmetry - spin-orbit interact.) Depends on perpendicular electric field on 2DEG; other FM contact is analyzer

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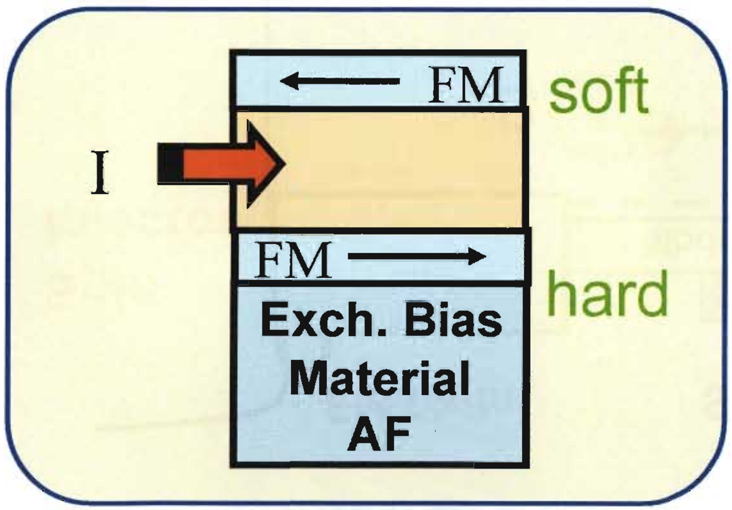
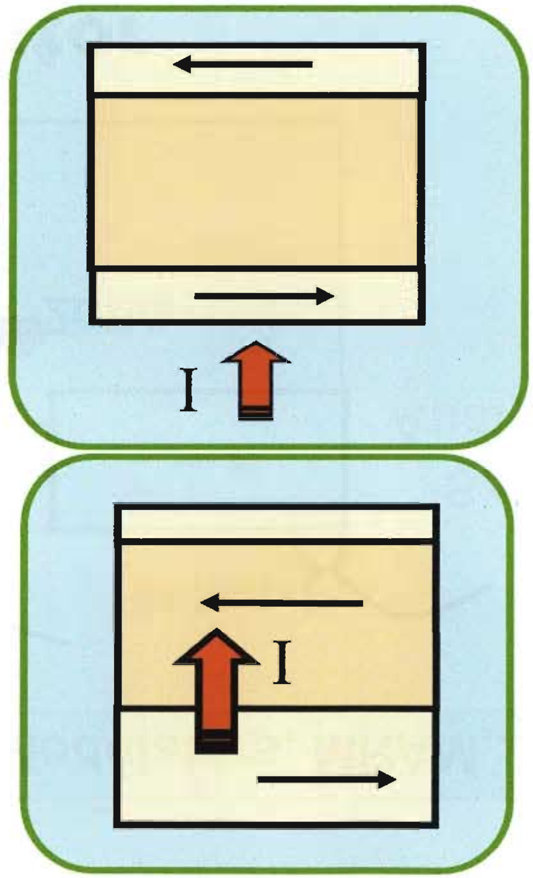
Conventional Electronics

Nonvolatile



Spin valve



Spin filter

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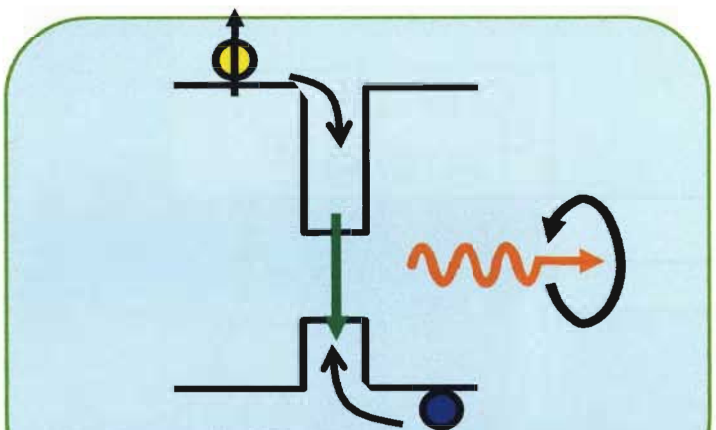
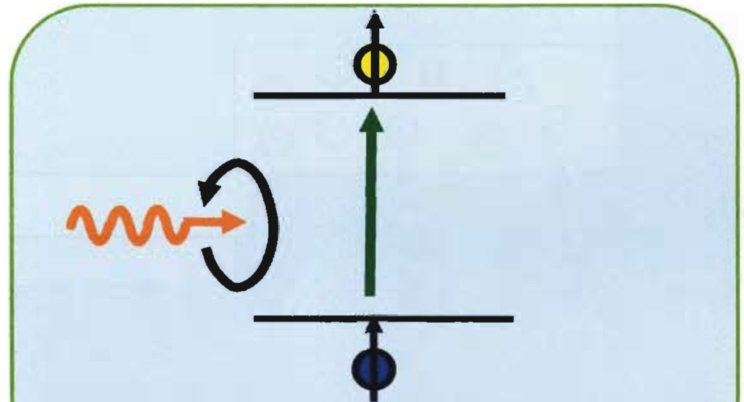
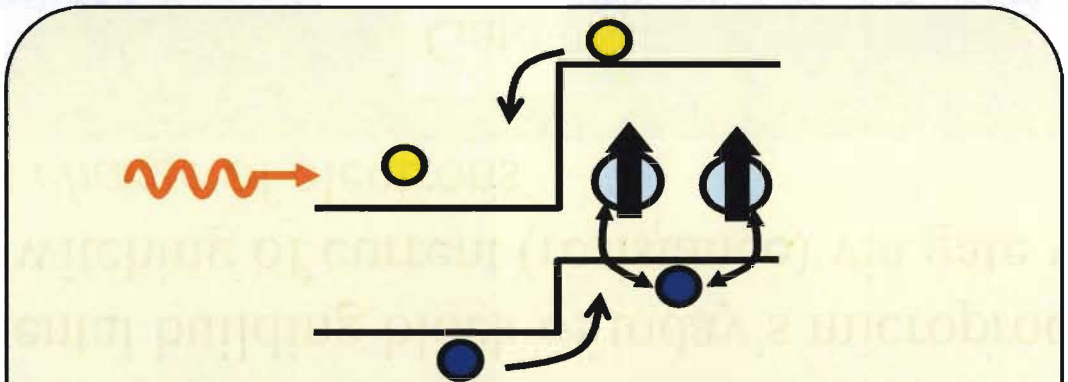
BUILDING BLOCKS FOR SPIN PHOTONICS



Spins to Polarized Photons



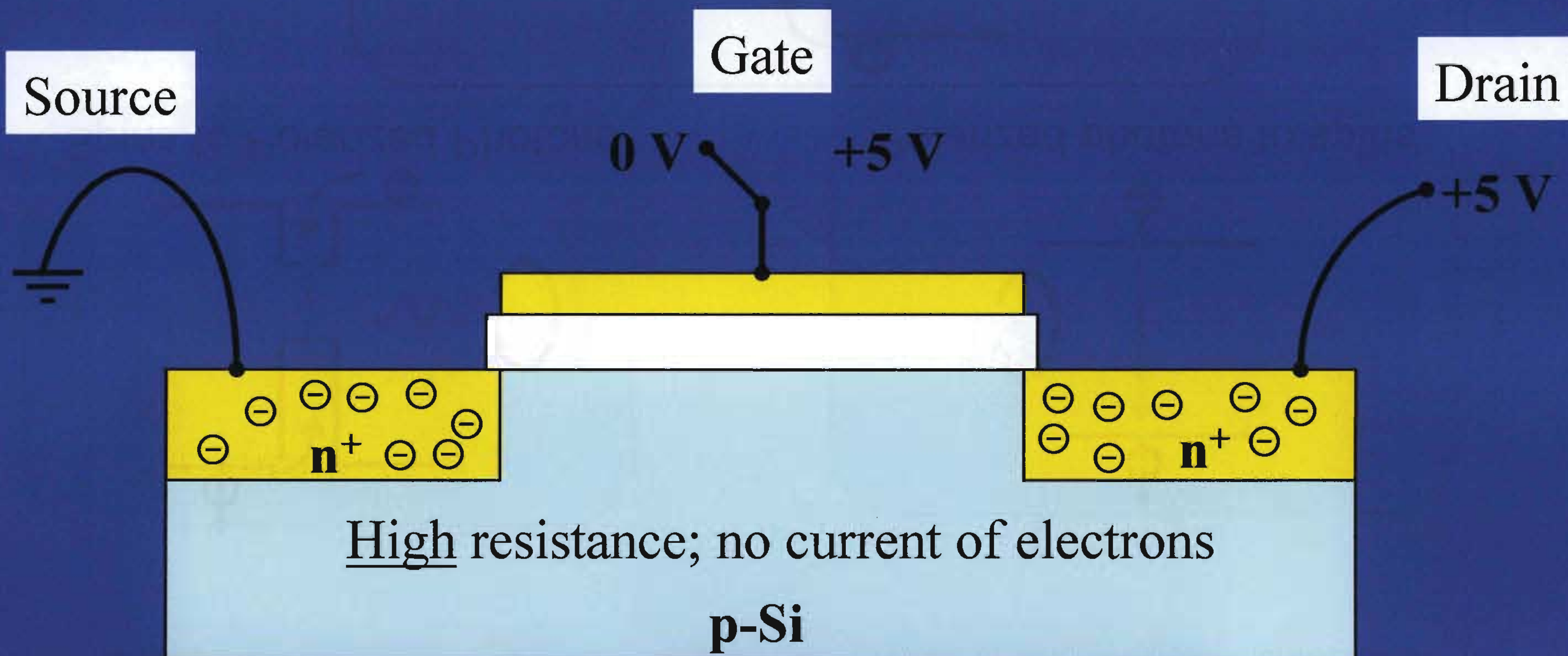
Polarized photons to spins



Photons modulate Magnetism

Conventional (field-effect) transistor
(silicon MOSFET)

- Fundamental building block of today's microprocessors
- On/off switching of current (resistance) via gate voltage
- Exploits *charge* of electrons



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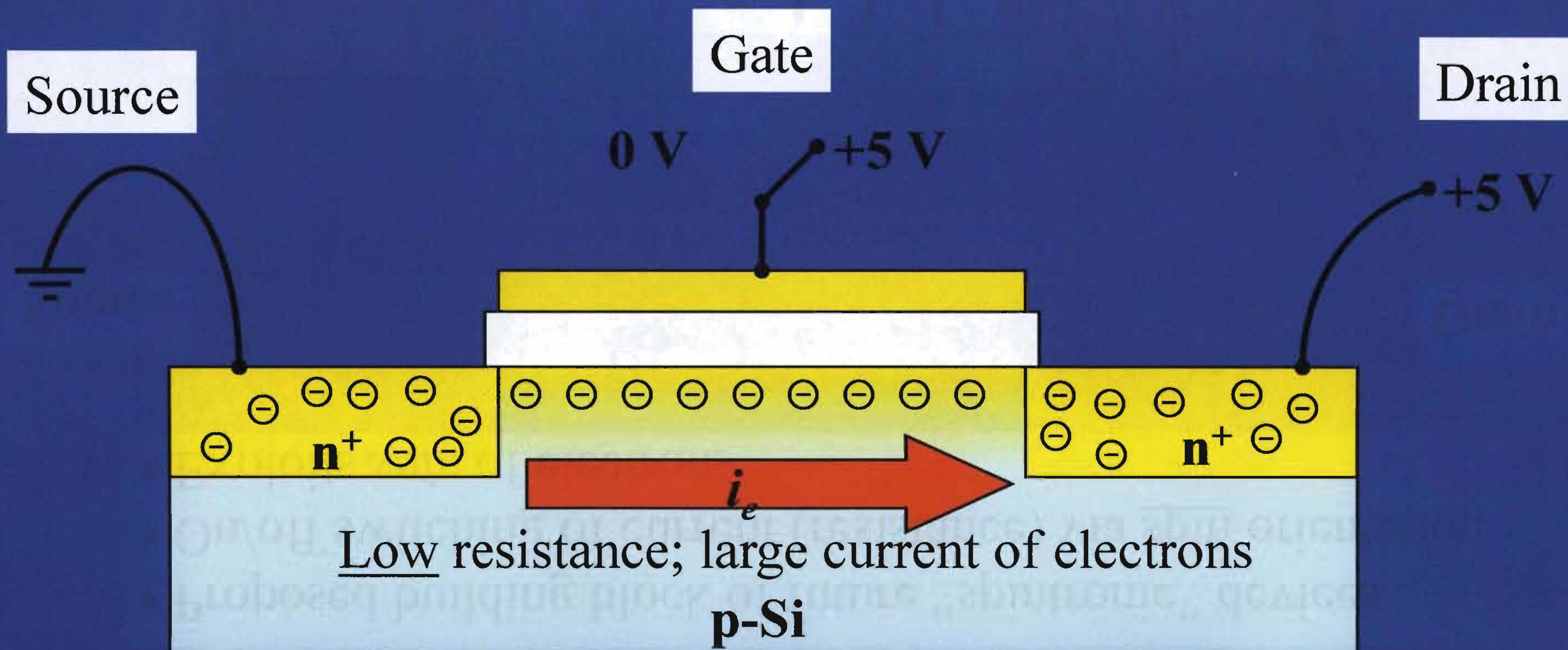
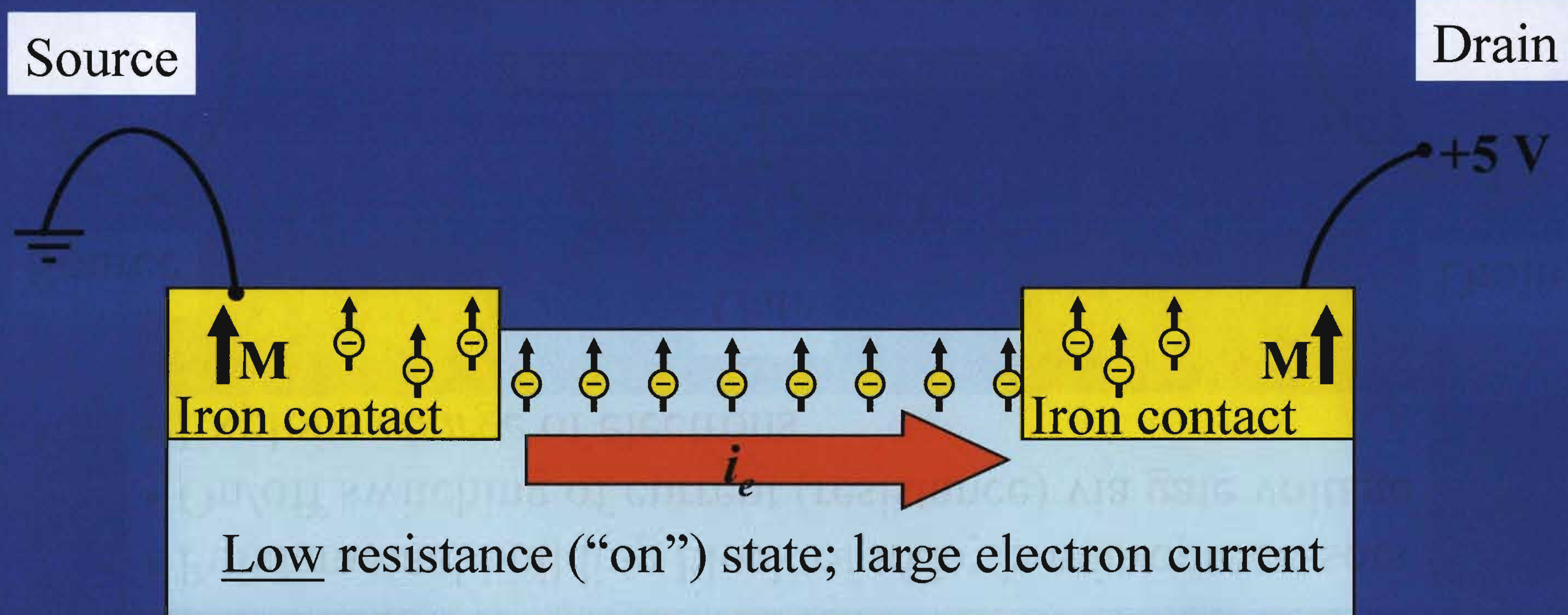


Proposed "spin transistor"

- Proposed building block of future "spintronic" devices
- On/off switching of current (resistance) via spin orientation
- Exploits *spin* of electrons



Datta & Das, *Appl. Phys. Lett.* (1990)

Proposed "spin transistor"

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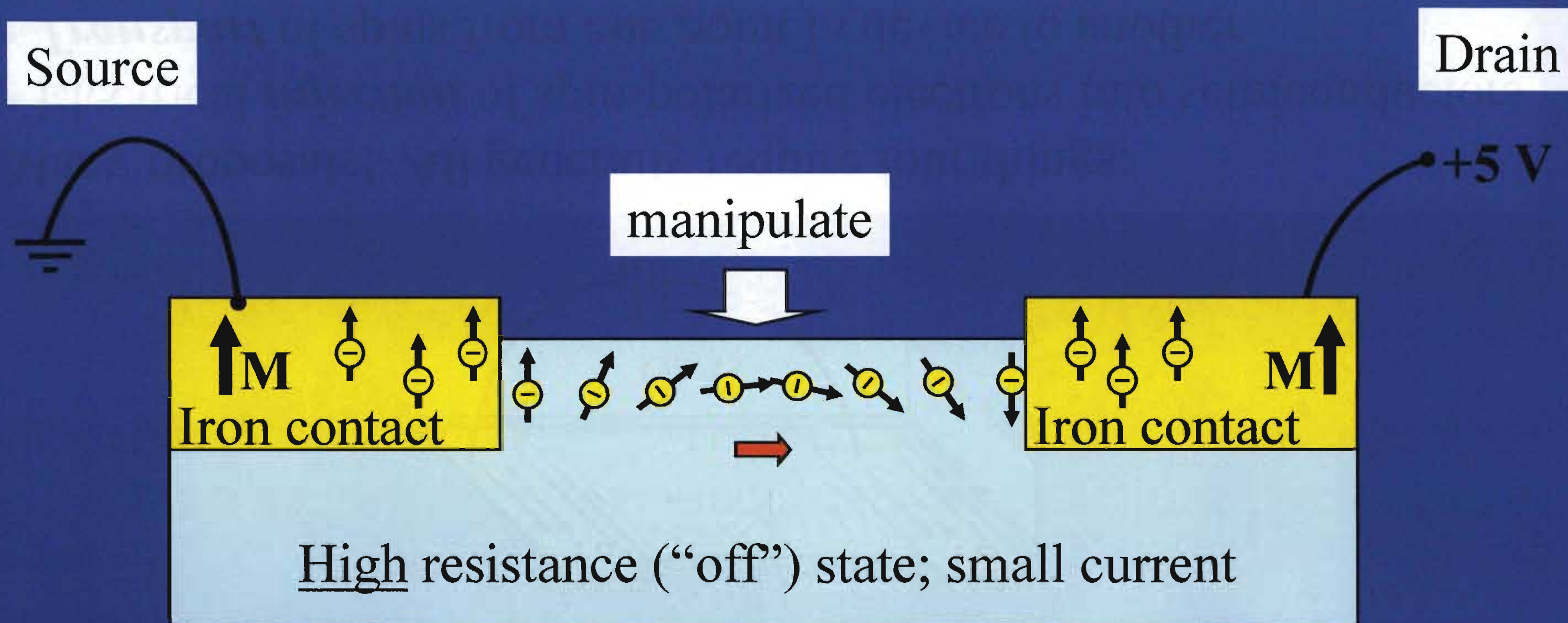
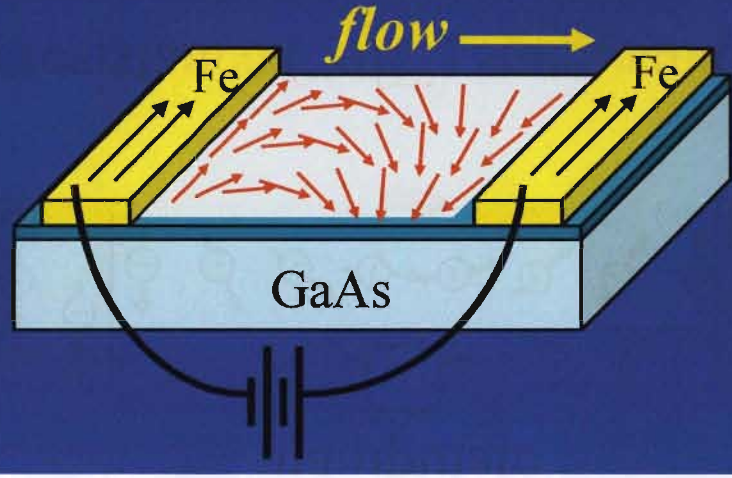


Datta & Das, *Appl. Phys. Lett.* (1990)

Imaging spin currents for spintronic applications



Many proposals! All generally require four things:

- Electrical ***injection*** of spin-polarized electrons into semiconductors
- ***Transport*** of spins from one point in device to another
- Means to ***manipulate*** spins w/ external fields (***B***, ***E***, strain, ??)
- Electrical ***detection*** of spin-polarized currents

Our goal: Image these processes via optical techniques

NHMFL

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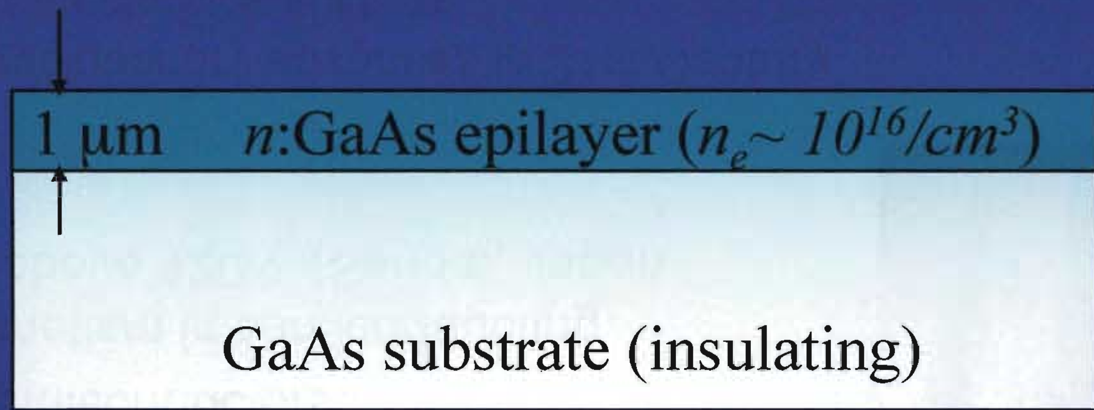
Samples : *n*-type (electron-doped) bulk GaAs



- Silicon doped (*n*~ 10^{16} /cm^3)
- Diffusive transport (not ballistic)
- Long spin lifetime: τ_{spin} ~120 ns

Spins IN Semiconductors

New Direction-SPINS

- Two recent discoveries
  - Optically Induced long lived coherent spin state in semiconductors
  - Ferromagnetism in semiconducting GaMnAs above 120K (Sendai, Japan 1998)

- Will lead to revolutionary advances in 21st Century photonics and electronics such as:
  - Very high performance opto-electronic devices
  - Very fast, very dense memory and logic at extremely low power
  - Spin quantum devices like Spin-FETs, Spin LEDs and Spin RTDs
  - **Quantum computing in conventional semiconductors at room temperature**
  - Many other applications that we can't even envision now

Why semiconductors are better

Bloch Wilson

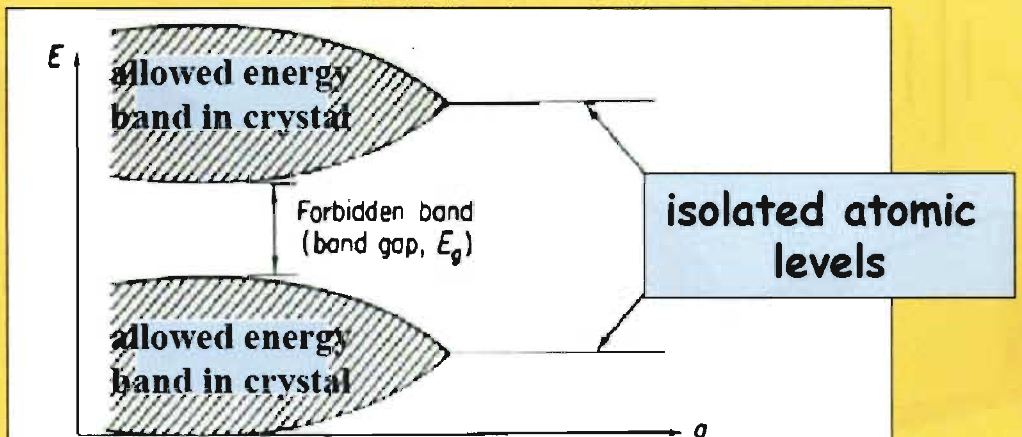


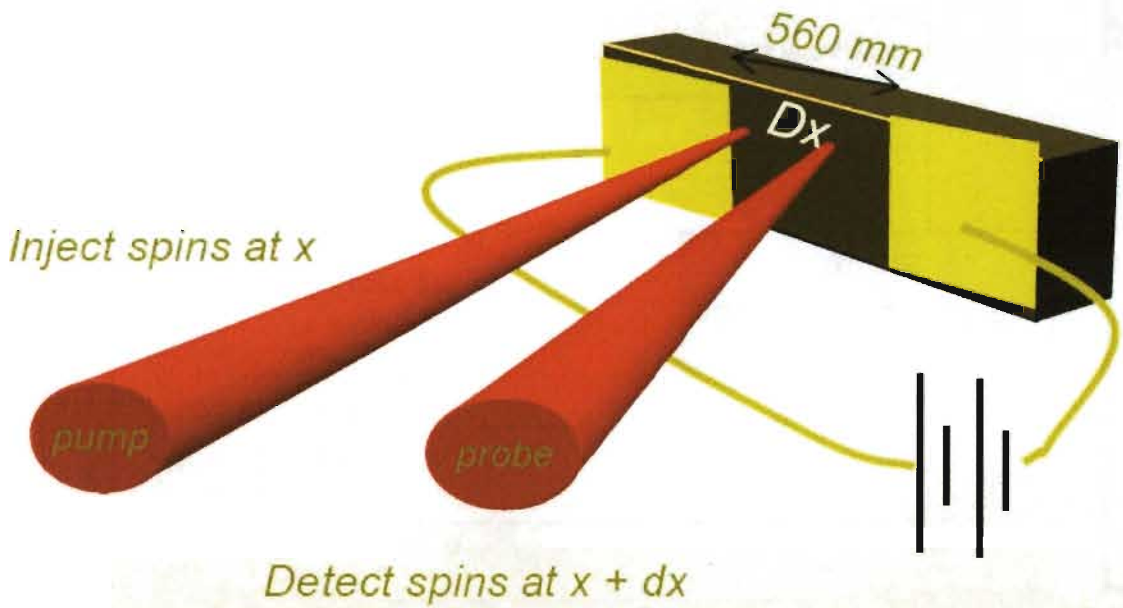
Figure 5.1 The spreading of discrete atomic levels into bands in a crystal, as function of interatomic separation, *a*.

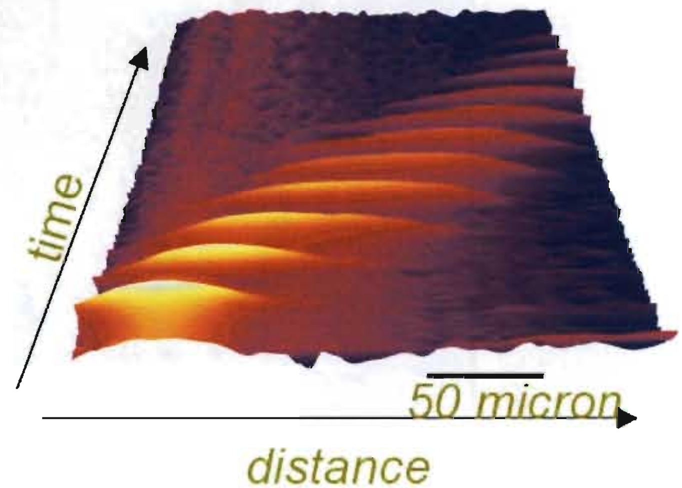
Semiconductors are interesting because their properties are sensitive to impurities and to charges on external gates; they can be engineered

Pauli 1931: "One shouldn't work with semiconductors, that is a filthy mess; who knows whether they really exist"

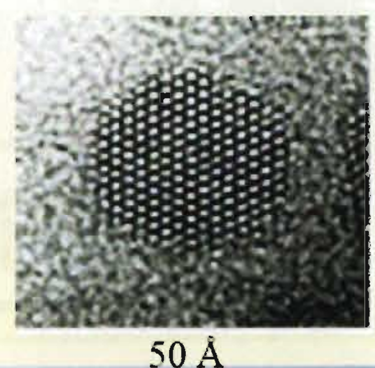
Injection and Motion of Coherent Spins in Semiconductors

- Spin coherence persists for 100s of nanoseconds over 100s of microns
- Largely insensitive to temperature



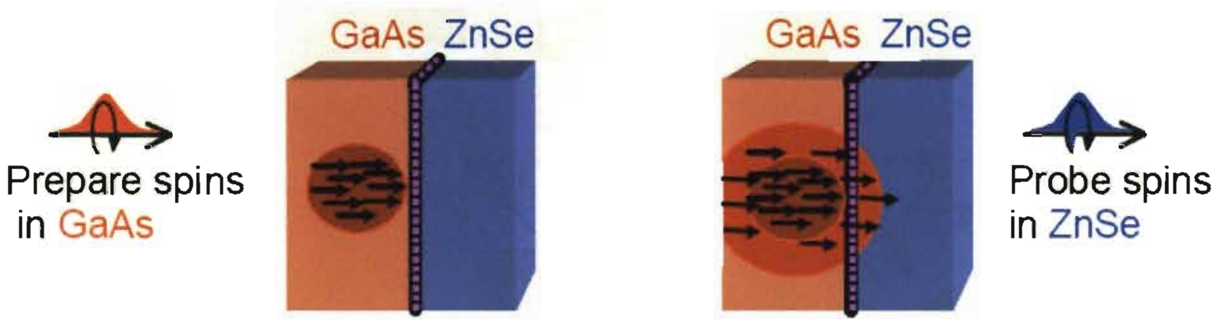


- *Spin coherence also demonstrated in CdSe Quantum Dots*
- *Room temperature operation with nanosecond lifetimes*

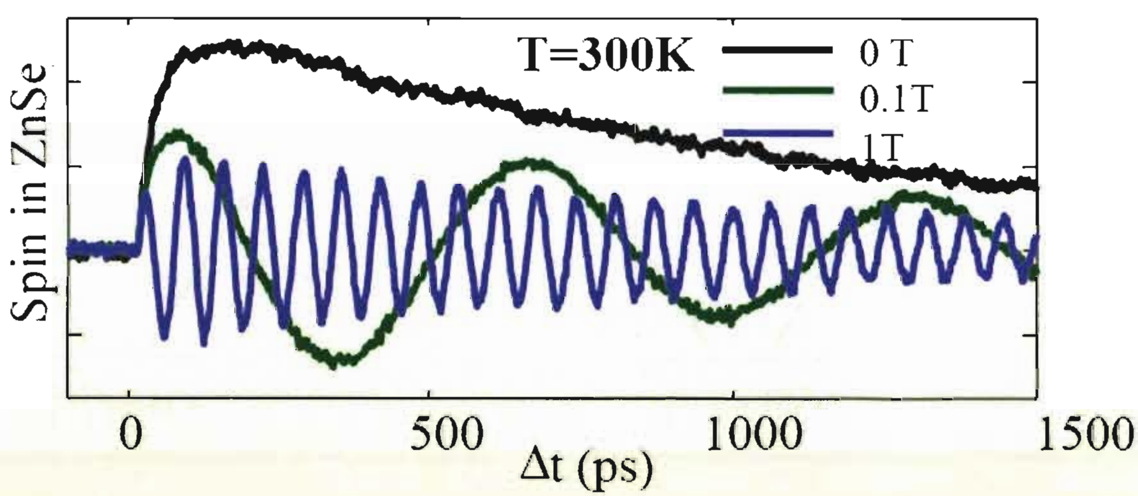


Enabler for Quantum Computation

Spin Transfer Through Heterointerfaces

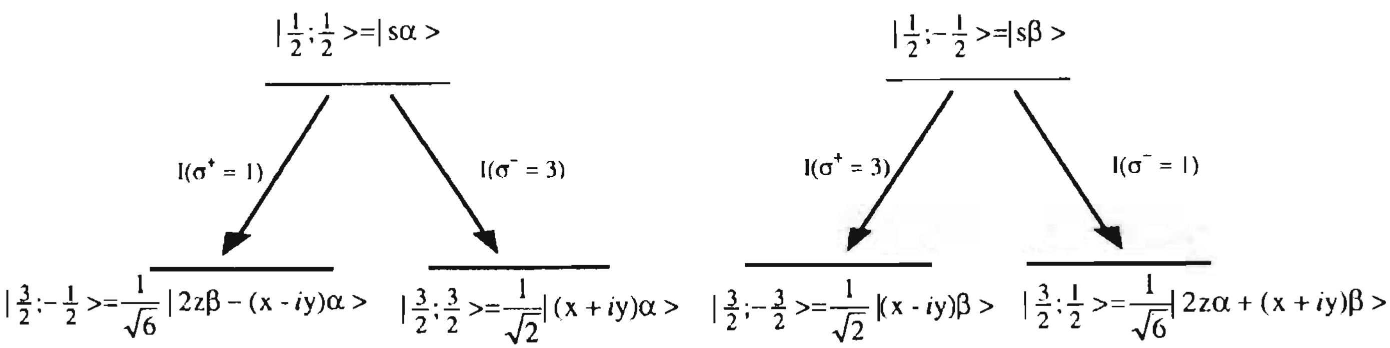


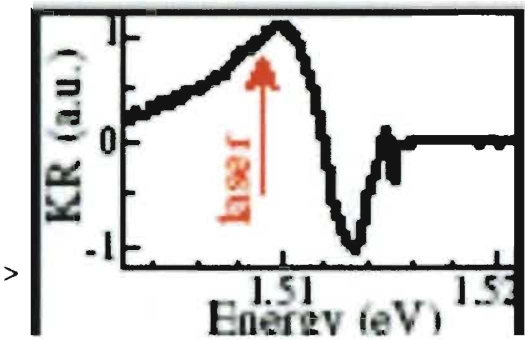
- Flow of coherent information across a heterointerface with dissimilar materials with very little scattering

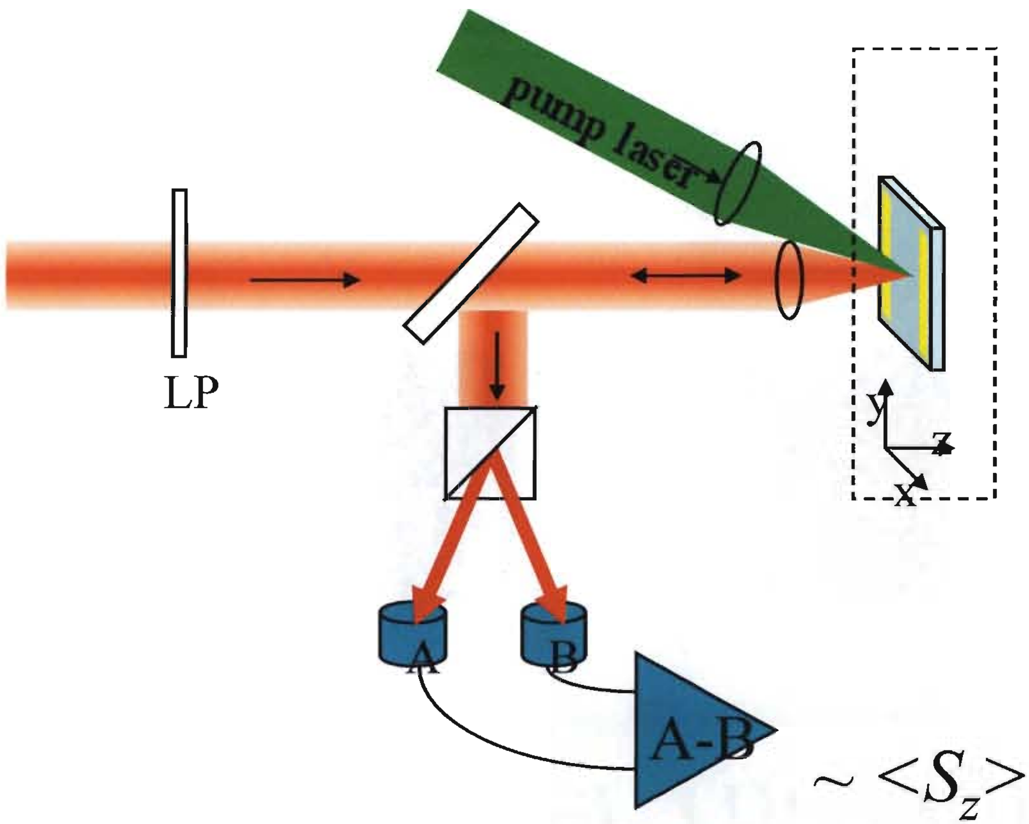


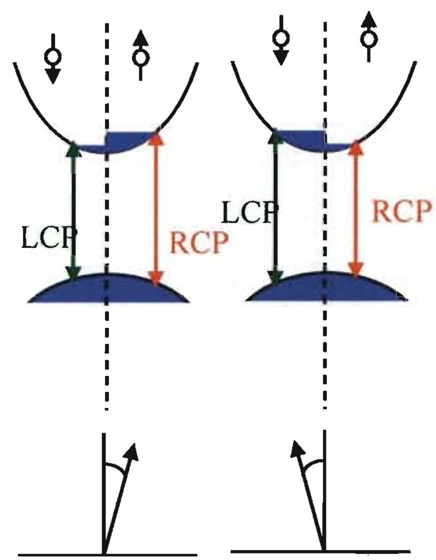
UCSB

Spin Dependent Optical Probes - Inorganic Semiconductors









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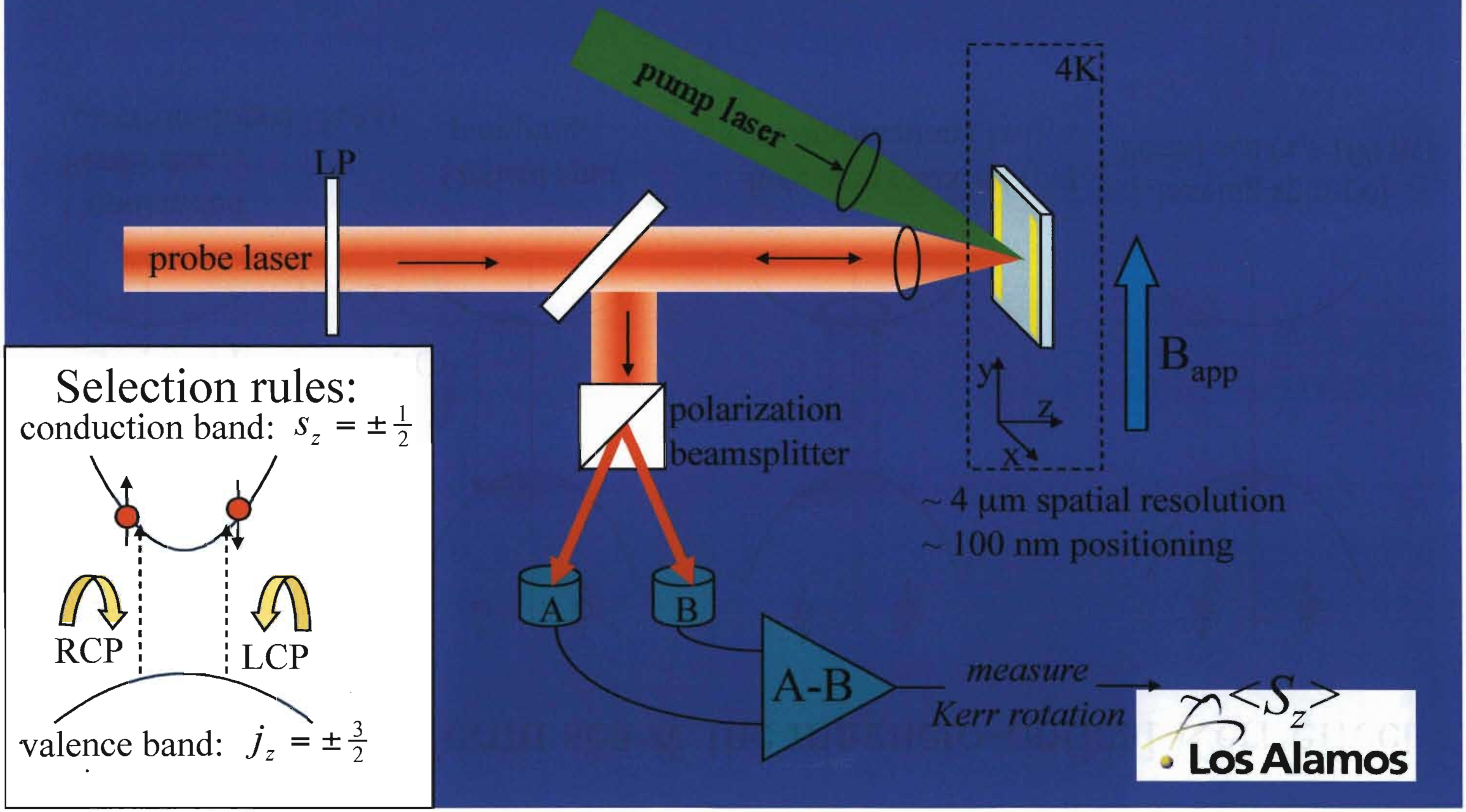
Scanning Kerr-rotation microscopy

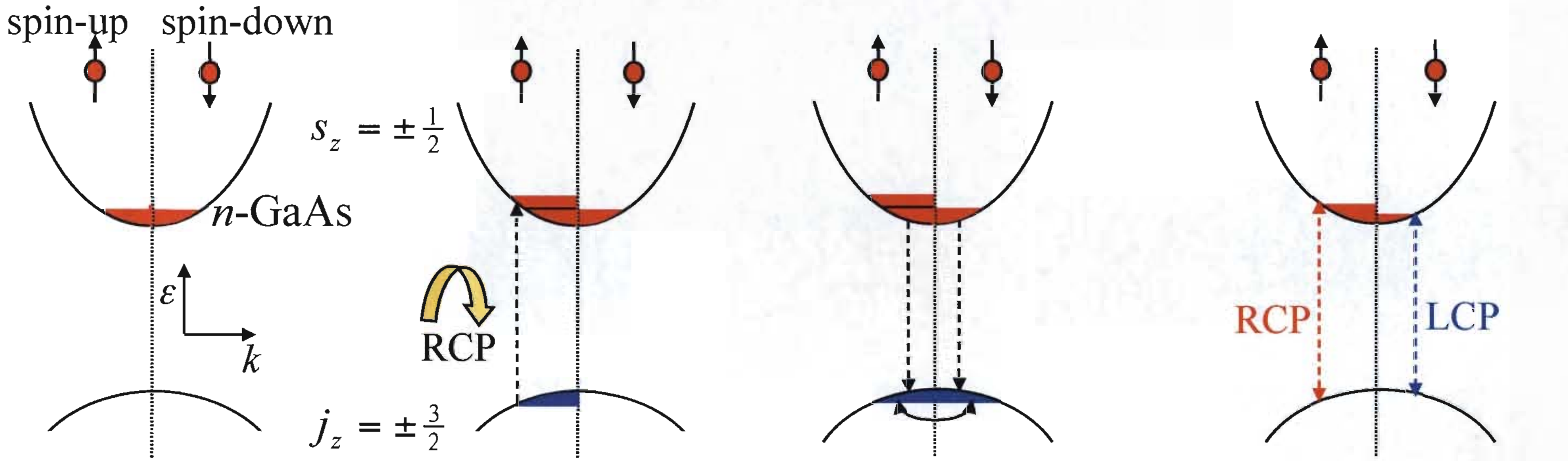
2-D imaging of drift & diffusion of electron spins in semiconductors

Optically *inject* spin polarized electrons (& holes) with circularly polarized pump laser (785 nm)

Optically *detect & map* electron spin polarization (S_z) via Kerr effect (~820 nm)



Spin-polarized Fermi sea & the magneto-optical Kerr effect

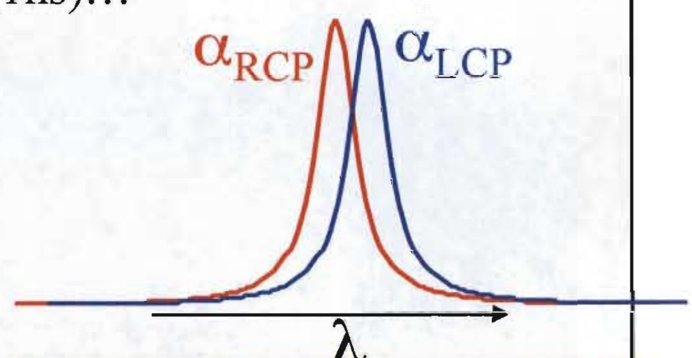


Unpolarized Fermi sea… (electron-doped GaAs)

Optical spin pumping…

…hole spin relax'n (1ps) + recombination (1ns)…

…leaving spin-pol Fermi sea (τ_s>100 ns)



Circular dichroism: ⇨ Kerr rotation ($\sim S_z$) at GaAs bandgap

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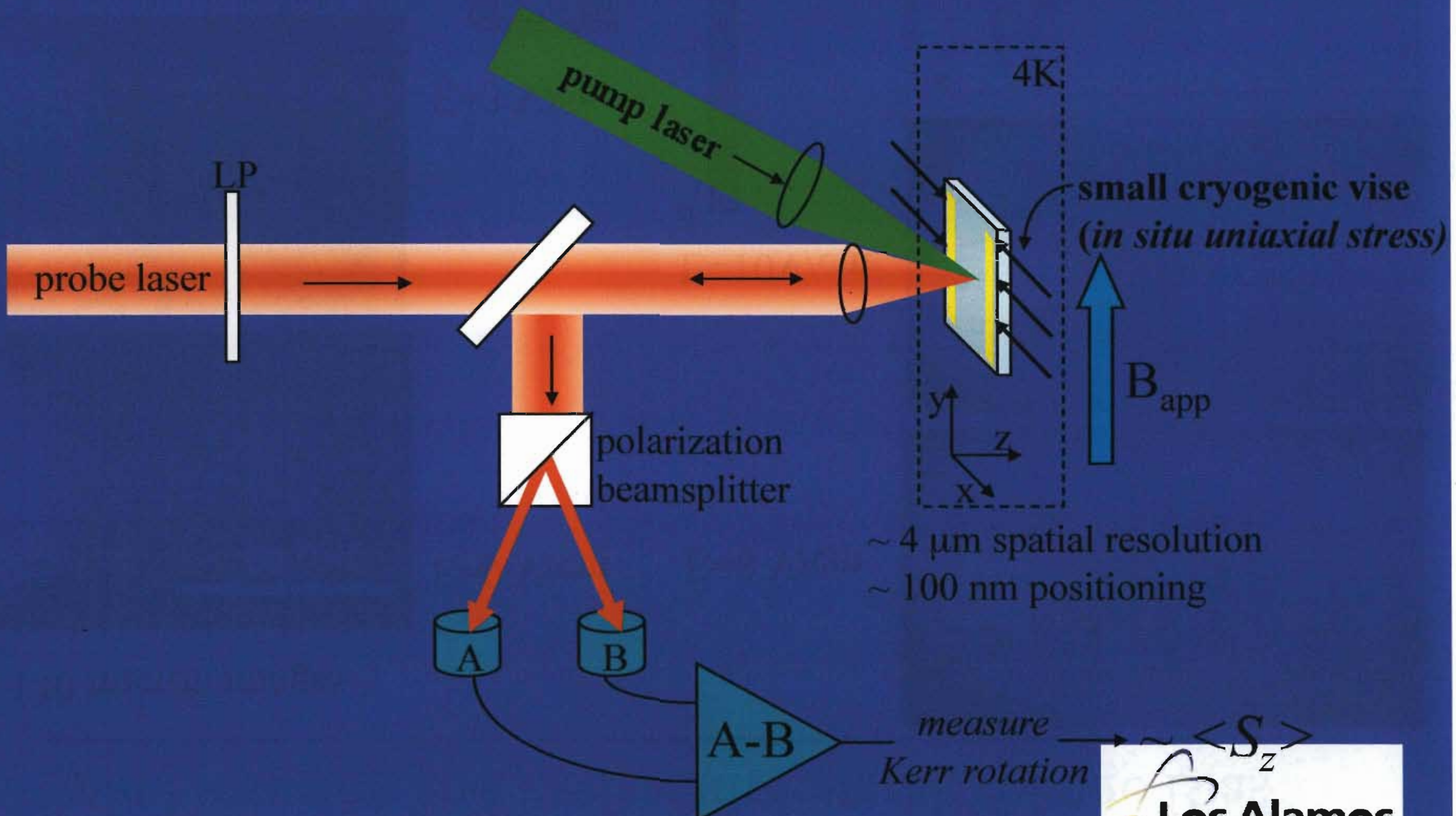

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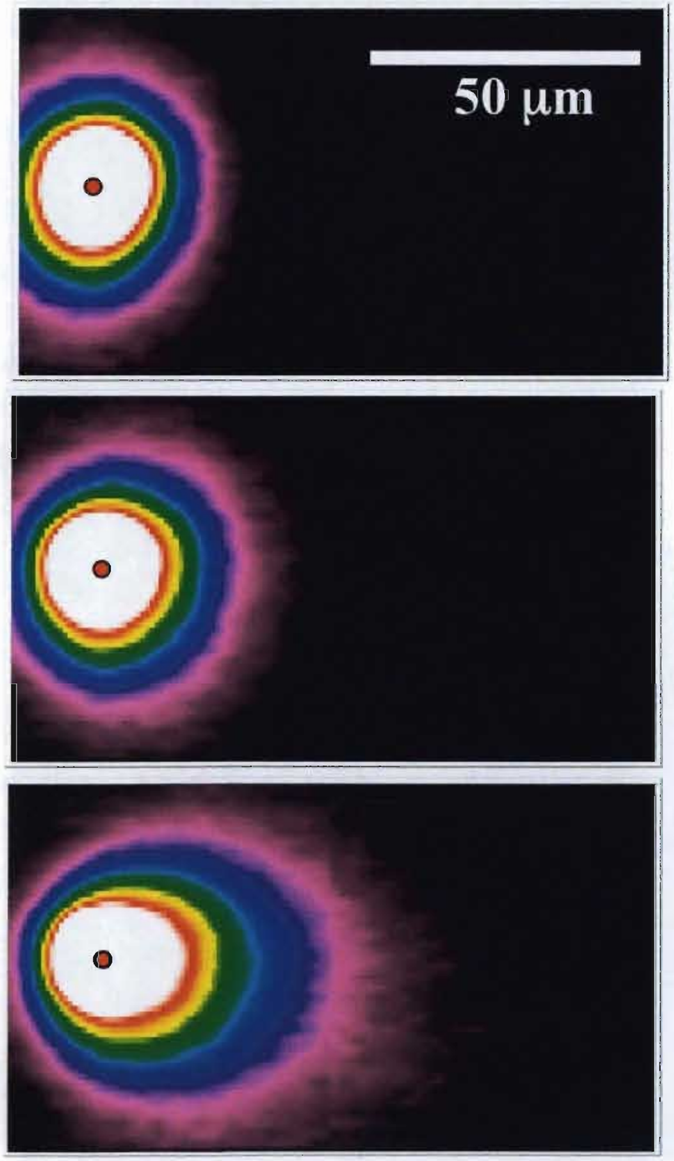
Spin Diffusion and Drift with Lateral Voltage Bias

70 x 140 micron images



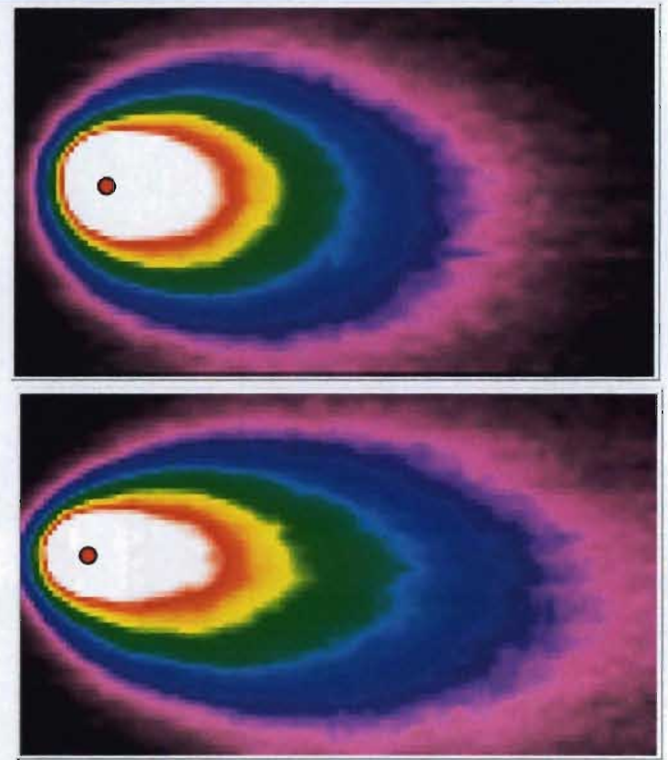
E=0 V/cm

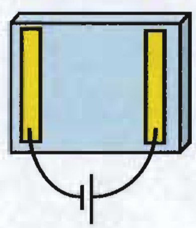
E=3 V/cm

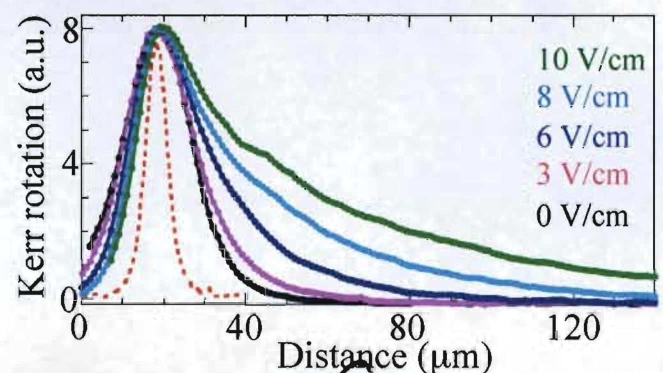
E=6 V/cm

E=8 V/cm

E=10V/cm







S. A. Crooker & D. L. Smith
PRL **94**, 236601 (2005)

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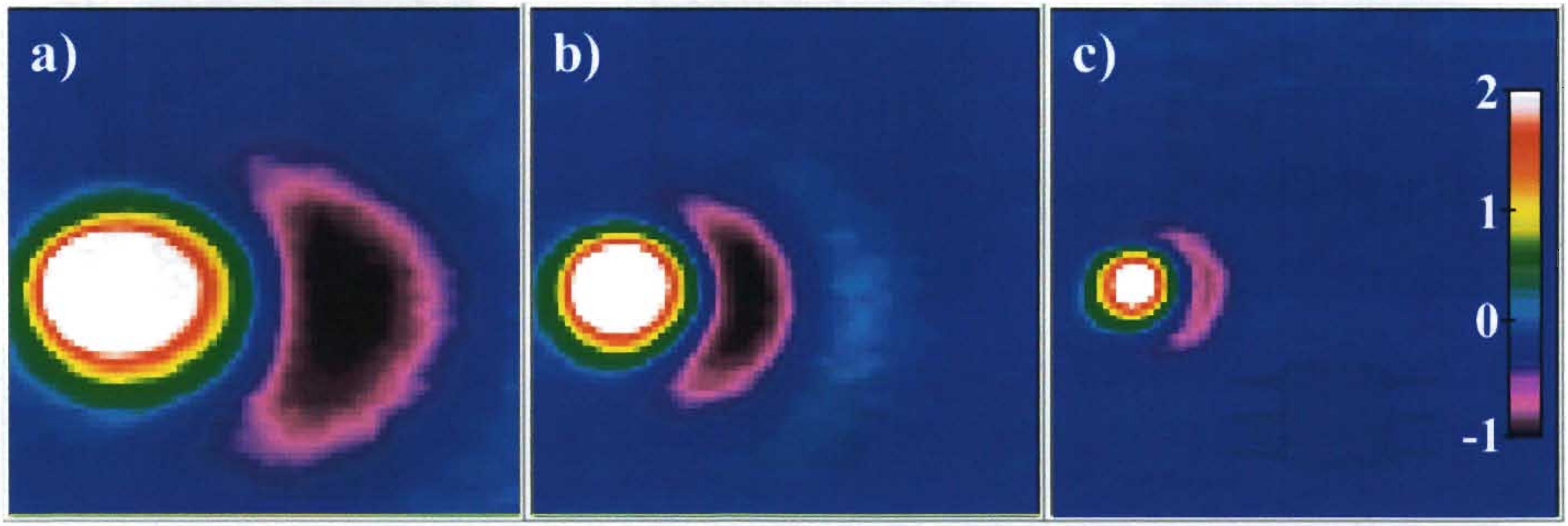
Electron Spins Precess in an Applied Magnetic Field

$$H_B \propto \vec{\sigma} \cdot \vec{B}$$



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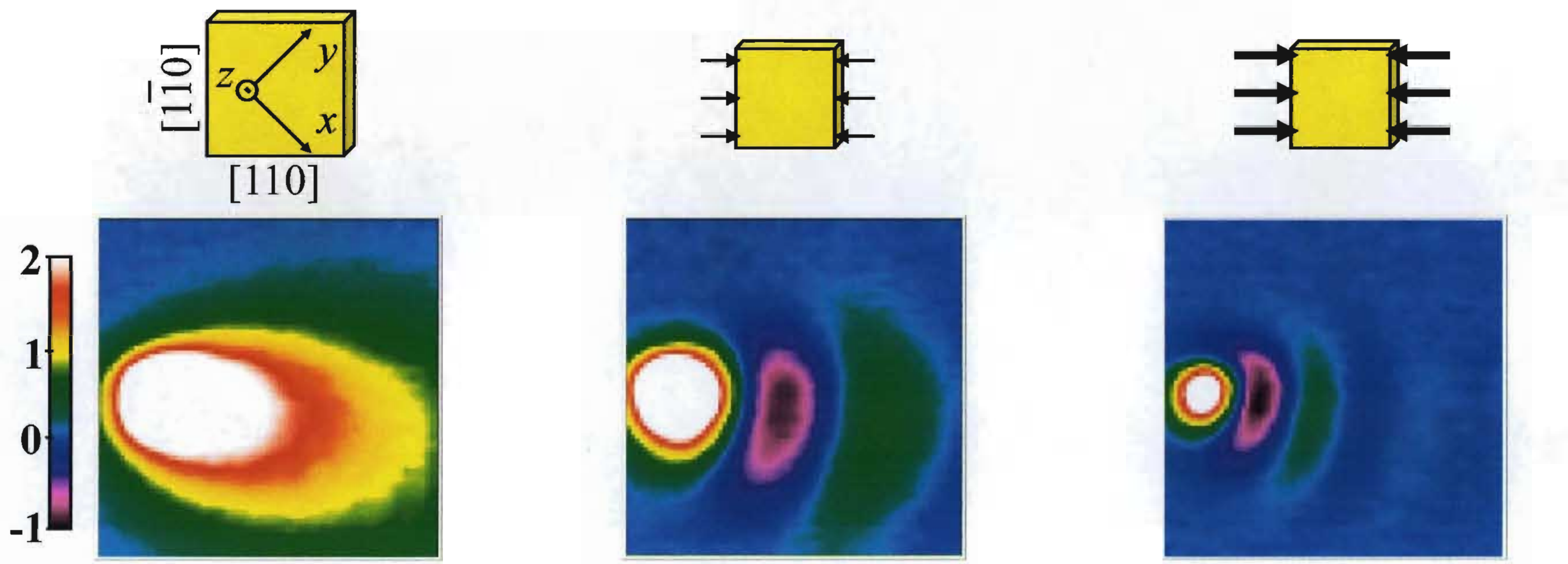
Electron Spins Also Presess in a Uniaxial Strain Field



$$H_{strain} \propto \vec{\sigma} \cdot \begin{bmatrix} \varepsilon_{xy}k_y - \varepsilon_{xz}k_z \\ \varepsilon_{yz}k_z - \varepsilon_{yx}k_x \\ \varepsilon_{zx}k_x - \varepsilon_{zy}k_y \end{bmatrix}$$

For electrons moving in x-y plane
stress applied along [110]

$$H_{strain} \propto \varepsilon_{xy}(\sigma_x k_y - \sigma_y k_x)$$

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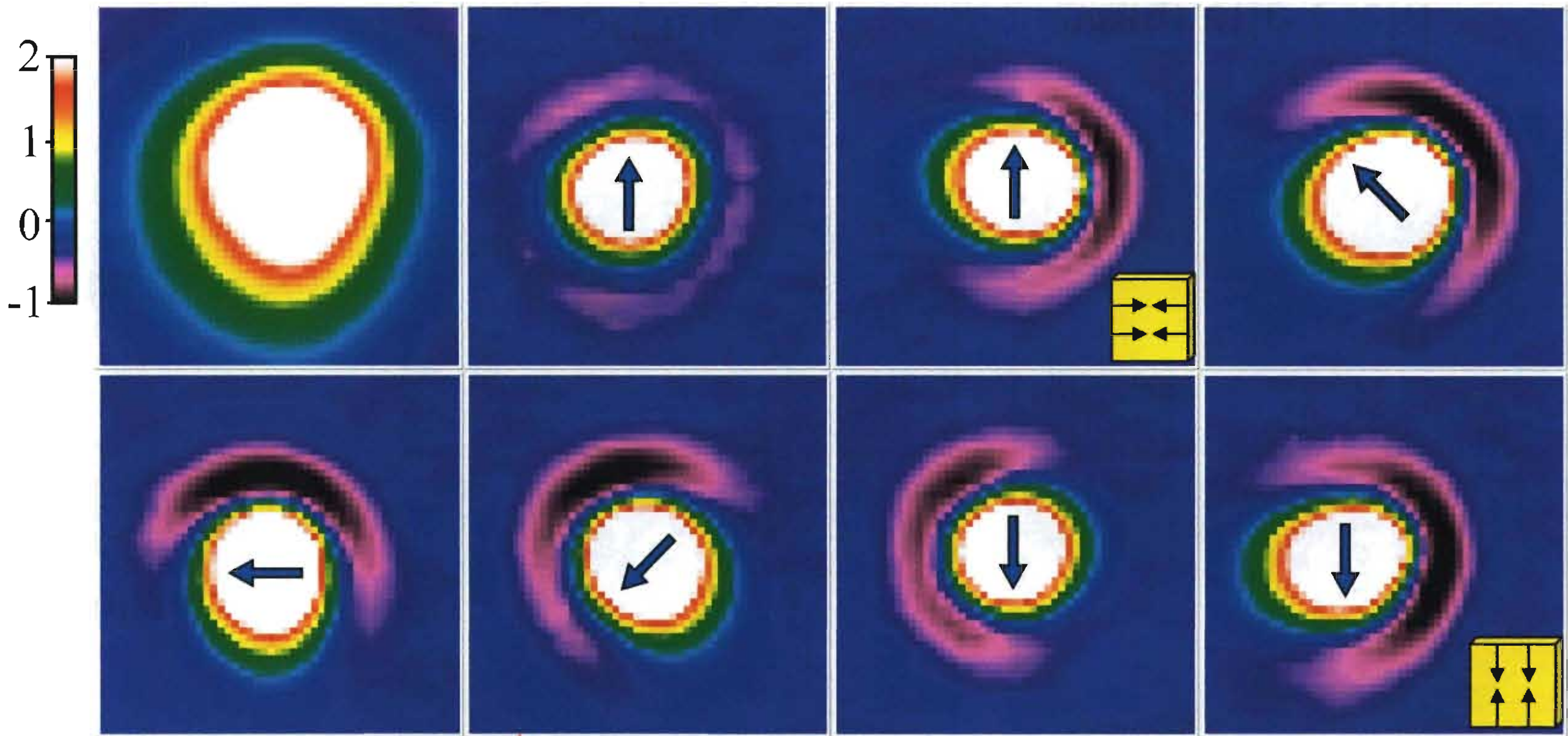
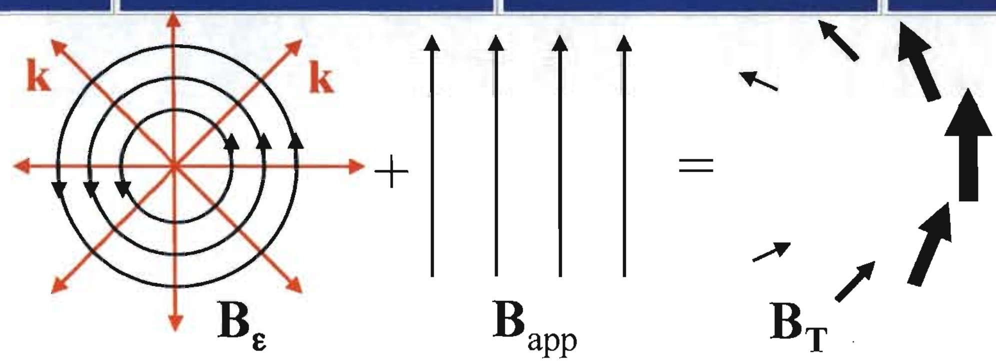
Combined Magnetic and Strain Fields

B_ε is chiral for radially-diffusing spins





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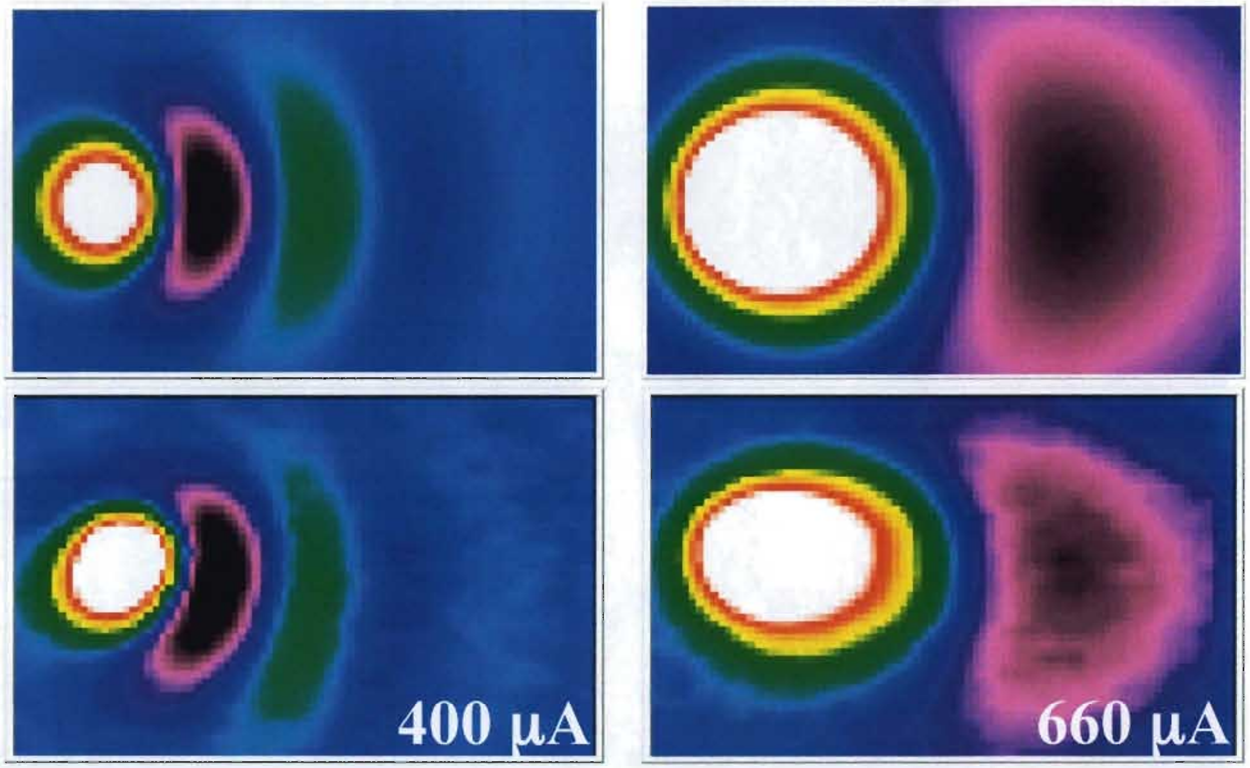
Modeling Spin Drift-Diffusion

Simulation:

Data:



Strain

Magnetic Field

M. Hruska, S. Kos, S. A. Crooker, A. Saxena, D. L. Smith, Phys. Rev. **B73**, 75306 (2006)

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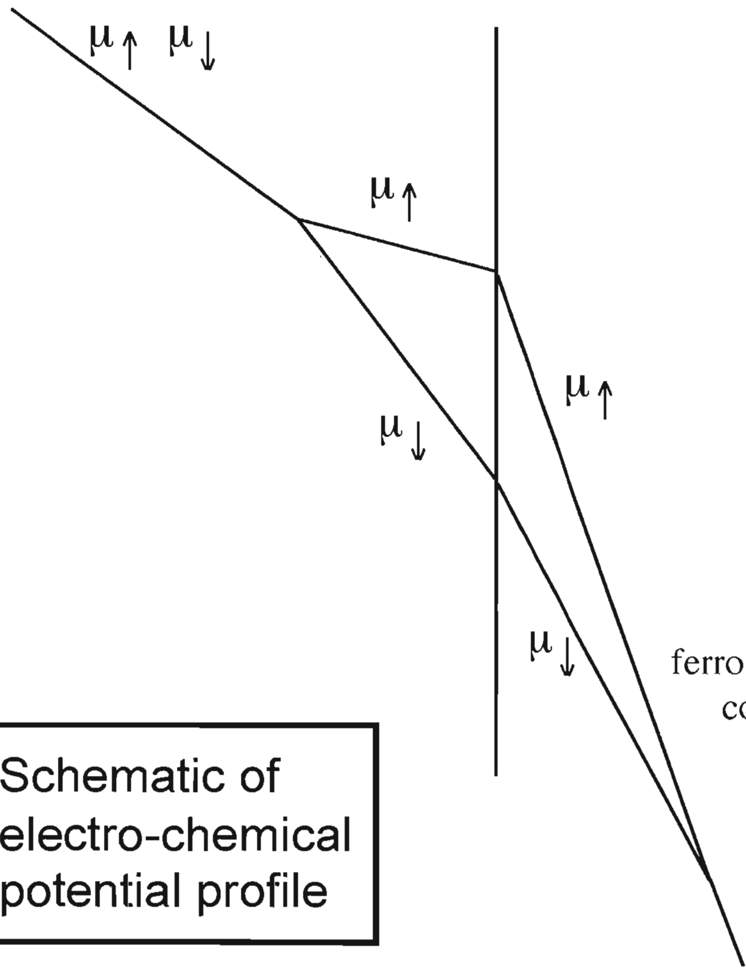
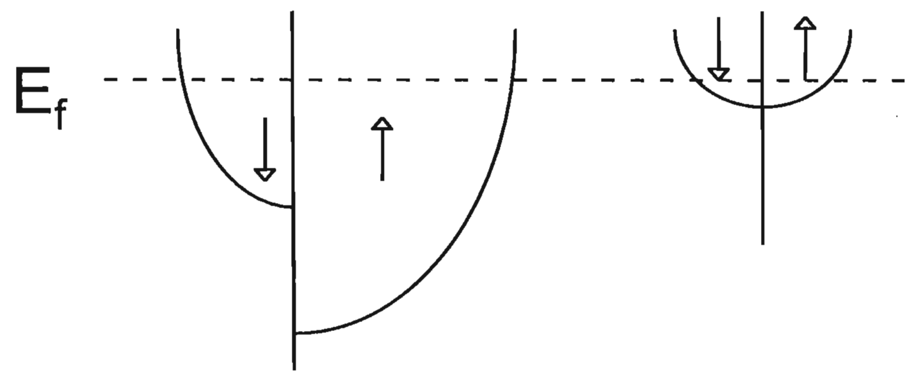
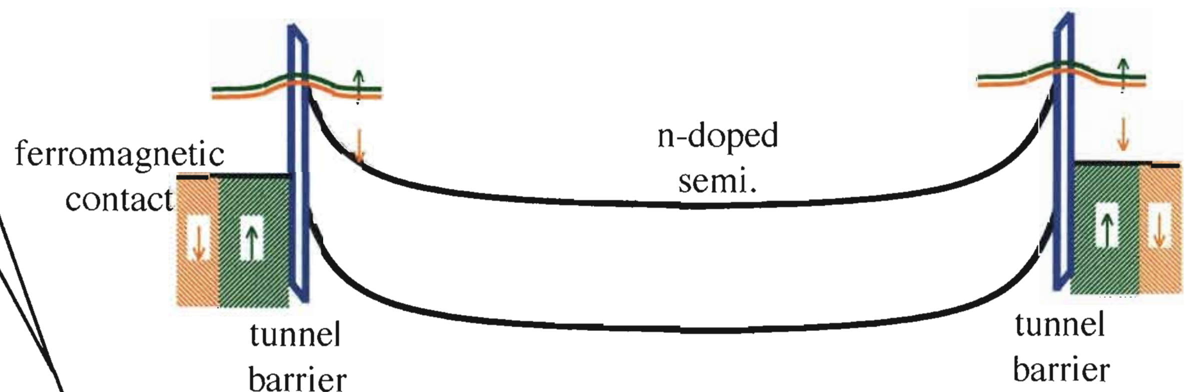
Electrical Injection and Detection of Spin Currents

Polarized Contact | Semiconductor | Polarized Contact | Semiconductor







Schematic of electro-chemical potential profile

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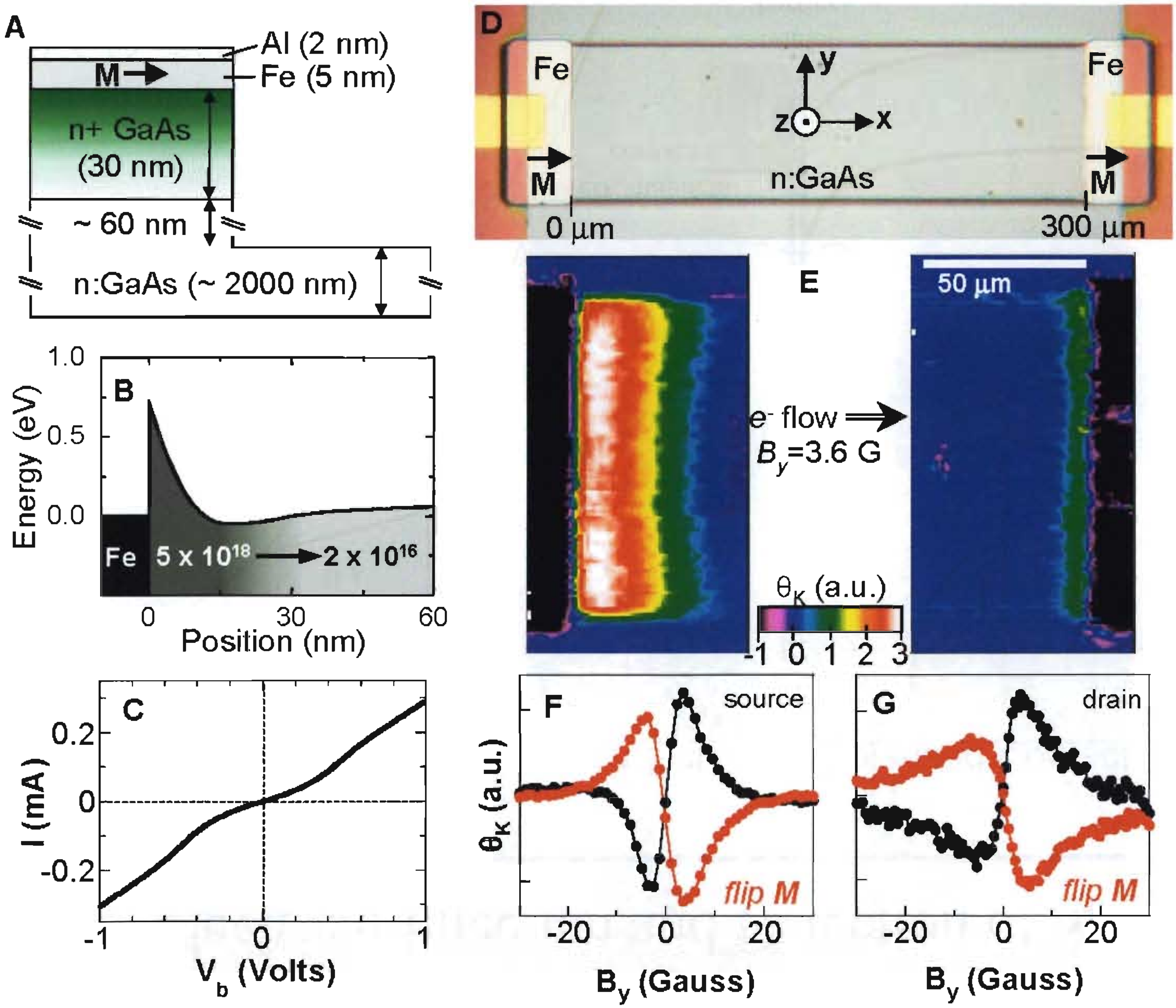
An Observation of Electrical Spin Injection Fe/GaAs



S. A. Crooker,
M. Furis,
X. Lou,
C. Adelmann,
D. L. Smith,
C. J. Palmstrøm,
P. A. Crowell

Science **309**, 2191
(2005)

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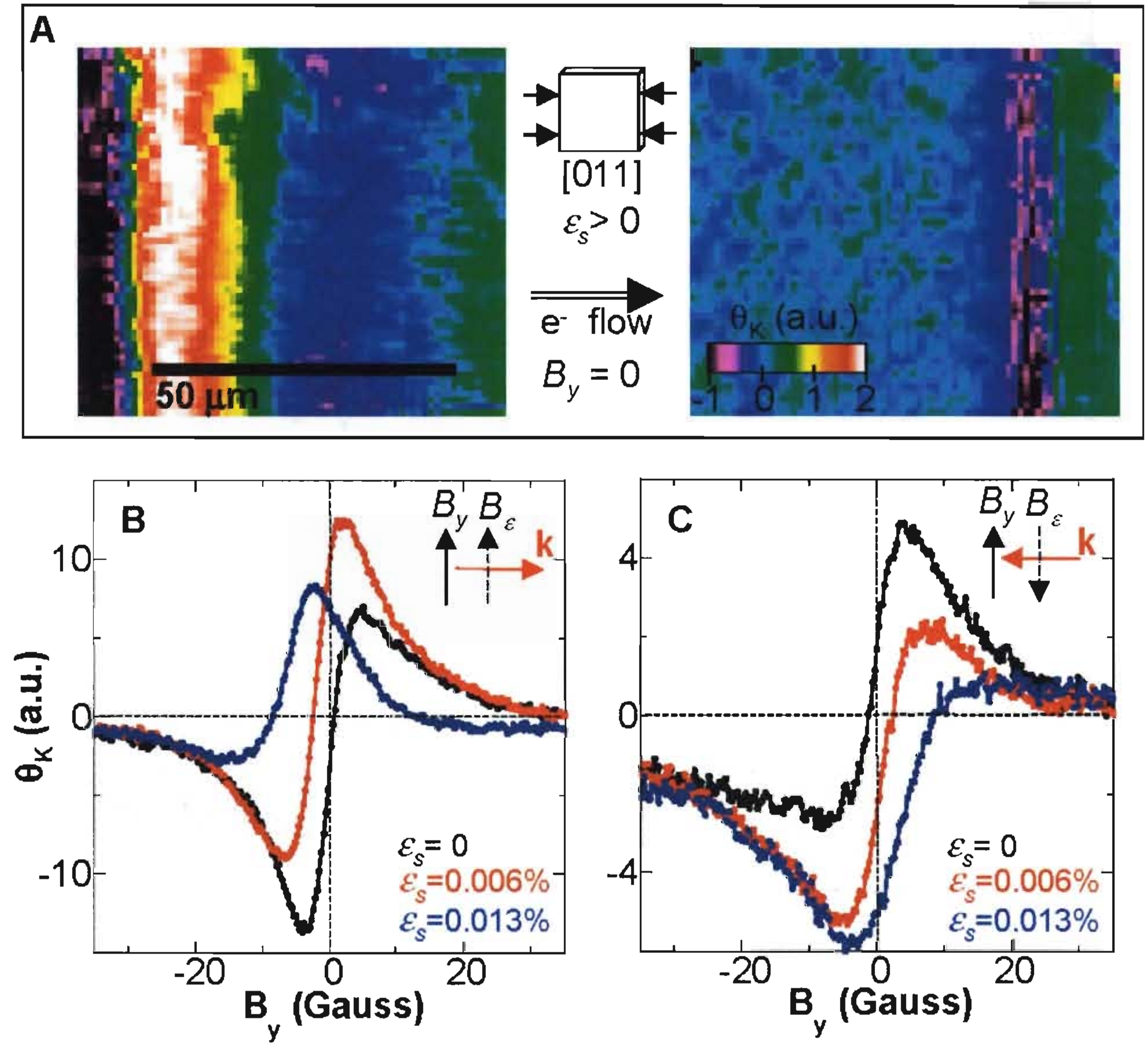
Response to Unixial Strain Determines Direction of Spin Current Flow



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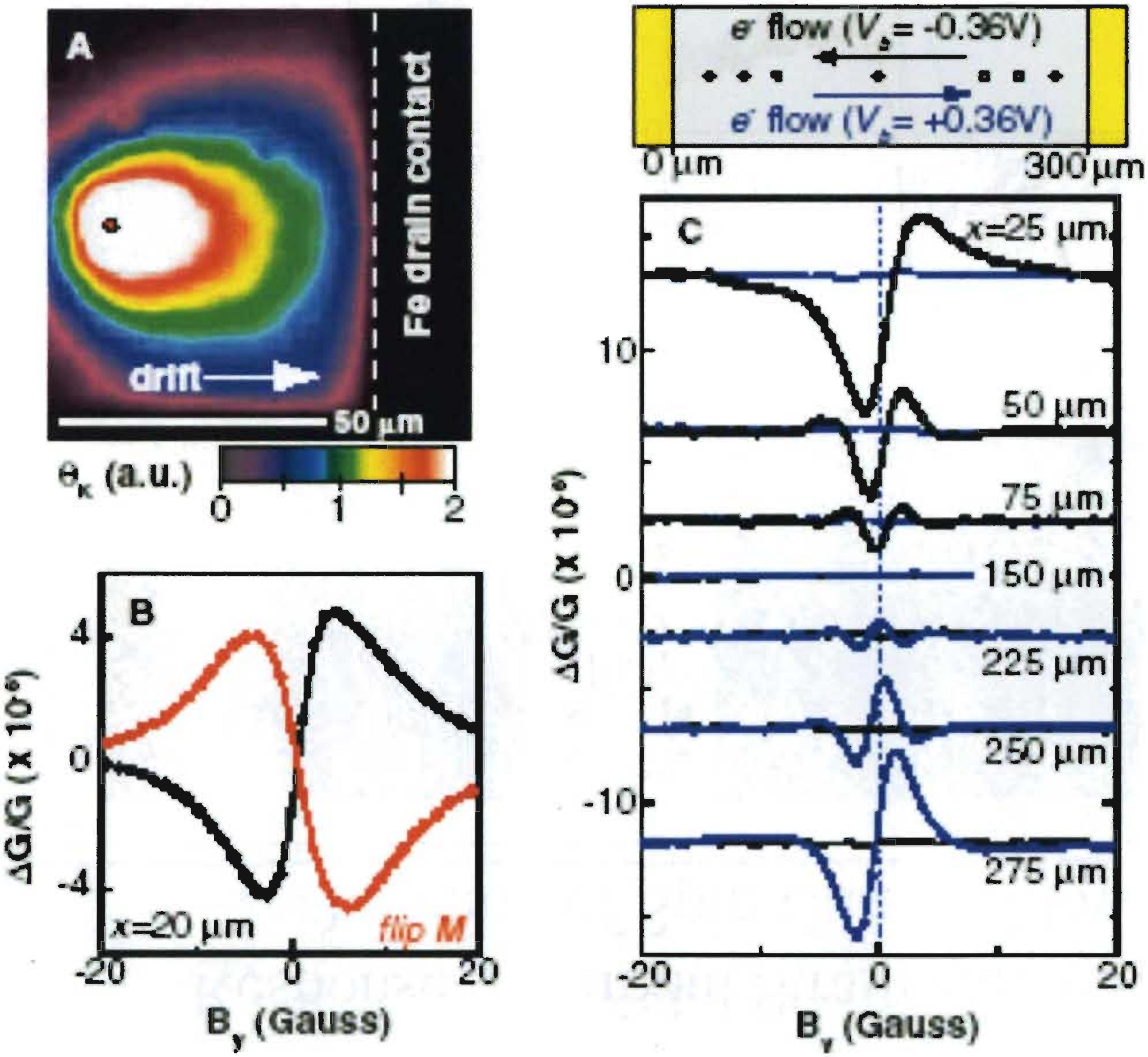
Spin Detection at Ferromagnetic Contacts



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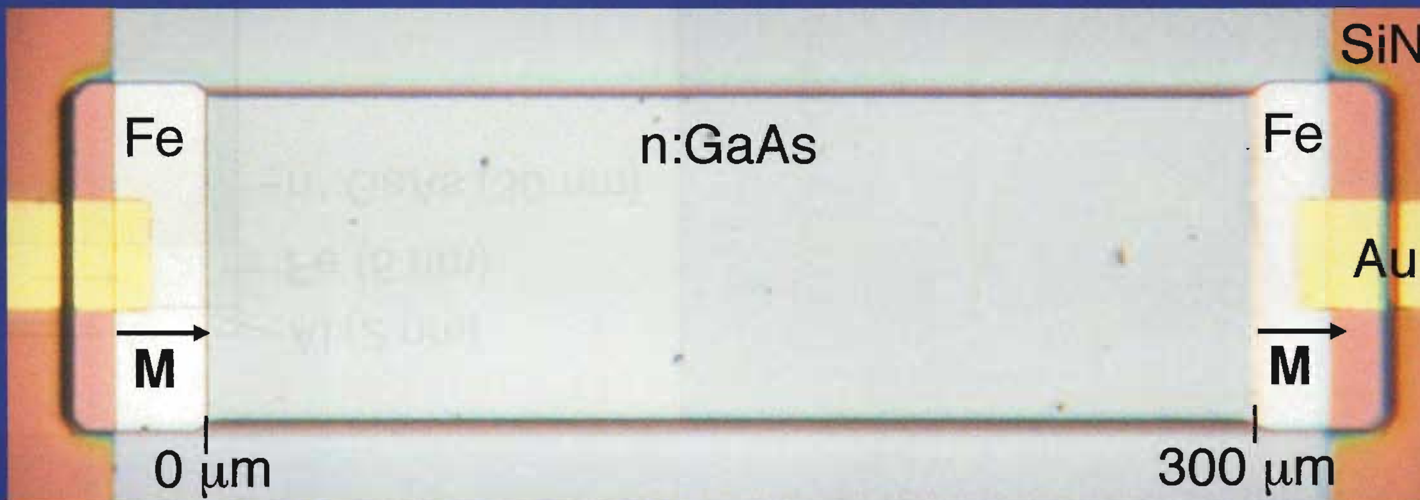
Ferromagnet-semiconductor lateral spin injection / transport / detection devices



-with C. Palmstrom and P. Crowell (U. Minnesota)

- Ferromagnetic source and drain contacts (Fe/GaAs tunnel barriers)
- Low-doped n:GaAs channel for long spin lifetimes, diffusion lengths
- Optical imaging reveals efficient spin injection and spin transport
- Accumulation of spins at drain contact

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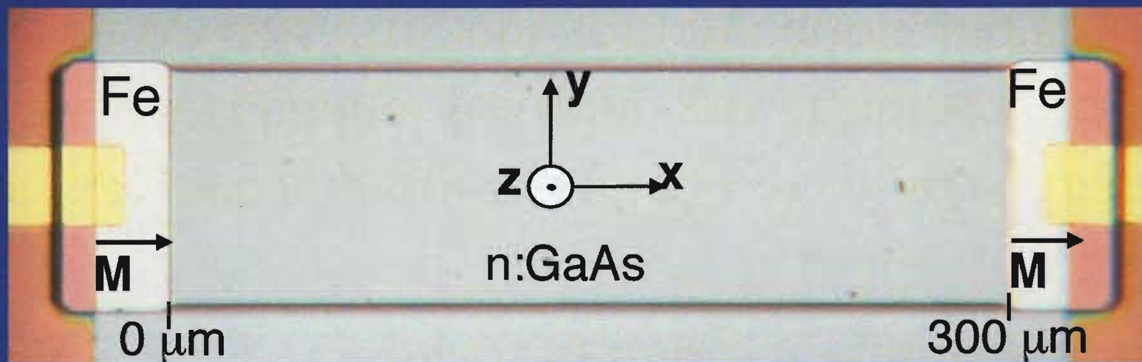
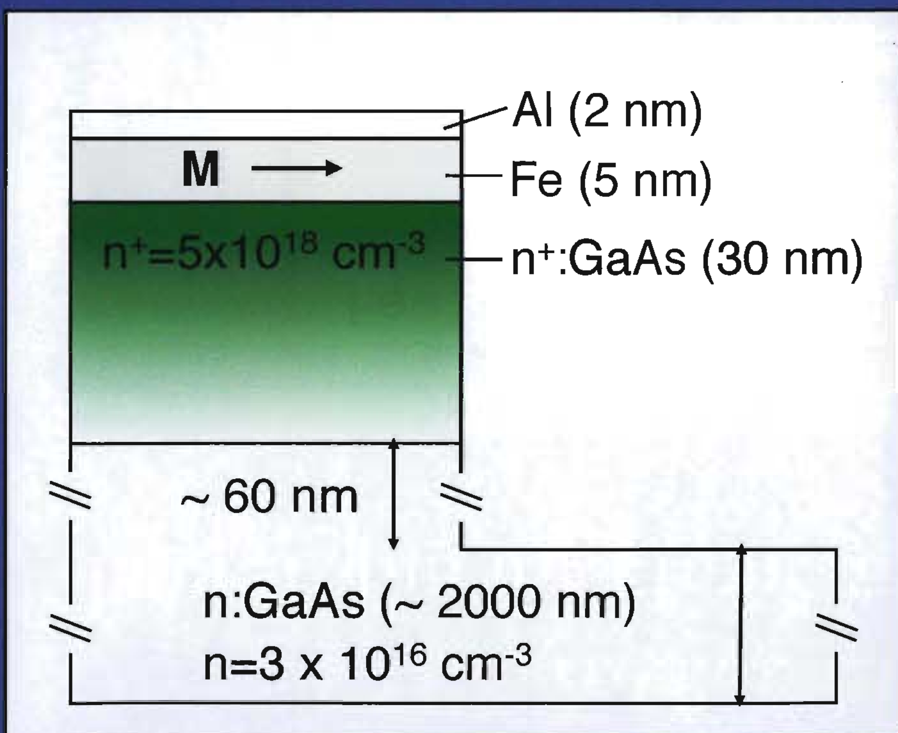
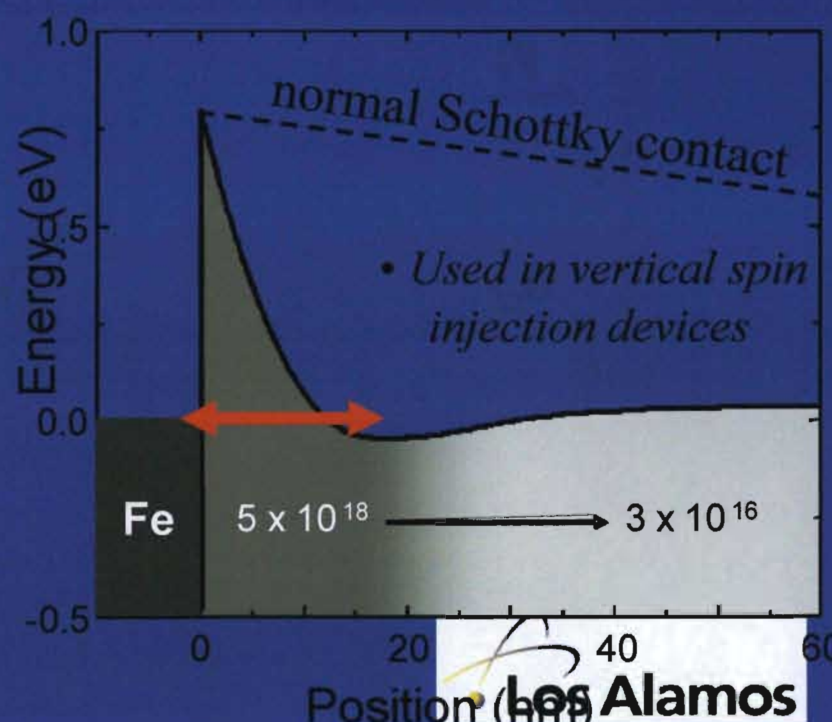
Fe/GaAs tunnel-barrier spin injectors



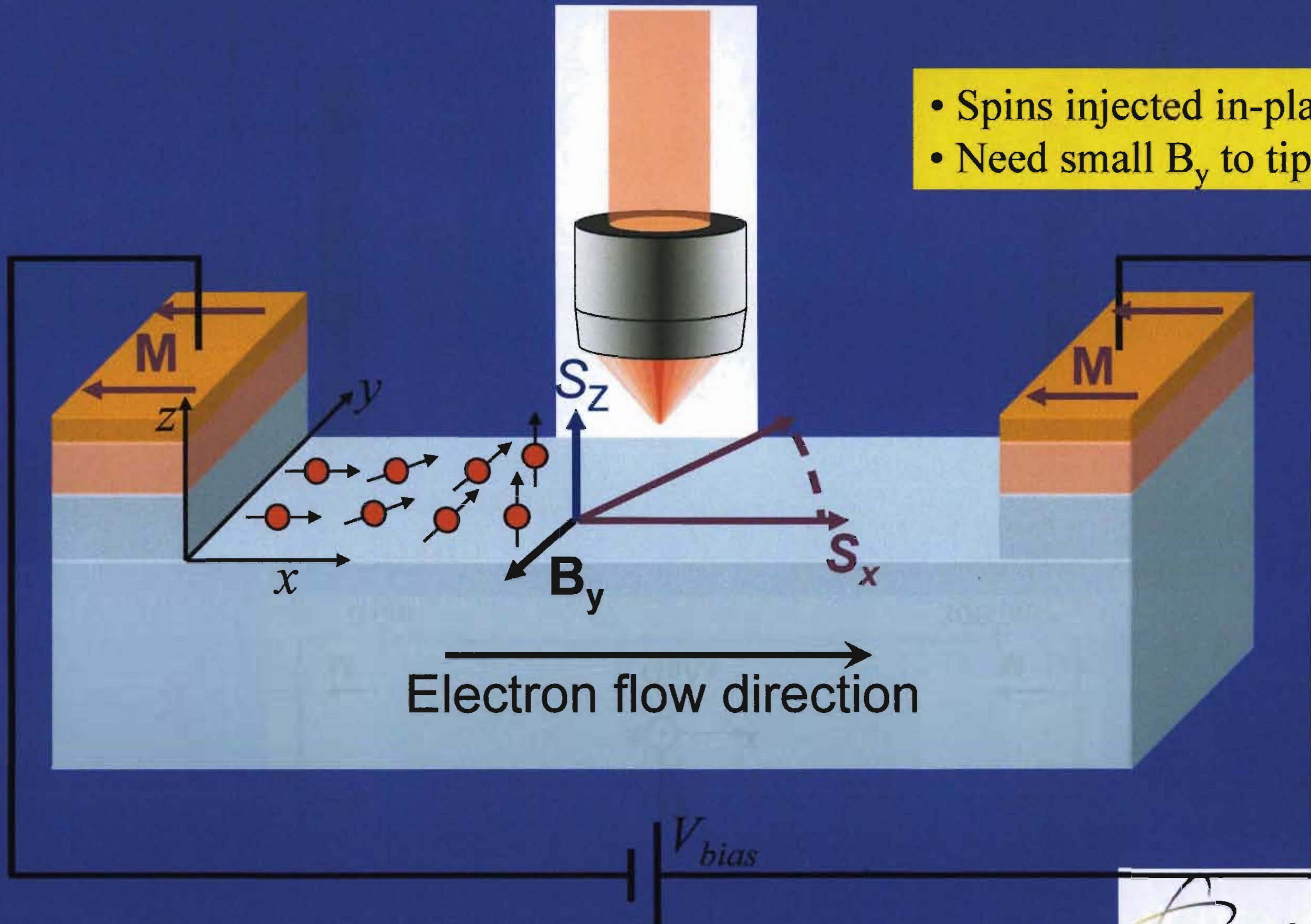
•Graded doping profile defines tunnel barrier [Hanbicki *et al.*, *APL* (2003)]





Imaging electrically-injected spin currents (scanning magneto-optical Kerr microscopy)

- Spins injected in-plane (S_x)
- Need small B_y to tip out (S_z)



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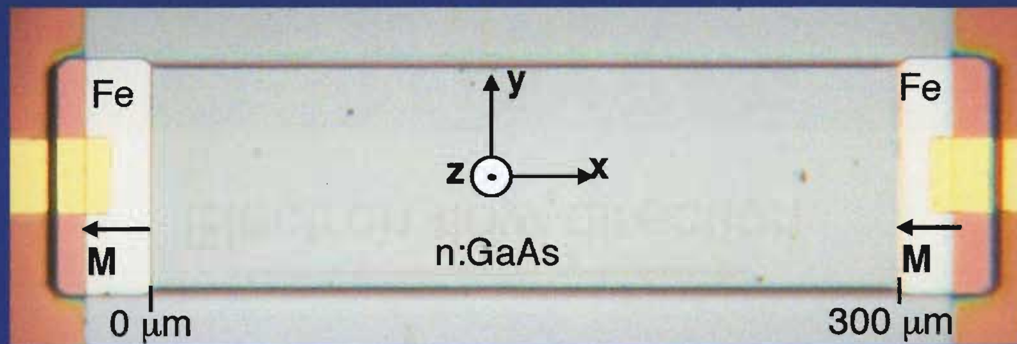
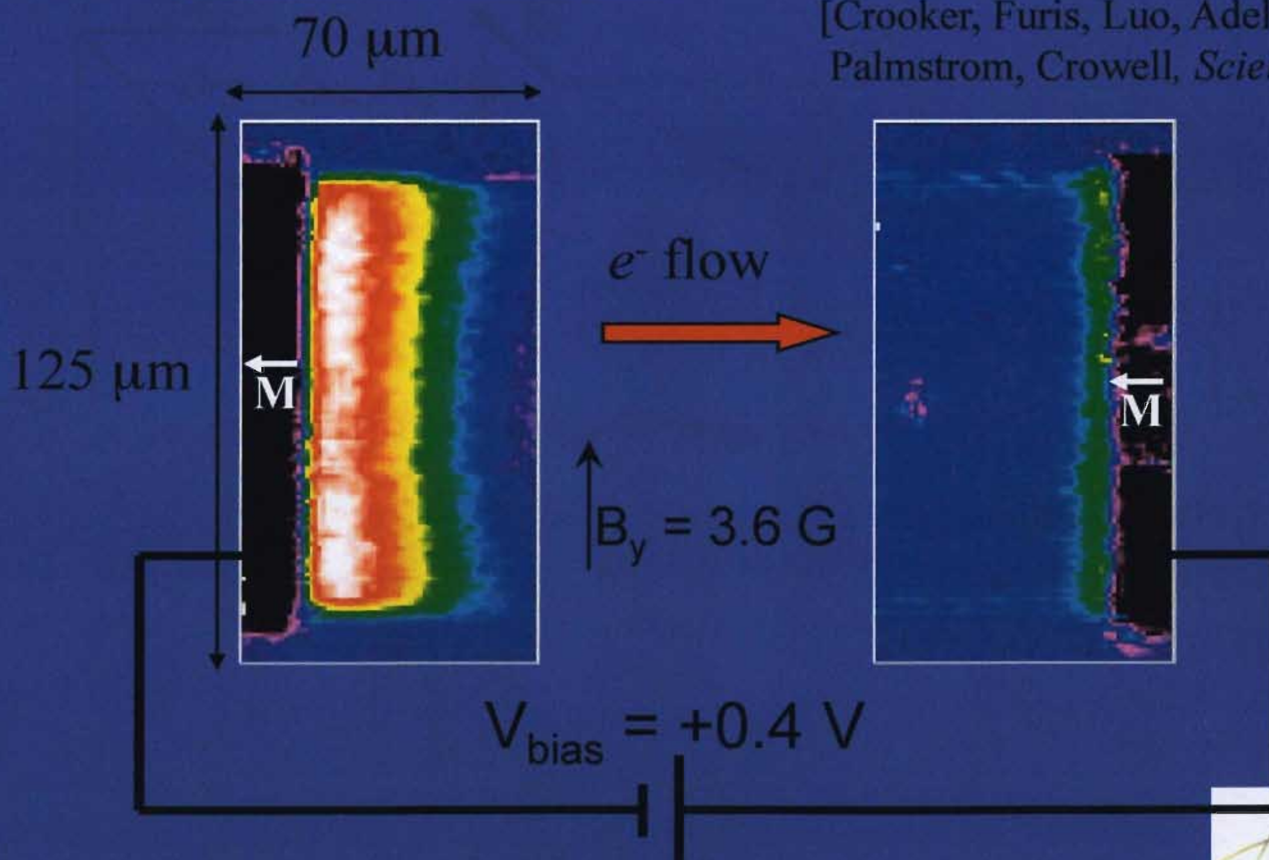
Imaging electrically-injected spin currents



[Crooker, Furis, Luo, Adelmann, Smith, Palmstrom, Crowell, *Science* ***309***, *2191 (2005)*]



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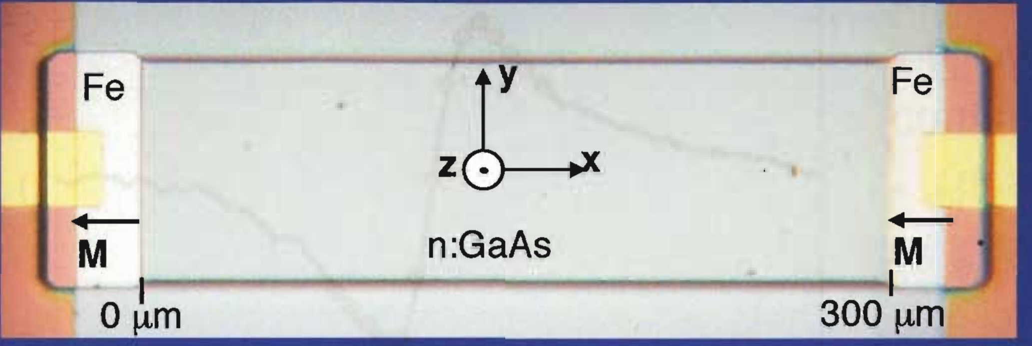
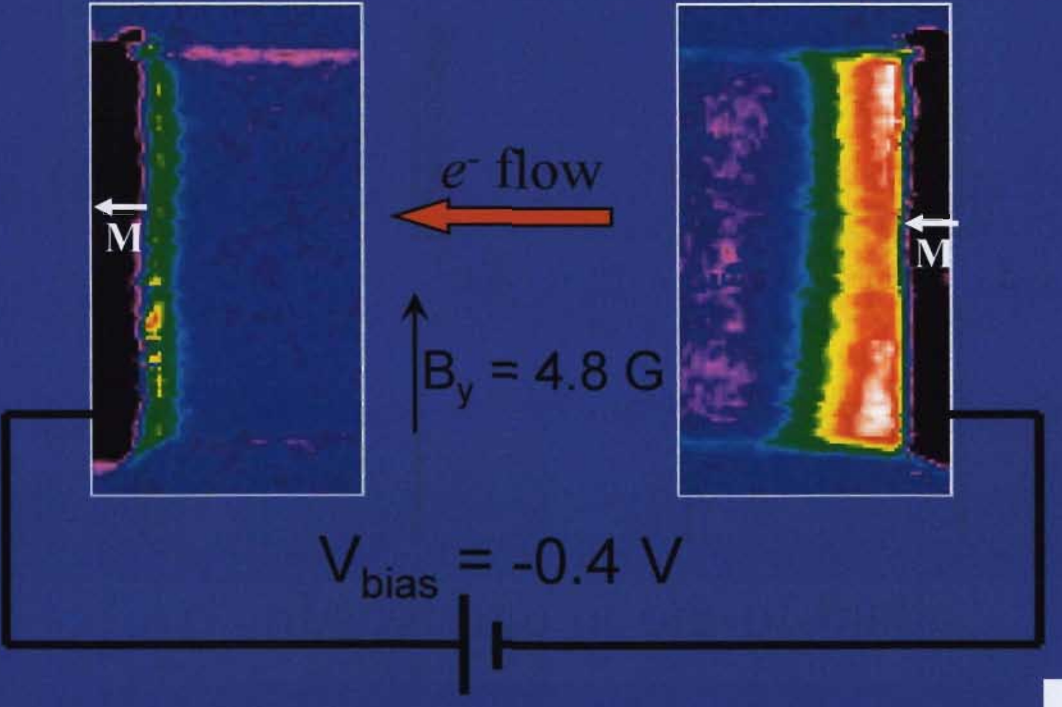
Devices are symmetric





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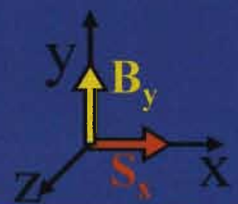
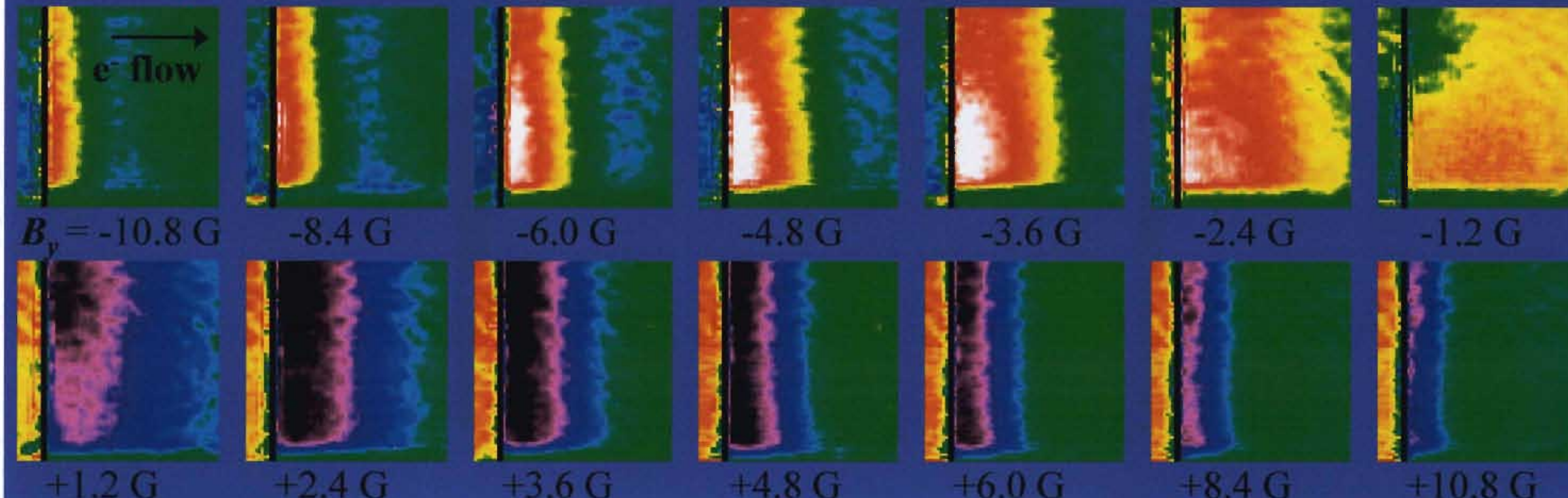
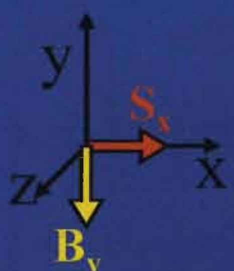
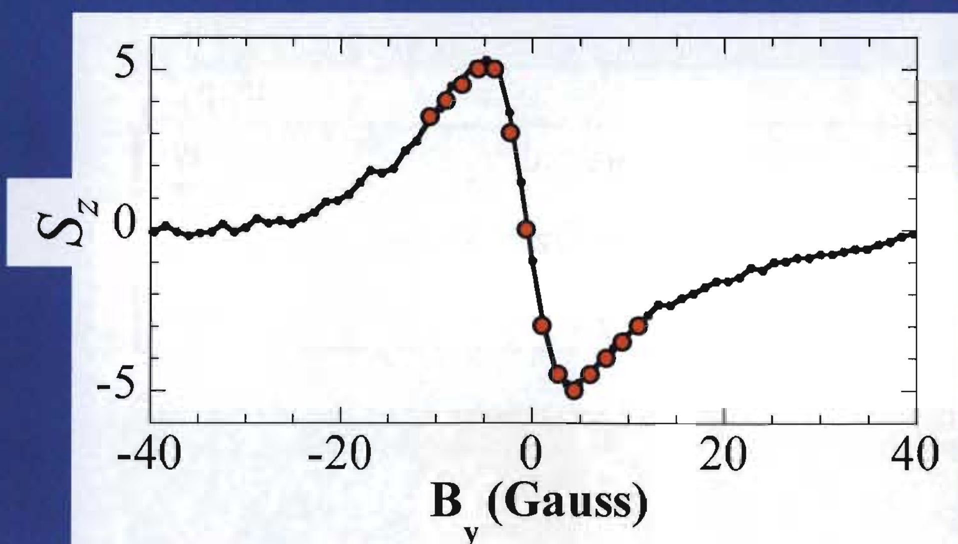
Measure S_z versus B_y : "Hanle curve"

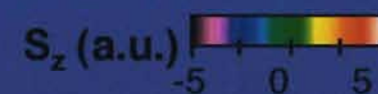


B_y tips S_x into or out-of-plane









- These "Hanle curves" contain all the physics
- *Explicitly* due to spin precession

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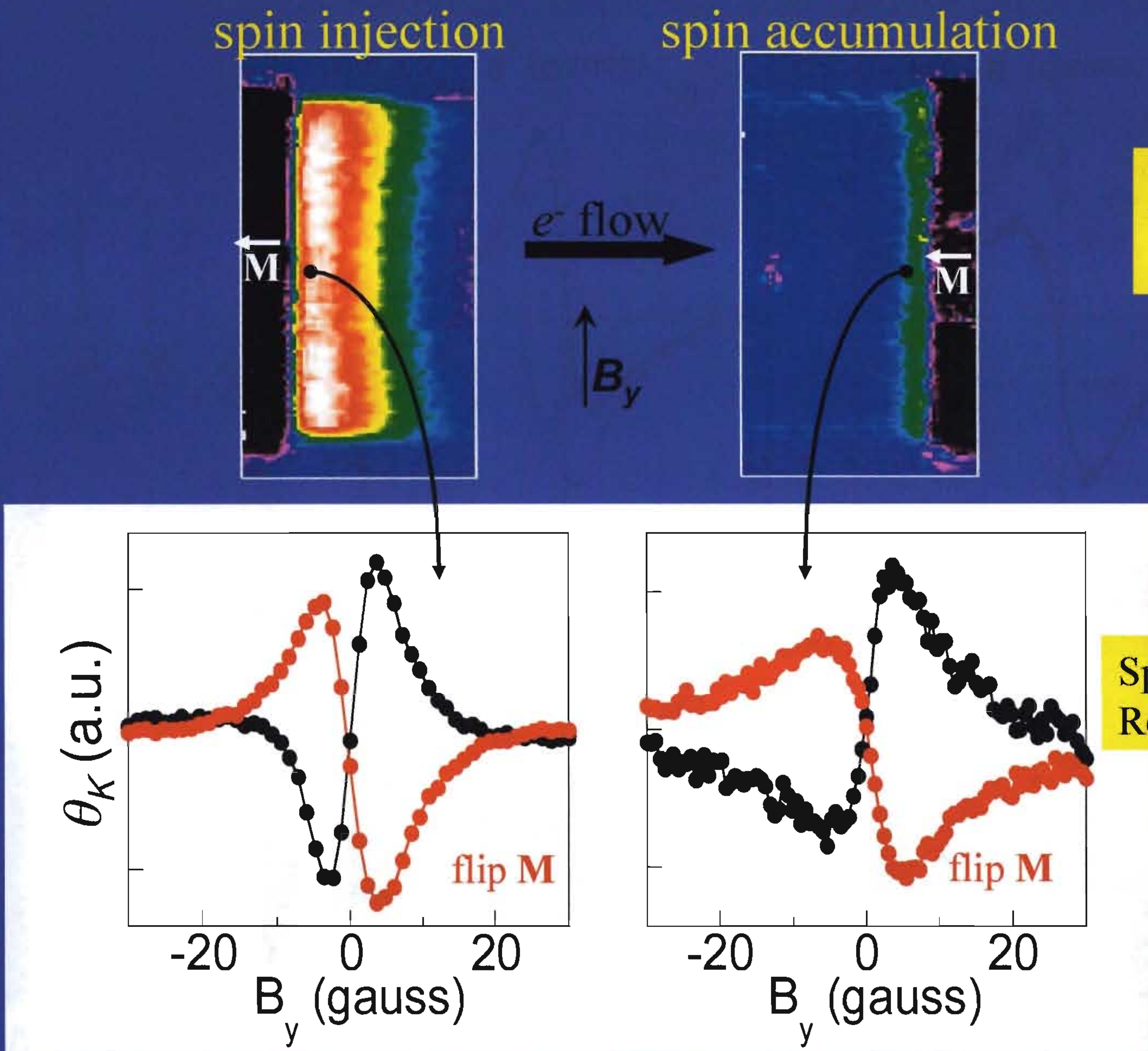
Measure S_z versus B_y : "Hanle curve"



B_y tips S_x into or out-of-plane

Spins are *antiparallel* to **M**
Reverses when **M** reversed

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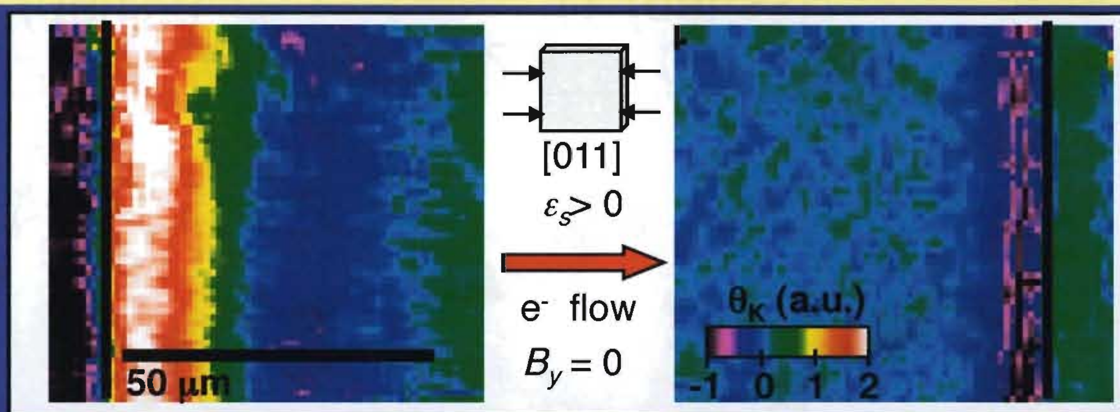
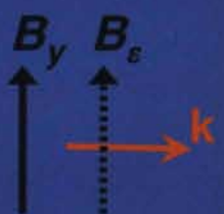
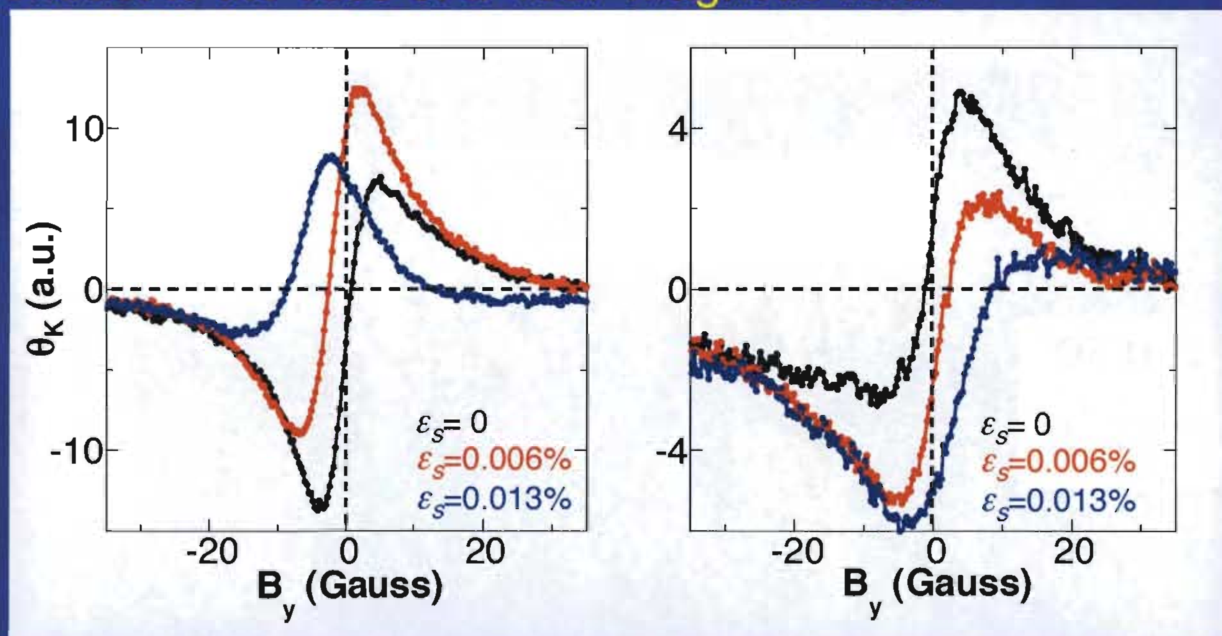
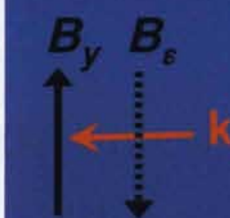
What's the momentum of accumulated spins? Strain the sample:



- $B_y = 0$, $B_\varepsilon > 0$: Signals from opposite ends of channel have opposite signs, in contrast to the case of a "real" magnetic field!



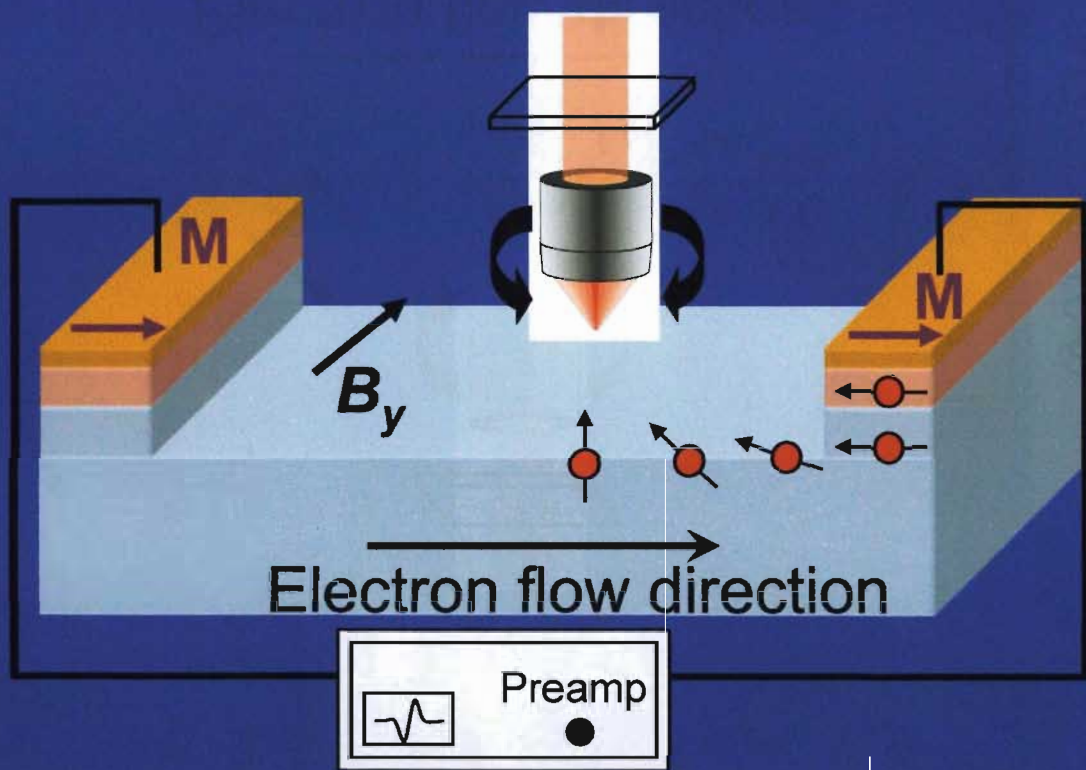


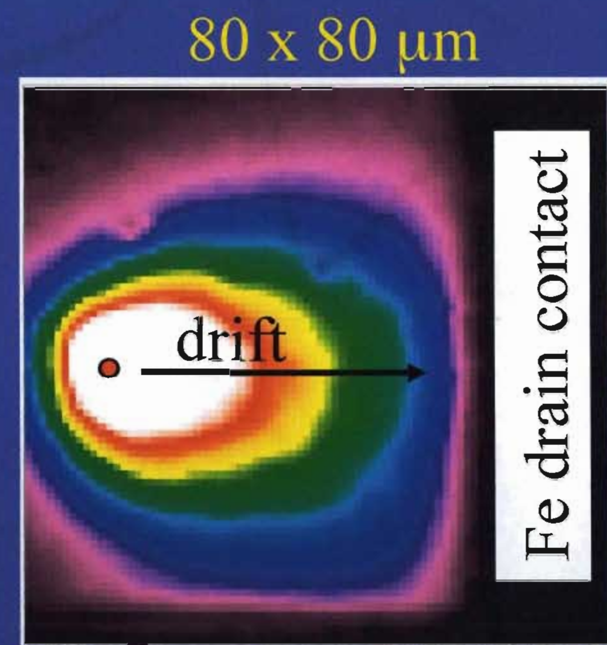


- At opposite ends of the channel, Hanle curves shift in *opposite* directions w/ strain. The (diffusive) spin current at the drain is flowing *against* the charge current.

Electrical spin detection: Ferromagnetic drain contact is spin-sensitive

- Measure changes in device conductance (ΔG) due to spin-polarized current at drain contact





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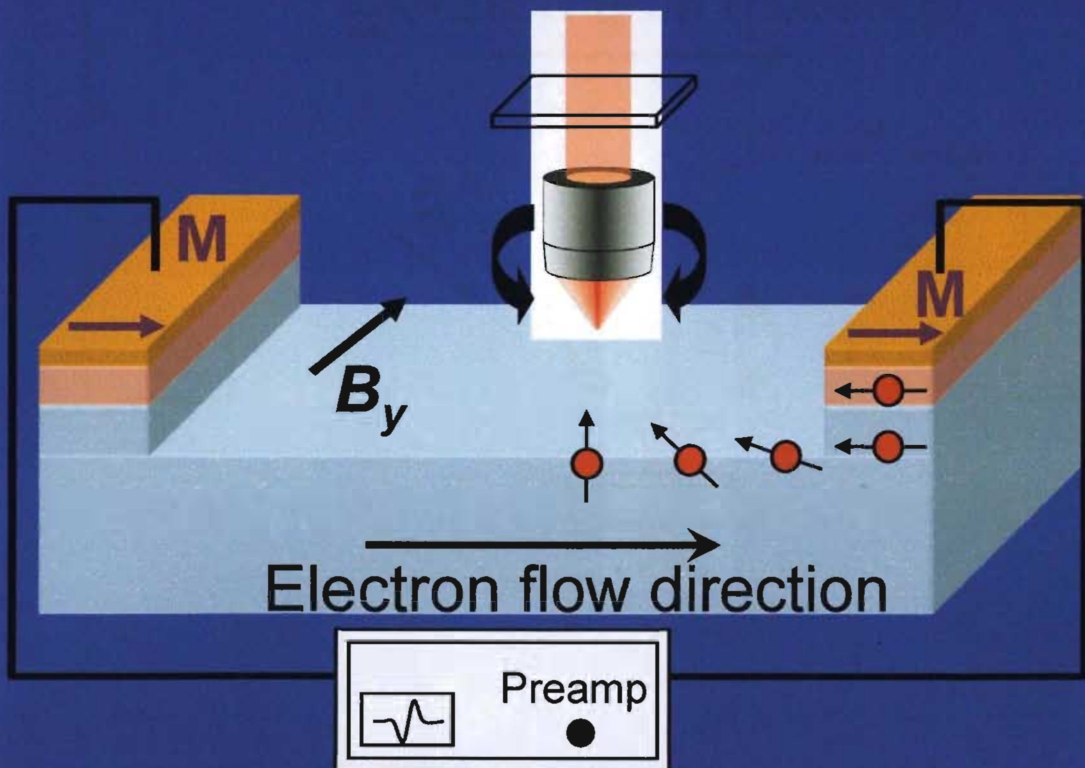
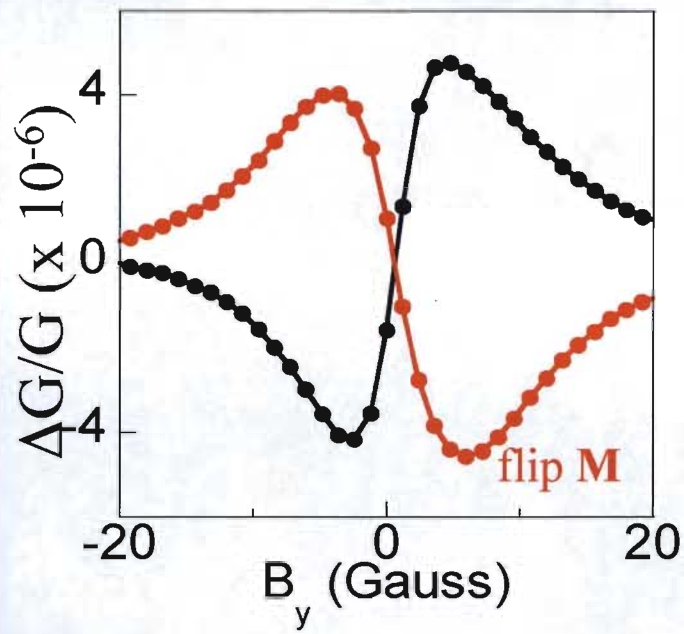
Ferromagnetic drain contact is spin-sensitive

- Measurement is effectively the "inverse" of previous Kerr studies
- Fe/GaAs tunnel barriers function both as spin injectors & detectors





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Quantum Semiconductor Spintronics

Classical Bit (Boolean) *0 or 1* *Two states*

Quantum Bit (Qubit) $\alpha|0\rangle + \beta|1\rangle$ *"Infinite" number of states*

Where $(\alpha^2 + \beta^2) = 1$

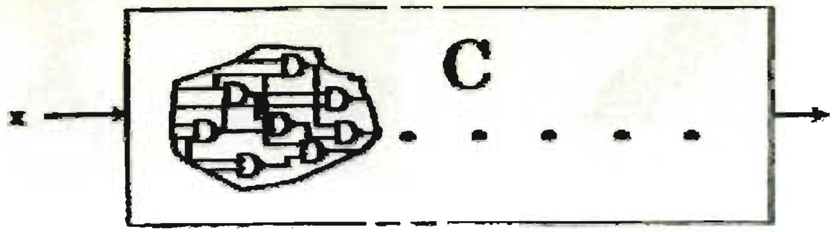
$|0\rangle$ $|1\rangle$ $\alpha|0\rangle + \beta|1\rangle$

"n Qubits is worth 2^n Boolean bits"

Quantum Spintronics

"Intel"

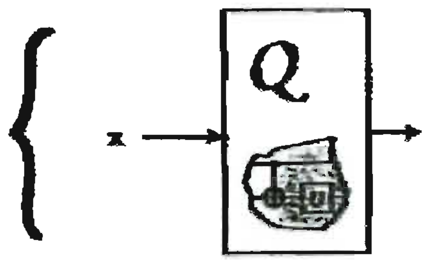
10,000,000 Bits x



f (x)

=

"Quintel" 10 Qubits



f (x)

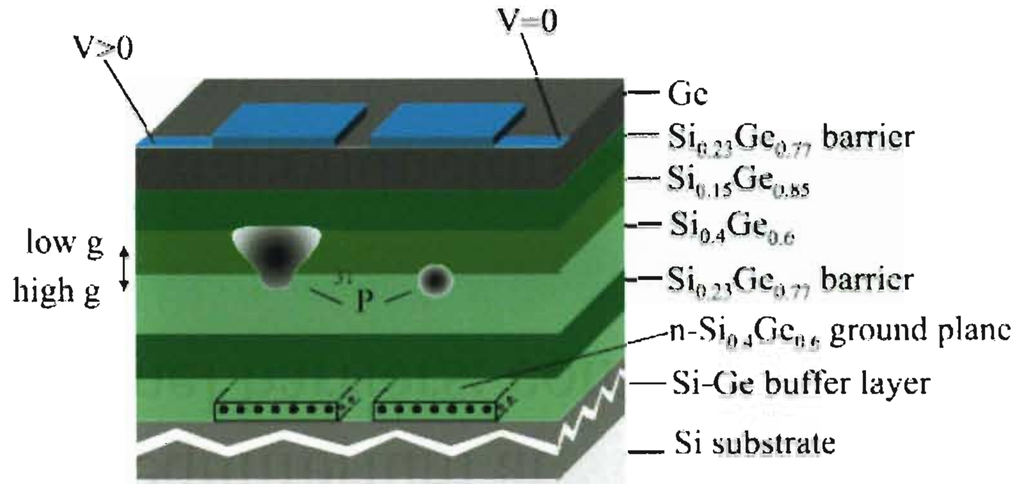
Time →

Factoring: *Given integer **N**, find integers **p** and **q** such that **N=pq**.*
Exponential Speedup: $2^{N^{1/2}} \rightarrow N^2$

Optimization: *Given algorithm for computing a function **g**, find input **s** such that **g(s)** is minimal.*
Quadratic Speedup: $2^k \rightarrow 2^{k/2}$

Qubit Implementations

- ➢ Electron-Spin Resonance Transistor (ESRT):



- ➢ Long Dephasing Times (msec)
- ➢ High Switching Speed (GHz)
- ➢ Uses Silicon Technology And quantum dot expertise

UCLA

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Conclusions

1) Spin-orbit interaction inorganic semiconductors: optical spin injection; optical spin detection

2) Spin injection - break quasi-equilibrium at ferromagnetic interface: tunnel barriers; control doping profile

3) Spin injection into organic semiconductors also requires spin selective tunneling

4) Utilize metal-organic molecules introduce spin-orbit effects

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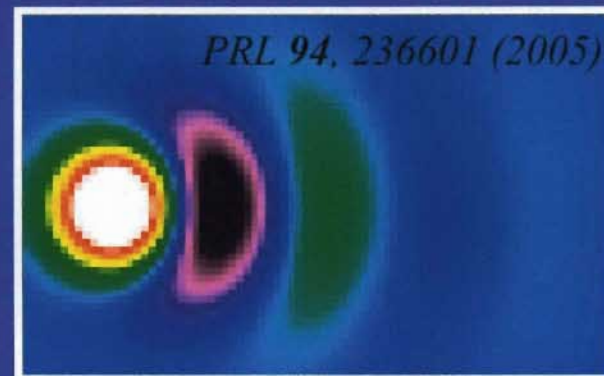
Conclusions

- **2-D imaging of spin flows in semiconductors.**
  - *reveal how flow of polarized electrons respond to electric, magnetic, and strain fields*
  - *applied individually or in combination*



PRL 94, 236601 (2005)

- **Direct |k|-linear coupling of spin to strain**
  - $\boldsymbol{B}_\varepsilon$ *is orthogonal to* $\boldsymbol{k}$ *(similar to Rashba S-O coupling)*
  - $\boldsymbol{B}_\varepsilon$ *chiral for radially-diffusing spins*

- **Robust spatial spin coherence ($B_\varepsilon \sim k$)**
  - *spatial precession period is independent of electrical bias*
  - *potentially useful for future "spintronic" devices?*

- **2-D spin imaging ferromagnetic/semiconductor structures**
  - *electrical spin injection, transport, accumulation, detection*
  - *with Fe/GaAs tunnel barriers as spin injectors* ***and*** *detectors*
  - *all in a single lateral device*

-Science ***309,*** *2191 (2005)*

I predict that there will be SPINS in your future

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